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Innovation in Construction

A Practical Guide to Transforming the Construction Industry

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ISBN 978-3-030-95797-1 ISBN 978-3-030-95798-8 (eBook)
https://doi.org/10.1007/978-3-030-95798-8

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This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The construction industry faces a challenging future. The ability of the industry to rise to the urgent needs of the twenty-first century remains fundamental to ensure the continued prosperity for society. Population growth and increased urbanization are creating a severe shortage of housing across the world, a growing list of ageing infrastructure is in desperate need for upgrade or expansion, an ongoing climate emergency is causing more natural disasters requiring both protection and reconstruction, and there is an indisputable need to achieve all of these goals with less carbon emissions to mitigate the risk of global warming.

Construction is one of the major industries globally and a cornerstone for economic competitiveness and the social well-being of citizens. However, the construction sector is one of the least digitized and automated sectors. This has led to deteriorating productivity, lack of performance optimization in products, a disproportionate number of work-related accidents, long-term health hazards, and a general loss of attractiveness as a career for the next generation of engineers. Given this urgent need for change, it is not surprising that there is a global trend towards greater digitalization in the construction sector using breakthrough technologies supporting technological sovereignty in construction. The construction industry requires exemplar projects where stakeholders demonstrate integrated breakthrough technologies such as additive manufacturing, human robot collaboration (Cobots), autonomous vehicles for construction activities, autonomous maintenance, diagnostics, and monitoring. In addition, the construction sector is experiencing a shortage of skilled labour. A higher degree of digitalization has a significant role to play in making the construction sector attractive for younger generations and in contributing towards making construction sites a safer working environment.

The construction industry is experiencing a major evolution as it enters the era of digital documentation and information exchange. The discipline of design began with pen and ink using drafting boards, then evolved to 2D computer-aided design (CAD), and has now progressed to data-rich 3D building information modelling (BIM) that acts as a key resource for construction and later asset management. At each step along the journey, gains were made in both information density and quality of information exchange. As Industry 4.0 continues to evolve, it is vital that the construction sector continues to implement breakthrough technologies, to ensure that the sector remains competitive and is ready to address global challenges, such as human overpopulation, resource scarcity, and climate change.

Industry 4.0 is a new industrial era in which a range of emerging technologies is converging to provide new digital solutions. Much has been written about these technologies, their potential for driving change and disruption, and the digital futures that may emerge; however, more immediately there is also lack of understanding of how companies can benefit and to implement these technologies in practice. This book focuses on the implementation of Industry 4.0 technologies in the construction sector. Smart manufacturing, smart products, smart supply chain, smart materials, smart working, and smart higher education are important elements for successful, effective, and efficient implementation of innovation in construction. The construction industry is a major economic sector and of high strategic importance, but it is plagued with inefficiencies, low productivity, resource wastage, and environmental issues associated with poorly planned or excessive development. Innovation in construction and the rapid changes in construction processes due to digitalization and globalization signify the importance of developing emerging skills to future-proof both professional and vocational workforces that pave the way ahead for smart and modern construction.

The leap from laboratory-scale success to industrialization and large-scale implementation of disruptive technologies, including novel materials and manufacturing methods, is often a difficult and expensive engineering challenge. Novel materials or emerging technologies that extend to a commercial level are often hampered by limited awareness within the industry and a supply chain that is built around traditional processes. Rather than focusing solely on technological advancements or engaging in a future-gazing narrative, this book aims to provide clear and practical guidance for the construction industry to embrace new technologies to achieve the realization of safer, more sustainable, and enhanced buildings and infrastructure. This will drive continued research into the development of disruptive and novel but feasible technologies.

The construction technology industry has many players offering point solutions that serve existing use cases or, in some instances, create new ones. As such, the construction technology landscape is experiencing a move towards platforms that will need to coexist. As the COVID-19 pandemic has forced many construction players to digitize to ensure safety and productivity, this dynamic will likely continue to be accelerated in the future years. There are significant opportunities to create value for both strategic and financial investors that are involved in consolidation and merging of technologies. The construction industry has invested little towards innovation, new products, processes, or services. Furthermore, the profit margins of the construction industry have been tightening over the past few years, leading to difficulties in financing investments on digital innovation. This trend is likely to be worsened by the economic impact of the COVID-19 pandemic on the sector. Using digital tools often requires an upfront investment from companies, as they need to purchase necessary equipment and software and train their personnel. This initial investment is in theory compensated by efficiency gains and more generally, by the added value that digitization brings. However, the benefits provided by digital technologies are often not clear. This is particularly the case for smaller and medium enterprises that are likely to work on smaller projects, either independently or as subcontractors, where efficiency gains are more limited. Indeed, lack of awareness and understanding is often seen as the main bottleneck for most of the technologies together with cost of equipment and software which is of significance when it comes to investment, for example, 3D printing and robotic devices. As a result, many fear that the implementation of breakthrough technologies would not provide enough benefits to justify the initial investment required. Therefore, governments are increasingly providing support to incentivize construction companies to invest in these technologies. This support may take the form of economic incentives, training, and technical assistance.

There is also an acute misunderstanding of innovation in the industry, what it is and what can be done to nurture and encourage its adoption on everyday projects. An unhealthy singular focus on emerging technology often misses opportunities to make simple changes driven by people-centric strategies. By avoiding common pitfalls and by focusing on the basic components of novelty and value, both transformational and incremental innovation can be achieved successfully through measures promoted by clients, adopted within businesses, and implemented across project teams.

Promotion of coordinated actions and synergy amongst professionals across the various construction phases is crucial to incentivize construction companies down the value chain to implement digital solutions. Currently, there is often a lack of collaboration between professionals involved in a construction project, even during the same phase. The design and construction phases are sometimes not appropriately coordinated and integrated, as construction companies are not involved in the design phase, and this leads to inefficiencies, delays, and potential errors. This hampers the integration of knowledge amongst stakeholders, diminishing the opportunity to influence design decisions and engage with other professionals involved in the methods and breakthrough technologies to be used. It is hoped that the knowledge and insight provided by the many contributors to this book can help readers overcome these barriers.

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About This Book

The Subject of the Book

The book will tackle the challenging and complex topic of implementing innovation and the successful application of advanced technology in a very competitive sector, namely the construction industry. It will provide a practical guide for the transformation of the industry by detailing appropriate and effective implementation methods, required skill sets, and structural changes necessary to facilitate the practical and innovative application of technology. The construction industry is acknowledged to be decades behind other industries in its level of innovation and adoption of technology, and is responsible for, and contributes to many of today's global challenges, such as climate change and resource scarcity. There is, therefore, a need for smarter and more efficient ways of managing available resources. This book will elaborate on how the innovative application of technology could offer hope for the construction industry in its imperative to rise to current and future global challenges.

The Main Benefit of Reading the Book

Construction is an important economic engine, but also one of the largest consumers of resources and energy. Whilst the construction sector has been one of the main contributors to climate change, it must now become the primary mechanism of global response, adapting its long-held paradigms to reverse both its current and historical impact. Smarter and more efficient resource management, including effective use and development of skills that are in increasingly short supply, is crucial in order to continue to make prosperity possible. The modern construction industry, therefore, has a moral and professional imperative to make a dramatic policy shift and prioritize change from short-term profit-making business models to a socioeconomic and environmentally sustainable sector. This book will provide readers from both industrial and academic backgrounds with an A-Z guide on transforming the construction industry with the efficient and effective implementation of technologies and modern methods of construction. This book will include the real-world case studies of innovative projects that go beyond the current state-of-the-art academic research. Projects which have resulted in practical and close-to-market solutions have improved productivity, quality, and performance in the construction sector.

Contents

Editors and Contributors

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Part I
Industry 4.0 and Drivers for Change

Chapter 1
What Is Industry 4.0?

Seyed Hamidreza Ghaffar, Paul Mullett, Eujin Pei, and John Roberts

Abstract This chapter briefly presents an introduction to key technological innovations in construction and their potential/current uses in the industry. Some of these technologies have been written about extensively; however, the summaries presented below are provided as a convenient introduction and reference for subsequent chapters.

Keywords Additive manufacturing · Data and analytics · Artificial intelligence · Robotics and automation · Virtual and augmented reality · IoT · Digital twins · Nanotechnology

1 Additive Manufacturing

Additive manufacturing (AM) is one of the essential components of Industry 4.0. As a result of mass customisation in Industry 4.0, disruptive manufacturing methods must be developed. AM has been recognised as a key innovative technology that is used for fabricating customised parts due to its ability in creating geometries using advanced new materials. AM is already established commercially in many sectors such as aerospace and in healthcare. However, the construction industry's implementation of AM is still taking its first steps. AM and its successful implementation as an eco-innovative practice in the construction industry may offer various benefits which are summarised in Fig. 1 (Ghaffar et al., 2018).

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_1

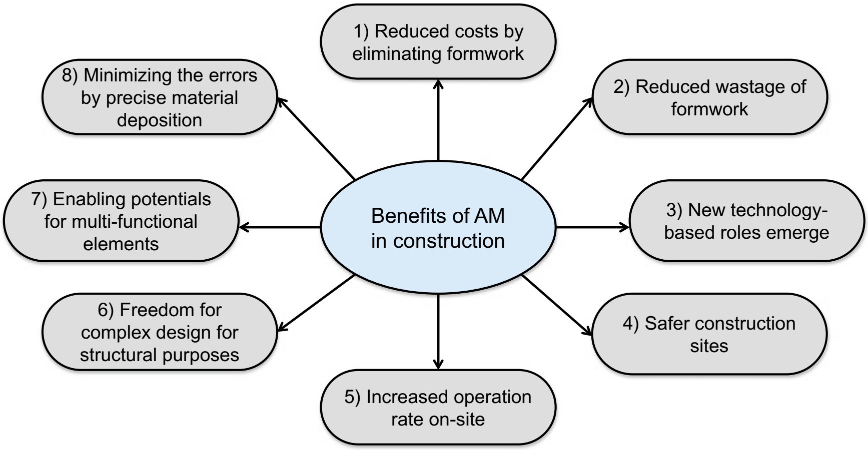

Fig. 1 Opportunities presented by AM for the construction industry (author's original)

Additive manufacturing (3D printing) of concrete in the construction industry has become the subject of rapid emergent research activities around the globe. It has the potential to open new applications for the construction industry. There are seven types of additive manufacturing processes that have been established by ISO/ASTM, namely material extrusion, vat photopolymerisation, powder bed fusion, material jetting, binder jetting, sheet lamination, and directed energy deposition. The most common process being used in the construction industry today is material extrusion, and often with use of cementitious material to create structures. The AM research for concrete is exponentially increasing through innovative projects and cementitious-based materials, which are often addressed using the generalised term '3D concrete printing' (Buswell et al., 2020; Ghaffar & Mullett, 2018; Ghaffar et al., 2018) Large-scale AM with cement-based mortars, known as 3D concrete printing (3DCP), has emerged in response to the call for the modernisation of the construction industry and its manufacturing strategy (Reconceiving the Global Trade Finance Ecosystem, n.d.). The current methodologies of AM with concrete could be categorised into these main groups: (1) deposition by extrusion, (2) application by spraying, (3) selective binding, (4) adaptive sliding formwork, and (5) reinforcement mesh as an integrated formwork (Mechtcherine et al., 2019). It is worth noting that the aforementioned categories are not exclusive, and comprehensive grouping of current and potential future approaches is still continuing in the growing 3DCP community, (e.g. RILEM TC 276-DFC 'Digital fabrication with cement-based materials'). The most promising AM technique for 3DCP is extrusion-based processing, producing elements or layers that are self-supporting. The international community of 3DCP has validated a wide range of applications, but the field needs to move from one-off production to routine production in volume. To do this, standardised approaches for testing and evaluating the parameters that affect the performance of the manufacturing system and the materials used are needed. This should be considered in the context of the design and application of the product being manufactured. In addition, there is also growing interest in wire arc additive manufacturing (WAAM) which is a deposition process that involves the use of an industrial robot linked to a welding machine. Large objects such as functional bridges and structural components have been produced by stacking welded parts on top of each other using welding wire. As AM is a digitalised form of production connected with operational systems for control, monitoring, and production, it offers strong links within the scope of Industry 4.0, enabling digital transformation and value creation within the industrial value chain.

2 Data and Analytics

Construction data is reaching a tipping point for innovation, described by some as a 'digital transformation'. The impact of digital technologies has been felt for the last four decades, but uptake has been patchy and not part of any industry-wide whole. In the last ten years, several technologies and methodologies have achieved sufficient uptake to bring a much-anticipated goal into sight—a seamless, value-adding flow of data starting from client needs, through to design, to construction, and finally into asset use and reuse. This data platform has the potential for being a key resource and repository for all aspects of Industry 4.0 across the construction sector. This has not been a linear process. Several strands of thought have combined over time with developing software and associated skills. It is unlikely that this evolution is yet finished.

2.1 Construction's Historic Data Problems

For the last forty years, a constant increase in computing power has been a key driver of innovation in construction. Initially, this was seen as the ability to analyse more rapidly, reliably, and completely, but of increasing importance has been the ability to store, share, access, and coordinate data. Frustration has often been voiced about construction's slow adoption of data and analytical methods already implemented in other industrial sectors. These are explored more fully in Chap. 6, but three of the key obstacles for data usage have been:

1. Construction is a 'mature' sector and design, and construction is competitive and commoditised with low profit margins. The risk of making a loss means that a new information technology has often been perceived as a risk, not an opportunity.
2. A large percentage of each project is unique. Even when building relatively standard infrastructure, the local conditions mean new design work is needed and

there are bespoke construction constraints. How can data from these dissimilar assets be useful in future?

3. Construction has a ‘dis-integrated’ supply chain, where clients, designers, contractors, and owners are often separate companies. Why should a building designer spend time and their own money, creating better data when they are not the ones that will financially benefit?

Now, these barriers are being overcome through industry-wide data and management standards, smarter procurement, and the adoption of more modular components, but adoption remains a key issue that every client, consultant, and contractor must address on every project.

2.2 *The Development of Analysis*

Structural designers have been key early adopters of new data tools—possibly because a structural model capable of being analysed can be more simply defined with 1D and 2D elements than, say, the performance of an air conditioning system.

Computerised structural analysis crossed the threshold from universities into practice with Arup’s design of the Sydney Opera House during the late 1960s (Computers and the Sydney Opera House, n.d.) where physical models, graphical analysis by hand, and purpose-written software for a mainframe created a structure right on the edge of what was possible. Analysis jumped to smaller computers based in the design teams in the mid-80s, was reinforced by spreadsheets in the early 90s, and then moved onto every designer’s desk towards the end of the decade. Subsequently, the innovations in structural analysis have been less dramatic, characterised mainly by speed and capacity. Outputs are recognisably like 25 years ago. In areas such as natural ventilation, people flow, or fire engineering, the ability of this new computing power to deal with the complexity of many interrelated calculations has opened analysis areas previously impossible. Recently, cloud computing has brought a further increase in analytical power. The ability for multiple designs versions to be assessed, each incrementally different, is allowing optimised answers to be better identified.

2.2.1 The Development of Drawing

Despite both aeronautical engineering and shipbuilding having previously implemented 3D wire frame modelling, UK construction’s move from drawing board to screen did not happen until 1984 when Arup Associates implemented Computer Aided Design (CAD) on the Broadgate Development in London. All drawings were produced as coordinated 2D information using general drafting system (GDS) that McDonald Douglas had developed for aircraft design. Project success led to the rapid adoption of CAD throughout UK construction, based mainly on Autodesk for buildings and MicroStation for infrastructure. Despite many other sectors abandoning

2D drawing, construction's focus remained using new technology as a faster way to produce conventional 2D drawings.

In 2002, Autodesk abandoned their efforts to evolve their existing products into 3D, instead acquiring Revit (Autodesk, 2002). Whilst uptake was initially slow, around 2010–11, many structural engineers realised it was cheaper to generate their 2D drawings from a 3D Revit model. Architects soon followed, and buildings began to be coordinated in a confederated 3D model. The complexities of building services meant that software frustratingly initially lagged around two years behind, but pressure from designers and clients meant progress was rapid. A key early issue was how much detail to put into the model. Psychologically, a 3D model gives the client the impression that the building 'virtually exists' and that design is complete and coordinated. The truth is often far from this, whilst many designers were drawn into the possibilities of the software, adding undesigned details just because was possible. Contractors were frustrated as designers, then retreated to the 'do not scale' approach of their 2D drawings, meaning model data still could not be trusted. Frameworks called Level of Development (LOD) have evolved that define how modelled objects should develop and refine during the design period. For example an initial design by the mechanical engineer will only show a zone for future ducts, insulation, and hangers, 'booking space' in future building. This will later be replaced by exact duct size when calculations are completed. Finally, the contractor may replace this data with the manufacturer's CAM model for every bolt, baffle, and hanger.

2.2.2 BIM—Building Information Management

The development of CAD through 2D and 3D, and the increasing reliance placed on it meant that management of this data became increasingly important. Before CAD appeared, drawings were literally sheets of paper hanging on racks. Drawings were 'checked out' by the drawing office clerk and then checked back in once updated. The information was managed and stored securely. The rise of CAD and accessibility through networks in the 80s and 90s broke this discipline down. Offices saved space by removing physical drawing storage and then decided there was no role for a drawing office clerk. Ease of access allowed easy copying or deleting of files, and finding current information in unstructured data became increasingly difficult.

The need for construction data to be managed had been recognised as early as the 1970s or 80s; however, it seems the arrival of 3D models and the added data complexity brought this to the fore. In 2002, Autodesk released a white paper (Ruffle, 1986) entitled 'Building Information Modelling', including the acronym BIM, and this term started to be used across construction. Over the next decade, it was recognised that data complexity was not only from models, but also all the other documents, spreadsheets, and other file types now needed. The BIM acronym slowly shifted from 'Building Information Modelling' to 'Building information Management'. There was nearly always a model, but the management issues were much wider than just that. Whilst software has been driven by US companies, implementation of information management standards has been led by UK initiatives. In 2011, the UK government mandated that all publicly funded projects would need to adopt 'BIM Level 2' as a minimum by 2016 (GOV.UK & Government Construction Strategy GCS, 2016). This triggered adoption across all UK projects and was paralleled by several other countries. BIM Level 2 was defined by PAS1192-2 in 2013, requiring storage of data in a Common Data Environment (CDE). Developing data passes stages of work in progress, shared, published, and archived. In 2018, this standard became ISO 19650-1:2018 gaining worldwide adoption, reinforced by documents such as RIBA's 'Digital Plan of Work'. The innovation enabled by industry-wide adoption of these standards should not be underestimated. It has been key on the journey from data chaos to managed information.

2.2.3 Enabling Wider Model Use

As computing power grew, all other stakeholders in the construction process—clients, contractors, quantity, and land surveyors, etc.—were developing techniques and thinking, but these often replicated non-digital information. Once coherent design models were produced by designers, there was immediate pressure across the project team to gain data access. Designers worried about increasing liabilities when others used these models and issued these 'for information only', but as access to CDEs grew so did the web of information referencing these models. New questions began to be asked. 'How do I find all the columns on the project?' 'How do I know which columns are steel and which are concrete?' Modelling software was based on parametric data, where a type of object 'knew' bespoke information about itself. For instance inspecting a column's data would show length, cross-section, and material. For reuse, this needed to be in consistent formats with a standardised reference.

Three key classification types now underpin construction's data predate the surge of model adoption after 2010:

(1) Industry Foundation Classes (IFC): a platform neutral, open, object-based file format, used for data collaboration, currently administered by buildingSMART. It originated in from a US industry consortium led by Autodesk in 1994.

(2) Uniclass: a standard classification system organising construction data at all scales, from buildings to individual bolts and currently administered by the UK's National Building Specification (NBS). It was created in 1997 by the Construction Project Information Committee (CPIC).

(3) Construction Operations Building Information Exchange (COBie): an international standard that captures and references project data at the point of origin. The wide scope encompasses models, data sheets, warranties, and maintenance information. Developed by the Construction Engineering Research Laboratory in 2007, it is now administered by buildingSmart.

Classification systems are now incorporated into all the main BIM software platforms, allowing easier, more reliable data reuse. Their application has been a key step in managing the previously unorganised data.

2.3 Data Use by Contractors

Computer Aided Manufacturing (CAM) in the 1980s saw the adoption of electronic data by many specialist subcontractors. As an example, major steel fabrication companies generated 3D models of complete structures, including all bolt holes, stiffeners, and welds that could then be fed digitally to the fabrication line. Amongst the first, uses of data by main contractors were project schedules and Gantt charts. Two of the earliest software systems were Primavera, launched in 1983, and Microsoft Project in 1984, but all these systems were 'stand-alone' without links to other data sources.

As 3D models gain adoption around 2010–11, contractors recognised the potential to use '4D-software'—adding the 'dimension' of time. By establishing links between model elements and activities on Gantt charts, animations of construction progress were generated and use of classification names gave a data 'handshake' that could make generation and revision almost automatic. Subsequently, contractor use of model data has grown both in amount, scope, and variety. BIM Execution Plans (BEPs) are controlled by the main contractor when the contract is won and define how the design, manufacturing, and construction supply chains must deliver data into a collaborative CDM.

Inability to work to the required data standards is a barrier to entry for many tenders. Use of models has expanded far beyond design and now forms a 'single source of truth' for cost, manufacturing, safety, stainability, logistics, and more. Several contractors consider that the digital framework and behaviours underpinning their work are well beyond the definition of BIM, and Laing O'Rourke uses the term 'digital engineering', which is gaining increasingly wide adoption. Increasingly, site offices require meeting rooms with large screens to facilitate multi-disciplinary reviews, where all project stakeholders discuss issues around a clash-fee model, confederated from the latest designer and sub-contractor data. This emphasis on early review and forward planning pays dividends by reducing the risk of errors and increasing productivity. In effect, the project is built twice—once virtually and then once in reality.

2.4 Data Use by Asset Owners

Many designers initially believe that BIM data could be easily delivered to a client at the end of a project to provide an improved resource for future operation. Useful asset data has proved much more complex and is the next key area for development. Traditionally, designers and contractors would issue 'as built drawings', updated with all the changes during construction, after the handover of the project. The advent of the Construction, Design, and Management (CDM) Regulations added the requirement for a Health and Safety File together with other maintenance documents at handover.

Alongside these uncoordinated printed documents, the owner's facility team would generate lists and spreadsheets of the assets they needed to track and maintain—doors, windows, boilers, and lightbulbs. Some software solutions were developed to help with this, but data quality was low, with no direct linkage to design information, and data was often out of date. This has become an important area for improvement as infrastructure needs to become part of a sustainable, optimised, networked whole. In 2018, the UK government launched the National Digital Twin Programme (NDTp) run by the Centre for Digital Built Britain.

This is now defining the data standard that projects must deliver alongside the physical product—in effect, a virtual deliverable alongside the physical one. The aim is to offer 'better outcomes for all stakeholders per whole-life pound spent in the built environment' (Bolton et al., 2018) across society, the economy, business, and the environment.

2.5 *Data and Analytics Now—A Platform for Industry 4.0?*

Despite a fragmented industry, the evolution of 3D models, the evolution of data standards, and, most recently, definition of digital twins offer a future with coherent data to support innovation. Software tools are available, and skills have developed to author, view, and reuse data. Methodologies and standards have been set for the storage and flow of information.

Construction Technology (ConTech) is a term now used to describe the many startups leveraging this data to optimise design, logistics, and operations. Individual and corporate behaviours remain a key barrier or enabler for effective data use. Increasingly, team members expected to behave collaboratively, and contractual frameworks such as the Institution of Civil Engineer's Project 13 aim to overcome past barriers to information flow. Construction's data platform for Industry 4.0 seems finally to be coming into focus.

3 Artificial Intelligence

Of all the emerging technologies, artificial intelligence (AI) is perhaps the one that provokes the greatest emotive response amongst the general public. Science fiction, and in recent decades popular culture generally, has watched very closely the development of AI and its potential to enhance our lives or—hopefully overdramatically—wreak untold terror and destruction. Of course, with Hal and Skynet as a baseline reference, it can be difficult to have an informed discussion on the subject that remains rooted in realism but also acknowledges future opportunities and risks. AI is, however, an enabler for many other forms of emerging technology and so an awareness of the subject is, therefore, vital to understand how AI is likely to impact both industry and wider society.

The fact is AI is an incredibly broad, complex, and specialised subject. Categorising it as a single emerging technology is technically incorrect—indeed, it has been recognised as a formal discipline since the 1950s when it was defined to differentiate its specific area of research from the more general discipline of cybernetics. Forms of AI have been used in many industrial applications for decades; however, the last decade has seen aspects of the technology breakthrough; permeating our day-to-day lives and becoming technically more accessible, leading to an exponential increase in its disruption potential.

In general terms, artificial intelligence is a definition which aims to distinguish it from biological intelligence. This is semantically deliberate and a great place to start in understanding its definition. AI is essentially any non-biological system that can undertake cognitive operations that would typically be associated with the human mind. This definition then splits into two: artificial general intelligence (AGI) (or sometimes termed strong AI) and narrow AI (or weak AI). The former is associated with machines that can replicate natural biological intelligence to a level commensurate with the human mind, whereas the latter is associated with forms of AI which are focused on operating within specific areas of cognition. Whilst AGI is acknowledged as a growing field of scientific research (and perhaps more aligned with science fiction representations), all practical applications of AI reside squarely in the category of narrow AI. There are many different approaches to AI, each distinct and using different methods to provide a solution to the particular problem at hand, and these approaches again divide into multiple subsets creating a myriad of techniques. At a high level, the approaches can be categorised into five 'tribes' (Domingos, 2017) as follows:

1. Symbolists—including inverse deduction approaches such as decision trees
2. Connectionists—including backpropagation machine learning methods such as neural networks and deep learning
3. Bayesians—including probabilistic inference algorithms such as Bayes theorem and Markov chains
4. Evolutionaries—including systems that mimic natural selection such as genetic algorithms
5. Analogisers—including systems that infer similarities such as the support vector machine.

Boosted by increasing computational power, the development of artificial neural networks, research with an emphasis on real-world problem solving, and increasing access to large amounts of data, AI has seen significant advances in recent years and is now present in many facets of everyday life and across a range of industries. Examples of applied AI are as follows:

- Natural language processing (NLP) is the ability for machines to read and interpret human language. It is used in automated telephone answering systems and personal digital assistants such as Siri or Alexa use NLP to understand spoken language and to articulate responses. NLP is also used in machine translation algorithms which are now found routinely on the Internet. NLP can be extended to write journalistic articles and even books.

- Machine perception encompasses AI technologies that enable machines to take input from sensors in order to understand the physical world. Applications include speech recognition, facial recognition, and object recognition, and it is, therefore, used side-by-side with machine learning in applications such as self-driving cars, robot vacuum cleaners, and industrial robotics.
- Machine learning (ML) includes a range of techniques that enable machines to learn from experience. ML is used in search engines, social media apps, and e-commerce sites which are constantly harvesting data on our activities and using this data to understand our behaviours and preferences. This information is then used to target news, advertisements, or product recommendations that may be of interest. ML is now finding its way into many other areas of industry. For example the healthcare industry has seen significant benefits in the use of ML to improve drug discovery and better diagnostic pathology, self-driving cars utilise ML to better understand the terabytes of road data collected, automated financial assistants learn about their clients' preferences, and personal digital assistants use ML to develop a better understanding of their users' habits and routines.

In the AEC industry, the use of AI has yet to become common place, with projections for its use described as only modest (Artificial Intelligence: Construction Technology's Next Frontier, n.d.). Usage to date and interest in its potential have, therefore, fallen behind other industries, such as telecommunications, financial services, and automotive, many of which have identified clear value propositions for its adoption.

Nonetheless, AI has made some inroads into the AEC industry with developments taking place for specific usage cases such as the following:

- Planning, logistics, and risk mitigation—The AEC industry has a poor reputation for delivery and so the application of AI in planning and risk mitigation is a logical step forwards. With large and complex projects, it can be difficult to fully appreciate the multiple interconnectivities and interdependencies in scheduling and logistics, particularly projecting forwards based on actual monitored progress and incorporating anticipated delays. AI can be applied to find patterns in schedules, identifying key interdependencies, and critical path issues to assist in providing greater surety and mitigating delay risks. Examples of AI-powered scheduling software are Alice (Stop Scheduling. Start Optimising, n.d.) and nPlan (Data-Driven Risk Analysis and Assurance, n.d.).
- Generative design—So-called generative design encompasses a range of AI technologies that can be used to generate and explore multiple design options and to optimise solutions based on user-defined goals. Genetic algorithms and forms of topology optimisation can develop many more solutions far more quickly than humans and used appropriately can also remove bias in solution generation. Examples include TestFit (Solve Deals Instantly with TestFit, n.d.), Autodesk Refinery (Project Refinery Beta, n.d.), and open source algorithms such as Galapagos (Evolutionary Computing, n.d.) and Millipede (Grasshopper, n.d.) used with Grasshopper (Grasshopper3d, n.d.).

- Safety monitoring—The use of machine perception via site cameras and machine learning tools to monitor site staff and to look for hazards is gaining significant interest; being able, for example to identify staff who are not wearing PPE, vehicles that are operating in undesignated zones or to find missing edge protection. Combined with Internet of Things (IoT) data, AI can be used to identify hazards or issues arising from movements of people, plants, or materials. Examples of currently available technology to monitor and manage site safety are Smartvid.io (newmetrix, n.d.) and Indus.ai (Construction Intelligence, n.d.).
- Site progress monitoring—Combined with the use of reality capture via drones or robots such as Spot (Bostondynamics, n.d.) or on-site workers, AI can be used to interpret progress and report against 4D programme data held in BIM models and scheduling engines. Of course, when also combined with IoT data, AI can be used to provide a by the hour update on construction progress. An example of this technology is Buildots (n.d.) and the collaborations between Trimble and Boston Dynamics (n.d.).

4 Robotics and Automation

Developments in robotics and automation have exposed a significant gap between industrial and academic research. Industry's focus has been automating standard earthmoving equipment and implementing prefabrication to lessen the on-site work, whereas academic focus has mostly been on ambitious and sometimes vague proposals for on-site additive manufacturing or discrete assembly, which may have limited applicability for the industry. Robotic technology for on-site applications is an evolving research field in the construction industry, where AM, automated installation systems, robotic assembly systems, and robotic bricklaying methods seem to have been the most investigated areas with a potential to encourage the development of robotics implementation in the construction industry (Bock & Linner, 2016; Buswell et al., 2007; Ghaffar et al., 2018; Gharbia et al., 2020; Khoshnevis, 2004). It is worth mentioning that most of the research conducted at universities and research institutes is often based on single construction products and activities, such as vertical reinforced concrete elements, steel beams, masonry walls, curtain walls, gypsum boards, and floor tiles. Only very few projects have proposed a fully integrated robotised construction site.

Robotics and automated systems have the potential to address the inefficiencies and low productivity of the construction industry; however, the level of adoption is very low. Several indicators suggest that conventional construction methodology has reached its limits. Using robotics and automation in the construction industry could lead to significant advantages such as reducing injury rates, conducting repetitive tasks reliably, and enabling construction activities in settings that are not currently possible, such as post-disaster habitation, in dangerous or challenging environments, and for extra-terrestrial environments. A fully autonomous construction system that operates without human intervention would be best suited for the aforementioned scenarios. This autonomous system should be able to handle unpredictable and changing conditions during the course of its operation for successful completion of the project. Since the early 80s, utilisation of robots in construction has been examined (Haas et al., 1995).

Warszawski (1984) published one of the first analyses on the use of robots in the construction industry, suggesting several different robot configurations to address various construction tasks. Around the same time in 1988, Skibniewski (1988) reported the generic expert system framework for robot implementation decision support that would purposely be suitable for all possible scenarios in the construction industry. Implementing the expert system was intended to contribute to more effective designs of construction robotics by providing comprehensive feedback to the robot designers. This should have led to a more successful application of using robots for the construction industry. However, to date, the use of automation in construction is still in its infancy, although it can be expected that with continued effort in research, these approaches could be adopted on a much larger scale. Robotics and automation have been keenly and successfully utilised in various industries since the 1970s; however, their implementation in the construction industry has still not been fully exploited and rare. Research conducted on this topic has shown that the industry's productivity has deteriorated and not been able to keep pace with the overall economic productivity (Bock, 2015). There are several reasons including: (i) resistance to bring together changes in a traditional, conservative, and sensitive sector, (ii) little mechanisation of construction processes, (iii) poor collaboration and data sharing. These reasons are just some of the major issues that make implementation of new methods extremely difficult. More specific challenges include: (i) contractor's economic factors, (ii) client's economic factors, (iii) technical and work-culture factors, and (iv) inadequate business case factors (García de Soto et al., 2018).

Achieving the goal of an entirely autonomous construction would entail more consideration, including: (i) site preparation, (ii) materials to be used by robot systems (e.g. 3D printable building materials suitable for AM on-site), (iii) embedded sensors, and (iv) coordinating operations between robot systems. Achieving incremental developments to advance technologies could be beneficial for the industry in the short term, but there are substantial limitations to incorporate autonomous equipment designed for human operatives (Melenbrink et al., 2020). Importantly, innovative hardware needs to be developed for specific construction-related tasks and in each case based on essential principles and at an applicable scale. This signifies the importance for an increase in interdisciplinary research and stakeholder collaboration with the construction industry.

5 Virtual, Augmented, Mixed, and Extended Reality

The terms virtual reality, augmented reality, mixed reality, and extended reality can be confusing and are often used interchangeably. In fact, these terms have specific meanings with reference to the reality-virtuality continuum introduced by Milgram (2011) shown in Fig. 2. The continuum describes the full range of experiences from the completely real 'physical reality' through to the completely virtual 'virtual reality' (VR). This whole continuum superset can be referred to as extended reality (XR) where the 'X' denotes anything that sits within it.

VR, as noted, refers to one extreme end of the continuum which describes wholly virtual environments without the presence of any objects or physical reality. Mixed reality (MR) covers the subset of everything that lies in between where there is an element of both (but excludes VR and physical reality which lie at the extremities).

Augmented reality (AR) refers to a specific zone on the continuum where physical reality is augmented, or added to, with an overlay of digital information. This is opposed to the lesser-known term 'augmented virtuality' (AV) which describes a zone on the continuum where virtual environments are augmented by real-world objects.

Of the various technologies seen on the reality-virtuality continuum, VR was the first to be developed and was a pre-cursor to all others. The modern idea of VR is synonymous with Jaron Lanier whose company, VPL Research (which was founded in 1984), developed some of the original concepts of VR and the first commercial VR hardware including the DataGlove, the EyePhone, and the DataSuit. Whilst companies such as Mattel, Atari, and Autodesk attempted to explore VR for low-cost commercial and consumer applications, VR remained limited primarily to research and high-budget commercial and defence applications only throughout the 1980's.

The 1990s witnessed VR enter the mainstream with the introduction of consumer hardware by both Sega and Nintendo. The movie Lawnmower Man also launched VR into the public's consciousness (and featured genuine hardware by VPL Research). However, there was little progress in commercial or consumer VR until the 2010s, when computing power, software, and screen technology started to finally facilitate experiences that were commensurate with expectations. Indeed, VR is the most immersive of the experiences on the reality-virtuality continuum, and so the development of head-mounted displays (HMD) with sufficient resolution, manageable size, and weight, and reduction of visual lag was paramount to its wider uptake.

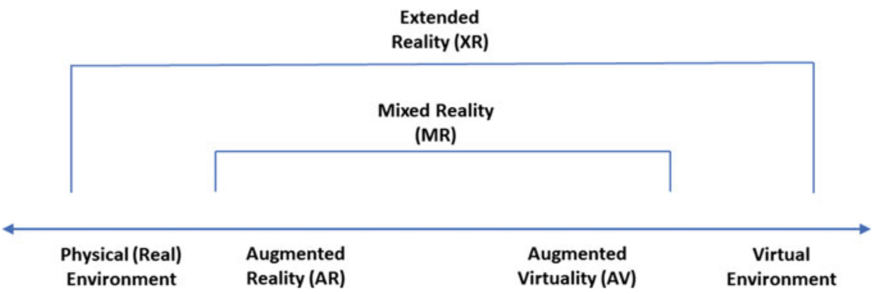

Fig. 2 Reality-virtuality continuum (author's original)

Commercial VR hardware now includes Oculus, Valve, Google, Samsung, PlayStation, and Microsoft amongst many others. The range of practical applications continues to increase including gaming, 3D cinema, design collaboration, business meetings, education, virtual social worlds, art and design, and a growing range of workplace simulations such as surgery, flight training, construction sites, mines, and the military.

AR (a subset of MR) offers an alternative experience to VR and, therefore, leverages different technologies and is suitable for other kinds of practical applications. AR is not immersive in the same sense as VR and, therefore, encompasses a range of possibilities, however, typically uses a physical environment which is augmented with additional digital objects or data, some real-time interaction between the physical environment and the digital objects or information, and an accurate 3D registration of digital and physical objects. This functional combination lends itself to several types of technologies that can provide the necessary AR experience depending on the application including; heads-up display (HUD), head-mounted display (HMD), smart glasses or lenses, and mobile devices.

Although AR has been a subject of research since the 1980s, it only entered mainstream consciousness in the mid-2010s with the launch of devices such as Google's smart glasses, Google Glass, and Microsoft's HMD, Hololens. However, it was the launch and meteoric rise of Niantic's Pokemon Go game for use on mobile devices that really brought AR into the public eye.

Whilst Google Glass and Microsoft Hololens have targeted high-end commercial applications on which to use their platforms, the increasing power of mobile devices and combinatorial technologies (e.g. those using artificial intelligence such as facial recognition and object recognition) has resulted in a boom in AR applications in recent years targeting both consumer and commercial use cases. The list of applications includes:

- Games
- Art and design
- Architecture and urban planning
- Education and training
- Industrial design and manufacturing
- Healthcare
- After sales support and maintenance
- Sales and promotion
- E-commerce
- Human computer interaction
- Workplace assistance
- Design collaboration and visualisation
- Military and navigation
- Translation.

Whilst the largest demand for AR and VR technologies comes from the creative industries (Hall & Takahashi, 2017), the uptake of VR and AR technologies in the AEC industry is promising, partly because of its immediate and relatively low-cost accessibility and also because practical applications can plug directly into existing technologies such as Building Information Modelling (BIM) and reality capture.

Applications for VR focus on either the design and collaboration phases of projects where stakeholder visualisation of designs benefits from an immersive environment or on simulations where a virtual environment can be used for training or planning. Examples include:

- Design collaboration and coordination—The ability to import and visualise BIM models in VR is now quite commonplace, and there are many tools available in the marketplace, including VR Collab (Your BIM Amplified, n.d.), Inspace (n.d.), The Wild (n.d.), and IrisVR (n.d.). These software enable multiple users to explore BIM model environments virtually to get a sense of scale and context, to view design progress, identify design issues, view BIM data, and annotate with comments (or even append additional information).
- Creative design—In line with the increasing interest in the creative design industries, there is a growing demand to use VR for creative architectural design and urban planning. The ability to move around a model at different scales and manipulate designs 'by hand' is seen as a more natural way of designing than on a 2D screen with a mouse and keyboard. An example is Arkio (n.d.) which facilitates architectural design, massing, and urban planning in VR.
- Construction planning and rehearsal—There are an increasing number of tools that enable contractors, construction engineers, planners, or health and safety personnel to plan construction and maintenance activities. One example is Mott Macdonald's Rehearsive (n.d.) which allows detailed planning of site activities including plant, hoarding equipment, and personnel. Robert Bird Group's Reveal (n.d.) is another tool which allows stakeholders to experience and interact with construction methodologies and sequences.

Interest in AR is growing more sharply than VR. Many of the aforementioned VR platforms also offer AR functionality to bring design reviews and collaboration into a real-world environment; however, there are also many on-site applications being developed to bring BIM visualisation to enhance site activities. Accessibility of AR is easier with the use of mobile devices which allows any stakeholder to have potential functionality at their fingertips. Some specific examples include:

- Akular AR (n.d.)—This software utilises multi-disciplinary BIM models to enable stakeholders to visualise completed built assets overlayed on the real-world environment, either at full scale on site or at a reduced scale in a conference room. The software is built for use with mobile devices.
- Visual Live (n.d.)—The software utilises the Unity gaming engine to overlay mechanical and electrical fit-out BIM information on site where it can be used to visualise and plan the works. Alternatively, the visualisation can be used to undertake quality control checks on works already completed. The overlay can be viewed via Hololens or on a mobile device. Other similar applications include Dalux Field (n.d.) and Gamma AR (n.d.) which are built for easy access via mobile devices.

- Fologram/AllBrick/UTAS Tasmania (n.d.)—In this collaboration, the bricklaying contractor used AR to assist in the setting out for a complex, curved brickwork wall. A geometric model of the wall containing information on the brick types was overlaid on the site using Hololens HMDs for the bricklayers enabling accurate set out and identification of brick types. A similar, custom-enhanced approach was also used for the bricklaying of the Katerini Winery (Mitterberger et al., 2020).

6 IoT and 5G

IoT refers to the Internet of Things, where such devices in construction allow remote monitoring, control, operation, tracking, and potentially supporting aspects of augmented reality (AR), Building Information Modelling (BIM), and predictive maintenance. These connected devices require a large bandwidth to send and receive information, often in real time and places demands on fast, reliable, and robust connectivity that can handle communication from distributed locations and capable of multiservice. The concept of IoT can be dated back to 1982 where a Coke drinks dispensing machine was connected to the Internet, with the idea of managing the inventory (Farooq et al., 2015). The concept was later established in 1999 by Kevin Ashton within the context of supply chain management 'as an interconnected network of physical objects with sensing, actuating, and communication capabilities that enable a unified framework for data syntheses and processing, through seamless access to domain-specific software and services' (Ashton, 2009). The IoT can be seen as a network of people and things that are connected, such that content can be collected and shared about the way that they are being used and also about the environment around them (Clark, 2016).

This information can be particularly useful in the industry to detect patterns, make predictions, and suggest recommendations before issues occur. Findings from a recent study by Arowoiya et al. (2020) found that the use of wireless fidelity (Wi-Fi), visualisation, wireless sensor networks, Bluetooth, electronic product code, and Internet protocols is the most adopted elements of IoT in the industry (Arowoiya et al., 2020). In another paper by Boton et al. (2021), they found that keywords associated with IoT and the construction industry include the following keywords: 'radio frequency identification', 'virtual reality', 'augmented reality', 'additive manufacturing', 'smart building', and 'information technology' which could suggest emerging or adjacent technologies (Boton et al., 2021). In essence, 5G-enabled IoT can be classed according to broadband IoT to serve high-volume and high-speed data transfer; critical IoT, often used for mission-critical applications that utilise a large bandwidth; and lastly, massive IoT where many devices are connected (How the Integration of IoT and 5G is Set to Shape the Construction Industry, n.d.).

5G brings three new communication aspects to the table with bigger channels to speed up data transfer, having a lower latency to be more reactive to requirements and the ability to connect several devices simultaneously. 5G also uses wider bandwidth technologies such as sub-6 GHz and mmWave that provide added capacity, multi-Gbps throughput, and with much lower latency. One of the key applications for 5G-enabled IoT is to provide real-time automation where applications such as remotely controlled robotic devices for transportation and building processes are linked to sensors to trigger specific actions in real time. This aspect of IoT can also be linked to supply chain optimisation, where bottlenecks, repetitive activities, or monitoring of resources would be useful to ensure that the timeliness of projects and tasks can be monitored, reported, and acted upon. The use of 5G technology also offers real-time streaming of content-rich information, usually by means of a video feed to the operators or site controllers. These video cameras could also be mounted onto robotic devices or flying drones and also useful for off-site inspections. A paper by Ghosh et al. (2021) on 'Patterns and trends in Internet of Things (IoT) research: future applications in the construction industry' established that IoT within the construction industry can be generally classed as being relevant to four key strands, namely (1) structural health monitoring, (2) construction safety, (3) optimisation and simulation, and (4) image processing (Ghosh et al., 2021).

UK-Connect, which is a communications provider based in the UK, provides examples where IoT could be implemented in the construction sector (Why the Internet of Things is the Future for Construction Sites, 2019). For example in Building Information Modelling, sensors can be integrated into a virtual model of a structure that can create data that models energy use, the impact of the environment, how the materials perform in different temperatures and provide predictions for building planners and civil engineers. Construction machinery can be lined with wireless connection so that they can be operated remotely without requiring workers in the vicinity. They also state that the use of IoT could be applied to improve safety of workers, by notifying and alerting them about danger zones, equipment, or activities about to take place. Equipment fitted with sensors can also be used to track goods being moved to prevent theft. These sensors can also be embedded within the equipment to detect and communicate when a maintenance regime is required.

A widespread industry implementation of IoT has the potential to bring about new economic opportunities especially in a digital data environment. Furthermore, the integration of IoT with BIM to create digital twins also presents a powerful paradigm for applications with the potential for improving construction practice and operational efficiencies. This feature of digital twinning in construction is discussed in the next section. The development of an integrated cloud-based Internet of Things (IoT) platform would be useful not just for supply chain monitoring but also for asset management and supporting aspects of lean industrial practices and to support sustainability. Despite some of the advantages and potential use of IoT and 5G in the construction sector, there are a few challenges that need to be considered for widespread adoption. For example with multiple connected devices linked to 5G, the level of security needs to be ensured so that these devices are reliable and robust. The hardware and software also need to be compatible, to take advantage of the high bandwidth and low-latency times for data to be streamed, collected, analysed, and communicated to key stakeholders. Lastly, there is also a risk of data overload where operators may be overwhelmed by the amount of information. This is also evident in a recent study that some of the challenges include lack of safety and security, lack of documented standards, lack of benefit awareness, improper introduction of IoT, and lack of robustness in connectivity within construction projects (Gamil et al., 2020).

7 Digital Twins

A digital twin is a digital replica of a living or a non-living physical entity. By producing a bridge between the physical and virtual world, data is transmitted to allow the virtual entity to exist simultaneously with the physical entity (Fischer & Ashwin, 2019). The term 'digital twin' was initially coined by NASA when they had produced an exact replica of their space rockets for mission rehearsals and planning. This was known as an information mirroring model where they created a virtual space as a replica of the real space to enable simulation and experimentation (Grieves, 2014). The white paper published by the Institution of Engineering and Technology provides a definition that the digital twin distinguishes itself from other digital models by its link or connection to the physical twin. This connection refers to a relationship and association between the physical and digital which can range from a simple 2D or 3D model of a local component, to a fully integrated and highly accurate model of an entire asset or facility (Evans, 2019). These elements are dynamically linked to engineering, construction, and operational data. As such embedded sensors are developed to become smaller and more affordable, the ability to gather, process, and communicate information becomes easier and faster, making the interface between the two worlds seamless. More importantly, the paper also describes the digital twin maturity spectrum, which was initially developed by Evans (2019) to define the elements and requirements of a digital twin and provide a framework for communicating the concept. This spectrum presents six key elements that increase logarithmically in terms of complexity and connectedness. They include: Element 0: reality capture; Element 1: 2D map/system or 3D model; Element 2: connect to persistent data and BIM; Element 3: enrich with real-time data; Element 4: two-way integration and interaction; and Element 5: autonomous operations and maintenance (Evans, 2019).

Within the construction industry, the use of a digital twin can be effective for prefabrication and for achieving industrialised efficiency, such as considering the behaviour and processes involved in the building process. This information would benefit architects, engineers and to make informed decisions from the data and be able to understand the impact of changes to better manage these assets over time. For example in the design of offshore wind turbines, engineers and fabricators are able to utilise the digital twin to design predictive simulations so as to more fully understand how the wind turbine will perform in different weather conditions. For civil structures, CadMakers used digital twins to design an 18-storey hybrid mass-timber building at the University of British Columbia in Vancouver. The process enabled the team to plan the prefabrication work and a simulation of on-site assembly of the manufactured parts. As a result, the project was completed and delivered in half the time of an equivalent building using traditional methods (Patterson, 2019). When well managed, the use of digital twins has the potential to improve coordination and productivity across people and processes within the project in terms of design, planning, build, operational use, and asset life cycle management.

8 Nanotechnology

The construction industry often shows a preference towards the use of traditional materials and conventional technologies over innovative materials and digital technology. The use of traditional materials and technologies does not sufficiently address the relentless drive by governments and the construction stakeholders towards better safety, environmental-friendliness, and performance of buildings and infrastructure. Nanotechnology could play a significant role in providing new solutions that meet the requirements of the construction industry. This is done through the enhancement of main properties of materials, such as significantly improving the mechanical performance of concrete (Chougan et al., 2020a, 2021) and/or enhancing the thermal insulation properties of novel insulation materials such as aerogel and vacuum insulation panels (Zhuang et al., 2017). Nanotechnology could bring new functionalities to building materials and products, such as antimicrobial, self-cleaning, and air-purifying paints, or even optically transparent insulation.

Nanotechnology has many applications in engineering disciplines. Nanotechnology could potentially have an extensive application in the construction industry. In principle, nanotechnology refers to the process of controlling and restructuring matter based on their size (0.1–100 nm) to develop materials with new and improved properties and functions (Rao et al., 2015). The application of nanotechnology has been successful in making insulators, sensors, smart, and eco-friendly materials. It has the unique potential to improve the crucial properties of conventional construction materials. It can also incorporate additional functionalities to existing materials, such as for paint, coating, or self-cleaning glass.

Nanotechnology could also help reduce the environmental impact and energy consumptions of structures, in addition to decreasing costs associated with infrastructure developments. Additionally, as energy usage worldwide grows, nanotechnology development has the potential to reduce energy consumption. Research has demonstrated that nanotechnology can contribute to novel cooling systems and improve the functionality of solar cells and insulation material (Gharzi et al., 2020; Moga & Bucur, 2018).

The construction industry faces a significant challenge with respect to the innovative materials upscaling for large-scale implementation such as for the performance of the materials, environmental and safety issues, and costs. However, recent developments in different streams of nanotechnology have demonstrated significant ability in addressing many of these challenges.

Research and developments have demonstrated that the application of nanotechnology can improve the performance of traditional construction materials, such as concrete and steel. Remarkable improvements in concrete strength and durability are being achieved with use of metal/metal oxide nanoparticles and engineered nanoparticles such as graphene, carbon nanotubes, and carbon nanofibres (Chougan et al., 2020b; Lamastra et al., 2021; Najafi Kani et al., 2021). Moreover, environment-responsive anticorrosion coatings using nano-encapsulation techniques have also shown potential at a laboratory scale (Lv et al., 2019; Niroumandrad et al., 2016).

Progresses in nanotechnology have also opened new opportunities for sensor-based structural health monitoring. This is an area in the construction industry that is rapidly gaining importance. Sensors developed using nanotechnology could one day replace the traditional methods of visual inspection of structures and in turn improve the accuracy of structural health monitoring and reduce labour costs (Chougan et al., n.d.). Nanotechnology could also play a substantial role in decreasing the environmental impact along with energy intensity of the buildings and mega structures. For instance some nano-additives such as metal oxide nanoparticles or carbon nanotubes (CNTs) can enhance the physical and mechanical properties of concrete made from industrial waste-based cements. Therefore, nanotechnology could help with the valorisation of industrial waste as secondary raw material for the production of concrete.

Nanotechnology and nanomaterials that can be used in the construction industry are at different stages of development, from conceptual design ideas to successful commercially available products. Interestingly, the awareness of nanotechnology and its potential amongst practising engineers and stakeholders are remarkably low (Broekhuizen et al., 2011; Zhu et al., 2004). Based on responses by construction industry specialists in a survey conducted by the *International Union of laboratories and Experts in Construction Materials* (RILEM), it was found that nanotechnology has been considered by the construction industry to be expensive and too complex to explain to clients who want a structure built as soon and as cheaply as possible (Zhu et al., 2004). This is not in line with the fast pace of growth in the interest and awareness of nanotechnology and its implementation in other industrial sectors such as chemical, energy, and automotive (Zhu et al., 2004). The negative perception of the construction industry with regards to nanotechnology can lead to current and future developments being ignored, where huge benefits in materials performance and multi-functionality might be overlooked. This is not ideal for the construction companies and the betterment of future infrastructure developments.

9 Conclusions

This chapter serves as an introduction to the breakthrough technologies identified to have the potential to transform the construction industry. Many challenges and specific bottlenecks remain to be resolved before the maximum impact of these technologies can be achieved in the conservative and difficult to change, construction sector. The critical challenge is the fragmented state of professional practice and lack of effective communication and dissemination in the construction industry.

The construction sector requires safe, scalable, flexible, and human-oriented innovative solutions to address everyday challenges. Skilled workers, able to work with breakthrough technologies and automation, also play a major part in the competitiveness of the sector. Large construction enterprises need meaningful digitalisation solutions that enable effective monitoring of distributed operations, able to ensure clean, zero-harm construction sites through automated workflows, and intelligent data interpretation.

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Chapter 2
The Global Environmental Imperative

Seyed Hamidreza Ghaffar and Mehdi Chougan

Abstract The cities are growing dramatically, while adding to the climate challenges. The construction industry has been criticised for generating high volumes of waste and obstructing Sustainable Development Goal (SDGs) targets. The UN Climate Change Conference in Glasgow (COP26) conveyed together 120 world leaders where the Paris Agreement goal of limiting the increase in the global average temperature to below 2 °C and pursuing efforts to limit it to 1.5 °C was reinforced. The countries must accelerate the development and implementation of innovative technologies, along with the adoption of policies, to transition towards low-emission energy systems, through rapidly scaling up the deployment of clean power generation and energy efficiency measures. It is important to realise that the technology is a fundamental element of the global efforts to get to net-zero; nevertheless, its implementation in the construction industry requires practical adjustments as the sector transitions from current routines' to a more climate-friendly one.

Keywords Climate emergency · Construction industry · Global carbon · Carbon mitigation

1 Climate Emergency

The construction sector across the globe has rapid growth because of the high level of investments in building, infrastructure, transportation, and energy sectors. Climate change's impact is already being experienced. On a worldwide basis, meteorological records are being broken over and over, as what were once life-threatening conditions are starting to become normal. Heatwaves, rising seas, weather disasters, and air pollution made more violent by altering weather patterns affect millions of lives and cost billions to the economy each year (Harlan & Ruddell, 2011). We are now in a climate emergency. Recently, Intergovernmental Panel on Climate Change (IPCC) published its latest report on global warming, which the Secretary General of the

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_2

United Nations described as a 'code red for humanity'. The report said it was now 'unequivocal' that human activity has warmed the planet and warned the average global temperature would be 1.5 °C higher by 2040 compared to pre-industrial levels. This level could be hit sooner if emissions are not reduced. The report said the higher temperature would lead to more frequent and intense heatwaves and extreme weather, including flooding.

The construction industry has a critical role in tackling this emergency. Thus, the construction industry's decarbonisation is an efficient method to alleviate the negative impact of climate failure. In the EU, the construction industry accounts for 18 million construction jobs, 33% potable water usage, 36% of all emissions, 50% of all raw material extraction, and 40% of energy consumption (Adams et al., 2019). Decarbonising the buildings and construction industry is essential to achieve the Paris Agreement commitment and the United Nations (UN) Sustainable Developments Goals (SDGs).

The global construction forecast for 2020 showed that the USA, Canada, China, Japan, and India are the leading contributors to carbon emissions. The aforementioned countries are responsible for more than 50% of the world's construction spending (Onat & Kucukvar, 2020). Environmental complications, including water, biodiversity loss, soil, and air pollution, excessive land use, and resource depletion, are considerably threatening the life-support systems of the earth (Geissdoerfer et al., 2017). As the global population reaches 10 billion, the building stock will double in size, and without any radical changes to the way the construction sector is operating, the global consumption of natural resources will double by around the middle of the century. This is followed by increasing the construction industry's emissions and climate impact. The urgent mitigations require an innovative response with a new vision for the sector which according to the World Green Building Council (WorldGBC) is a highly connected value chain enhancing wider life cycle environmental impacts, radically diminishing both operational and embodied carbon, and effective contributing to the UN SDG (Adams et al., 2019). SDGs have played a critical role in encouraging and speeding up industrial sustainability. This will lead to enhancements in social welfare via driving the efficiency of energy and resources, reducing the greenhouse gases and environmental pollution, and increasing the employment rate and income (Onat & Kucukvar, 2020).

2 Overview of Construction industry's Contribution to Global Carbon

Based on the Global Status Report for Buildings and Construction, the buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO_2) emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement, and glass (Global Status Report for Buildings and Construction, 2019). As part of their plans to limit greenhouse gas (GHG) emissions, 184 countries have contributed Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC), although most countries (136) mention buildings in their NDCs, few detail explicit actions to address emissions within the construction industry. Nations must prioritise actions and more importantly specify them to decarbonise this essential industry. This means switching to renewable energy sources, improving building design, being more efficient in heating, cooling, ventilation, appliances and equipment, developing low-carbon building materials, using nature-based solutions and approaches that look at buildings within their ecosystem (Global Status Report for Buildings and Construction, 2019). Some countries have established strategies to move towards achieving a net-zero-carbon building stock by 2050 or earlier. For example Japan and Canada are developing new policies to reach net-zero and net-zero-ready standards for buildings by 2030. As more countries prepare their NDCs, more ambitious strategies to address existing building stocks will be put forward.

Across the world, there are around 40 building environmental rating systems (Lu & Lai, 2019), where the most established ones are Leadership in Energy and Environmental Design (LEED) of the US, Building Research Establishment Environmental Assessment Method (BREEAM) of the UK, BEAM Plus (Building Environmental Assessment Method) of Hong Kong, Green Star of Australia, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) of Japan. The examination methods have separate rating tools for assorted types of buildings (e.g. residential and commercial) and different stages (design and construction, operation, and maintenance) (Lu & Lai, 2020). These assessment methods are comprehensive and include materials, water, sustainable sites (ecology and land use), indoor environmental quality (health and wellbeing), and energy. With the highest weighting of 22–38%, energy is considered a primary aspect in measuring building environmental performance.

Buildings are responsible for 39% of carbon emissions in the US (EPA, n.d.), whereas in Hong Kong, it is 60% with 90% of the total electricity consumption (Bureau, 2015). In Latin America, buildings account for 25% and 65% of total carbon emissions and waste generation, respectively (Cesano et al., 2013). Buildings in the EU are accountable for about 59% of the total electricity consumption (Vittorini & Cipollone, 2016) and about 30% of energy consumption in China (International Energy Agency (IEA) and Tsinghua University 2018), while the building industry in Australia is accountable for about 20% of the total CO_2 equivalent greenhouse gas emissions (Australia Department of Industry and Science (ADIS), 2018). According to the Australian Council, buildings are the source of about 60% of the total energy consumption (Department of Climate Change and Energy Efficiency, 2012).

In accordance with a 1.5 °C global warming, Levesque et al. (2021) assessed carbon content reduction of energy by means of supply-side decarbonisation and fuel switching as well as a decline in total energy demand as two main building decarbonisation strategies (Levesque et al., 2021). It was shown that in a 1.5 °C scenario combining mitigation policies and a reduction of market failures in efficiency markets, 81% of the buildings emission reductions are achieved through the decline of the carbon content of energy, even though the remaining 19% are attributed to the efficiency enhancements that lead to a reduction of energy demand by 31%. Levesque et al. (2021) concluded that reducing the carbon content of energy through supply-side decarbonisation and fuel switching is extremely important for the decarbonising buildings (Levesque et al., 2021).

Onat and Kucukvar (2020) evaluated the universal carbon footprints of the construction sector in the world's main construction markets such as the USA, Canada, China, Japan, and India (Onat & Kucukvar, 2020). The findings revealed that the construction industry's regional and global supply chains account for the majority of carbon emissions. They came to the conclusion that carbon mitigation policies should not only concentrate on the limited regional impacts but should also recognise the position of the construction industry's complex, interconnected, and indirect global supply chains. National policies will help regulate carbon emissions from the building industry and the supply chain of each country. Since the construction industry's carbon emissions are heavily reliant on the electricity sector, investing in renewable energy technology can be a beneficial intervention.

The overall carbon footprint of the construction sector per person in the USA, Canada, China, Japan, and India has been quantified along with their net carbon emissions per GDP (see Fig. 1). The study is based on the Eora database, which contains the most comprehensive time series data from 1990 to 2012 (Ivanova et al., 2017; Stadler et al., 2018). For this analysis, national accounts for population and GDP are compiled using World Bank GDP and population growth statistics (Zhong & Wu, 2015). To calculate per capita and individual carbon emissions, the overall carbon footprint is divided by population and GDP for each related country's construction industry. Figure 1a shows the overall construction industry's carbon footprint in each of the analysed countries per person. It is evident that Japan and Canada have the highest per-person total carbon footprint. China and the USA, on the other hand, have the smallest carbon footprints. The overall carbon footprint of the construction industry per person in China is slightly rising. India and the USA show a comparable amount of carbon emissions. Figure 1b illustrates the net carbon emissions per GDP. India, Japan, and Canada have the highest emissions in this examination, while the USA and China have lower emissions per $ of GDP, and their total emissions per GDP are comparable to each other. The overall trend in carbon footprint is a downwards trend. This indicates that the environmental performances have improved over the past 22 years, while net carbon footprints were dominated by GDP growth, and China and the USA have the lowest emissions per dollar of GDP, which can be attributed to their rapid economic growth.

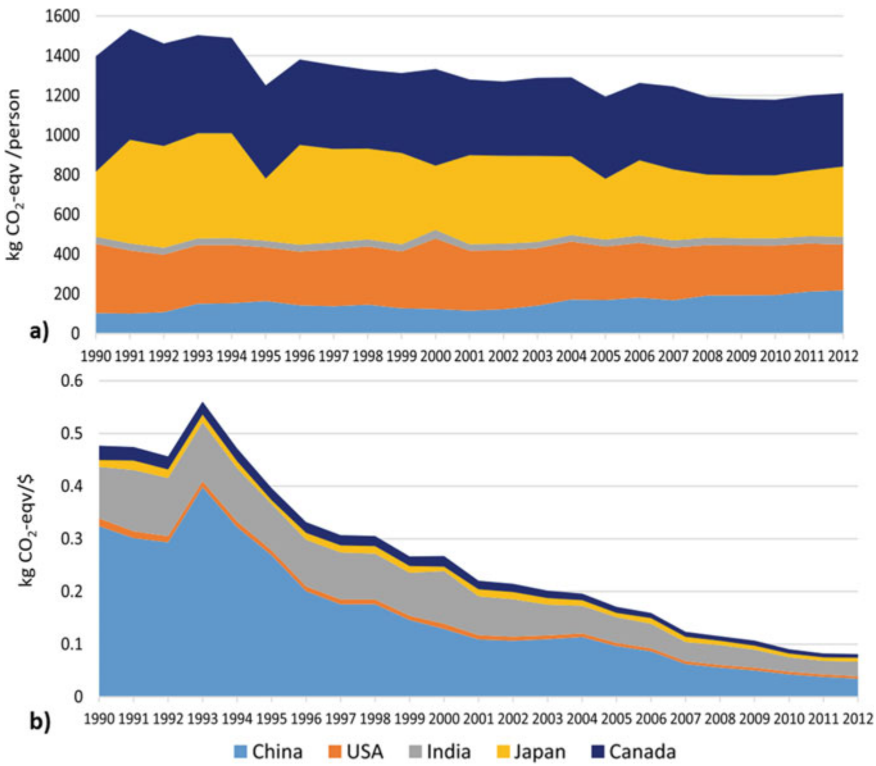

Fig. 1 **a** Total carbon emissions per person and **b** total carbon emissions per GDP (Onat & Kucukvar, 2020)

3 Carbon Mitigation Initiatives and Sustainable Development

The term 'sustainable development' encompasses the three dimensions of social inclusion, ecological sustainability, and social inclusion. Much of the sustainability work focuses on the concept of resilience, i.e. change is inevitable. The sustainability concept's uptake traces back to the cumulative global-scale signs of environmental risks, such as biodiversity loss, climate change, and ozone depletion. These risks have been scientifically investigated since the 1960s.

The commitment to eliminate greenhouse gas emissions by 2050 requires profound, universal changes in the way that energy and energy-intensive materials such as steel, aluminium, and cement are used. Several technically feasible options for change remain underexploited despite the ambitious climate change targets set into some country's law, e.g. the UK. China, the world's largest carbon emitter, has promised to achieve carbon neutrality by 2060, while the EU has committed to achieving net-zero GHG emissions by 2050. More than 190 countries have ratified the Paris Agreement, which is a multinational initiative. While the USA made headlines around the world when it formally withdrew from the deal on 4 November 2020, it was only a matter of time before it re-joined the agreement by one of Joe Biden's first actions (Biden, 2021; European Commission, 2019; London School of Economics and Political Science, 2018).

In 2015, all countries signed the Paris Agreement, which aims to minimise CO2 footprint (United Nations Framework Convention on Climate Change (UNFCCC), 2015). In addition to monitoring schemes on carbon emissions, individual countries have introduced their own emission green building strategies, trading systems, and carbon mitigation initiatives. (Brander et al., 2018). In 2005, the European Union Emissions Trading System (EU ETS) was developed. This is a carbon trading system that works on the 'cap-and-trade' standard. The EU ETS, also known as the world's first multinational emission trading scheme, is responsible for 75% of international carbon trading and can be used in both industrial and residential buildings (Lu & Lai, 2020). Meanwhile, in the USA, the Regional Greenhouse Gas Initiative (RGGI) is the first compulsory market-based programme to limit and minimise carbon emissions in the building area (RGGI, 2021). In particular, Senate Bill No. 350—Clean Energy and Pollution Reduction Act of 2015—was presented to strengthen energy efficiency for buildings (Legislative Information California, 2015). The Carbon Neutral Programme and the National Carbon Offset Standard (NCOS) were initiated by the Australian government in 2010. After 2017, this is a standard for calculating, monitoring, and minimising carbon emissions that also applies to buildings (Australian Government Department of the Environment and Energy (ADEE) & National Carbon Offset Standard, 2011). The Chinese government has implemented a circular economy as a national regulatory policy urgency. They have enacted a slew of legislation to aid in its execution. The Cleaner Production Promotion Law, which has been in force since 2003, is one of these regulatory acts. In 2005, the revised Law on Pollution Prevention and Control of Solid Waste added to this legislation. The Circular Economy Promotion Law was passed by China's National People's Congress in 2008. This law endorses the implementation of the circular economy, improving resource use efficiency, natural environment preservation towards sustainable development (Geng et al., 2012).

The European Green Deal is the European Commission's blueprint and roadmap to make Europe the first climate-neutral continent by 2050, with a sustainable economy that leaves no one behind (European Green Deal, 2019). In 2020, the European Commission launched a €1 billion call under the Green Deal initiative for research and innovation projects that respond to the climate crisis and help protect Europe's unique ecosystems and biodiversity. This investment could potentially accelerate a sustainable transition to a climate-neutral Europe by 2050. Project proposals under the themes of '*Clean, affordable, and secure energy*' as well as '*Industry for a clean and circular economy*' were the top priorities.

A clear economic case for climate action has already been developed. The benefits of effective and early action to curb greenhouse gas emissions greatly outweigh the economic costs of not intervening, according to climate change economic analyses.

According to research conducted by the Global Commission on the Economy and Climate, low-carbon policies can be economically appealing on their own. They have indicated that by 2050, low-carbon investment in cities may have a net present value of US $16.6 trillion (Gouldson et al., 2018).

4 Conclusions

The built environment is responsible for a large portion of the world's total carbon emissions. Therefore, changing the infrastructure development practices is paramount to ensuring the future generation's needs. For instance new buildings will have to incorporate a range of new technologies to reduce their energy use and to cut the energy needed to build them, including the embodied energy in the materials they contain. It is extremely important to move towards increased use of solar energy and other renewables, maximise passive measures of more effective insulation, improved airtightness and greater thermal mass, using low-carbon building materials and concrete alternatives. COP26 UN Climate Change Conference will accelerate actions towards the goals of the Paris Agreement and the UN Framework Convention on climate change. As countries begin to recover from the coronavirus pandemic, the opportunity should be taken to tackle climate change at the same time—to build back better, greener, and with low-carbon, functional, durable, and high-performing materials. This can potentially deliver recoveries across the globe that bring in good jobs, investments, and ground-breaking new technologies.

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Chapter 3
Industry 4.0 and Drivers for Socioeconomic Sustainability in the Construction Sector

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Abstract The construction industry is anticipating a plethora of transformative processes that will instill change and will require decisive actions from leaders to tackle the issues in the foreseeable future. The first tide of transformative processes envelopes the ongoing societal challenges like population collapse, environmental problems, and resilience, while the second is the emergence of Industry 4.0 that will be responsible to tackle and future-proof the construction industry from the ongoing social sustainability problems. The interaction between these two tides will decide how well the construction industry will be able to adapt, thrive, and meet the needs of society. For instance, the ongoing population trends are exhibiting a tectonic shift from population growth to population collapse, meaning that labor shortages will become more apparent and population aging is inevitable. Thus, digital automated technologies like 3D printing or semiautonomous robots will be vital to outweigh the human labor scarcity to have affordable housing. Emerging technologies like 3D construction-scale printers are already showing promising results in the reduction of CO_2 emissions in the building process, which requires less transportation, manpower and can open possibilities of bio-recyclable material use. The prefab building methods could help developers become more resilient not only from future pandemics, but also from any weather conditions since modular homes, or printing can be done in off-site locations. Therefore, the future of the construction industry depends on how well the Industry 4.0 technologies can be adopted to confront the upcoming social sustainability problems.

Keywords Urbanization challenges · Population forecasts · Industry 4.0 · Construction 4.0

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_3

1 Introduction

Industry 4.0 emerges as a transformative process that alters the very fabric of our socioeconomic paradigm (Culot et al., 2020). Industry 4.0 was first introduced as the digital transformation of the manufacturing industry. It mainly involved implementing advanced digital and operations technology such as additive manufacturing, industrial robotics, artificial intelligence (AI), and data analytics and developing desirable conditions such as real-time capability and decentralization (Ghobakhloo, 2018). More recently, Industry 4.0 is regarded as the digital transformation of value-creating networks, involving various industrial sectors such as energy, transportation, distribution, and even health care (Tseng et al., 2018). Among many other industries, the construction industry is undergoing a significant transformation under the Industry 4.0 scenario (Oesterreich & Teuteberg, 2016). In reality, the construction industry is experiencing a significant paradigm shift concerning digitalization, commonly referred to as Construction 4.0 within the scientific literature (Dallasega et al., 2018; Maskuriy et al., 2019). It involves the application of most advanced digital technologies such as smart fabrication, 3D printing, robotics, smart sensors, high-performance computing (HPC), computer-aided design, and big data, all the way to the vertical and horizontal integration of information, knowledge, sub-systems, processes, and people across the construction supply chain (Newman et al., 2020; You & Feng, 2020). The digital transformation of the construction industry may offer valuable advantages such as product customization, time and cost efficiencies, smarter products, automation of hazardous jobs, transparent collaboration among stakeholders, and better decision making (Schiele et al., 2021, Tahmasebinia et al., 2020).

The construction sector is closely related to and exhibits a reciprocal relationship with society and economic pursuit. Thus, a foundational understanding of future trends in a socioeconomic dimension is vital for the construction sector to thrive in the Industry 4.0 era. First, the upcoming technological revolution bears many elements of uncertainty for the population forecast. The old theories of Malthusian that population will grow geometrically are being replaced by an alarming notion of population collapse, which has already taken place in most western countries. It appears that as the well-being of a society increases, the population loses interest in reproducing on a sustainable level, hence becomes dependent on donor countries for labor. The most recent example of China declaring that there might not be enough people on their mainland after pulling around 600 million people out of extreme poverty means that similar population evaporation trends will occur in India and Africa sometime in the future, thus eliminating all donor countries in the long run. Due to migration, some wealthier countries might sustain their economic activity, but construction sector in demographically decaying nations will need to rethink their strategic objectives. According to AHA (2007) by 2030, baby boomers will be managing at least one chronic condition which might require twice as many hospital admissions. This could require the construction industry to focus on building more healthcare facilities than kindergartens. Secondly, due to COVID-19, digitalization processes have accelerated immensely. The social media giant "Facebook" already predicts that 50% of its employees could be working remotely in the next decade. Consistently, urbanization rates might slow down or even reverse in some cases completely. Some of the largest metropolitan areas in the US have already experienced a decline in their residency, which, in turn, might create hardships to the office market but form the demand for housing space with dedicated workrooms further away from the central business sub-district. Experts even argue that office space might need to be converted to living space to help combat growing housing prices and address social inequality (Forbes, 2021; France24, 2021; Lewis, 2021).

Additionally, due to the COVID-19 outbreak, a consideration of prefab powered by digital technology might become more prevalent. The prefab factories assemble construction components in the factory, reducing traffic times of delivering materials back and forth, allowing better robotic automation, decreasing human interactions, and reducing the carbon footprint. It has been shown that the manufacturing component in a factory can reduce CO_2 emissions by 40%, and robotic automation will make the construction industry more resilient to future pandemics and market turbulence.

2 Population Forecasts and Urbanization Challenges Under Industry 4.0

Industry 4.0 is still in its embryonic stage but is believed that as digital technologies advance and AI matures, the impact of Industry 4.0 will exponentially alter the landscape of business and human being life by the next few decades (WEF, 2016). Overall, the emergence of the Industry 4.0 phenomenon comes at a fascinating time with regard to population progression, and the interaction between the two will have detrimental effects on the entire economy, including the construction sector. First, it is important to understand that the old Malthusian theory of exponential population growth that was created in 1789 is already being thrown out of the window and replaced by the population collapse theories (Bricker & Ibbitson, 2019; Burger, 2020). Malthus was partially correct to state that as higher agriculture technology improves and more food into the system is delivered, the population will increase. However, what he failed to consider was that the technology covariate does not work in solitude and other forces might completely outweigh its effect. Many researchers like Caldwell (1980), Castro and Juarez (1995), Skirbekk (2008), and Snopkowski et al. (2016) have documented that educational attainment for women has a negative effect on fertility rates, and in many developed countries, the educational attainment together with other factors has completely reversed the population growth trends below population replacement rates. Intuitively, this makes sense since in rural areas children are considered as investment, additional hands that can help out with farming activities, while in urban areas children are an expensive burden. For the latter mentioned reasons, the demographic transition model, which originally had four stages (high stationary, early expanding, late expanding, and low stationary), is nowadays being updated with five stages that might be called the “decline” or “depopulation” (Smeeding, 2014).

As shown in Fig. 1a, an exact inflection point has been delivered in 1970, when the population growth rate reached the peak and is now downward sloping. Still, the population is increasing in aggregate, but this will not last for long as the United Nations (UN) projects. Somewhere around 2100, the depopulation phenomenon should occur. However, some demographic experts say that the UN forecast is too optimistic. Wolfgang Lutz believes that the depopulation procedure will come as soon as 2040 since the rapid expansion of education, birth control, and women’s rights is reaching the most distant corners around the world. It is hard to say, whether after the depopulation process, the world will simply maintain a sustainable level of population or an existential crisis will occur. As claimed by economist Elizabeth Brainerd, pro-natal policies have had a minor effect on post-soviet countries, while others like Sabotka et al. (2019) or Bonner and Dipanwita Sarkar (2020) found a positive effect, although emphasized that many other factors like education or future uncertainty were at play. Thus, artificially enhancing the depopulation might not be that simple.

Interestingly, as shown in Fig. 1b, the three-way highway is currently at play as different parts of the world are in different stages of the population cycle. The most developed regions of the world are already experiencing negative population growth, while the least and less developed regions are still growing. Surprisingly, the UN is projecting that by the end of 2100, the developed regions will bounce back to positive growth, primarily due to the migration from donor countries. In 2017, the largest five countries in terms of population size were China, India, USA, Indonesia, and Pakistan, with 1.4 billion, 1.38 billion, 325 million, 258 million, and 248 million, respectively. Nonetheless and in 2100, India, Nigeria, China, USA, and

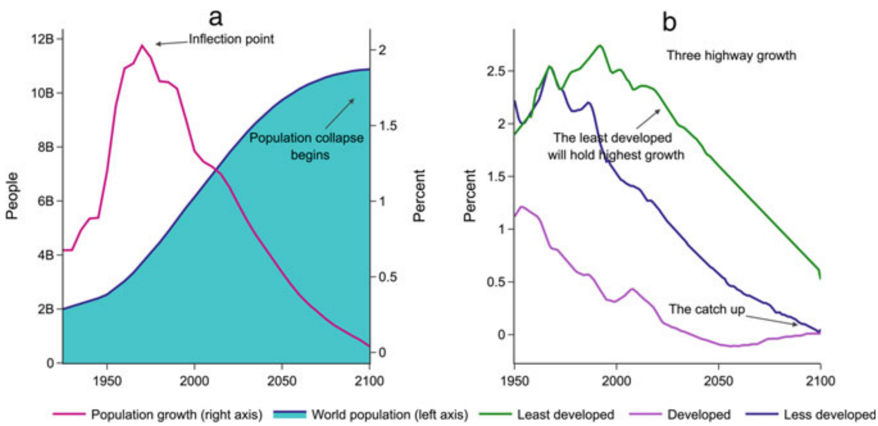

Fig. 1 **a** Historical population growth rate and population aggregate size, and **b** Countries’ growth rates classified by development (Authors original). Based on: *Source* **a**—UN Population Division and Our World in Data, **b**—UN Population Division (2019 Revision)

Pakistan, with. respectively, 1.09 billion, 791 million, 732 million, 336 million, and 248 million, will adjust their positions.

The urbanization trends will have substantial implications for urbanization processes, city planning, and the real estate and construction sectors. First, the UN projects that the total number of people living in urban areas from 2018 to 2050 will increase to 68% from 55%. This situation will intensify the construction activity immensely. According to the Statista database, in 2018, around 11,098 buildings were built daily worldwide. In 2050, however, this number will increase to 14,704, around 25% higher. Furthermore, the three-way highway phenomenon will split the urbanization trends in the near future. The least developed and less developed regions worldwide will continue to see cities massively expand, as shown in Fig. 2a. Megacities such as Lagos, Mumbai or Delhi, will have a massive population explosion, respectively, reaching 88 million, 67 million, and 57 million people. Because of such proliferation, cities will experience more poverty, overcrowding, terrible social and physical infrastructure and infrastructure decay, unaffordable housing, environmental pollution, slums, crime, and many more issues.

On the other hand, the major metropolitans in the developed regions, as shown in Fig. 2b, are beginning to notice mass emigration. Cities like Los Angeles, Chicago, and New York are already in negative growth while others, although still growing, have a very strong and negative trend. Many reasons are behind the exodus, but the most popular narrative usually revolves around high taxes, unaffordable housing, unmanageable homelessness, overcrowding, eye-watering rents, and lower immigration. This raises doubts whether the original projections in Fig. 2a that the New York population will increase are valid. This trend of reduced growth is also happening in European cities like Paris, where the negative trajectory has been constant for almost ten years. According to the French national statistics agency, in 2006, only 68% of

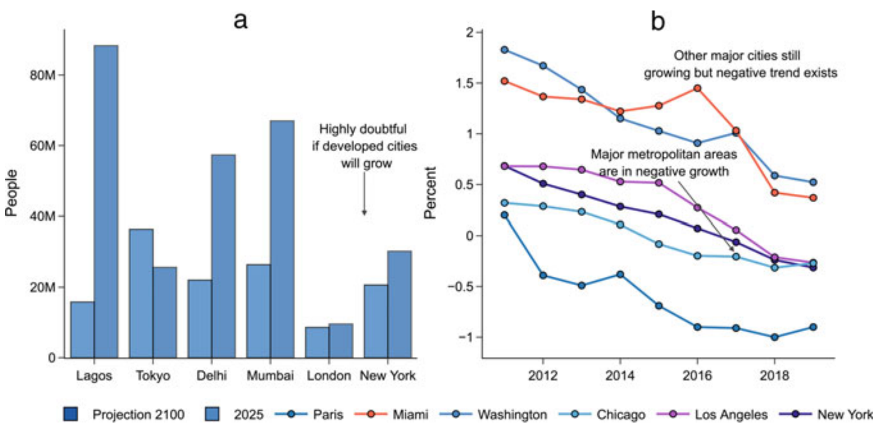

Fig. 2 **a** Projections of the population for some of the world's largest cities in years 2025 and 2100 and **b** Cities' population growth rates. (Authors original), Based on: *Source* **a**—Ontario Tech (2021). University Population Data, **b**—Lnsee (2021) (France Population Census) and US Census Bureau

people born in Paris stayed during their lifetime. The latter processes should also raise questions on whether London will grow as projected before. In the 1960s and 1970s, statisticians underestimated London's decline, thus it would not be the first time where wrong predictions are made.

3 Construction 4.0 and Sustainable Development

Today, the social sustainability concept is at the core of many worlds institutions starting from the UN to the European Union. The understanding of sustainable development is straightforward: "it is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Edum-Fotwe, & Price, 2009). It holds three pillars:

(a) Economic implications pillar, including improved efficiency and growth by adopting new technologies that effectively allocate resources like labor and materials. Improved rate of return, net profit, and labor costs are examples of economic-productivity development indices;
(b) Social implication pillar that concerns the need of the population during the construction process and afterward. Social development indices are usually job displacement and creation, health issues, education, and training;
(c) Environmental implication pillar that reduces the damaging externalities to the environment. Energy consumption, recycled materials, CO_2 emissions, and waste are among the more crucial environmental sustainability metrics within the construction sector.

All of these issues have particular nuances. For instance, to solve the massive urbanization challenges, construction experts, urban planners, architects, and other parties involved will have to work together shoulder to shoulder to alleviate some of the burdens that cities, regions, and people are facing. Nevertheless, different regions will require different approaches from the construction industry for problem solving. As mentioned before, the developed cities are facing population shrinkage on their horizon. A crucial point to understand is that the negative growth in major metropolitan areas is not a COVID-19-induced situation as these trends started in 2018, but the COVID-19 impact might further exacerbate these processes. According to Bartik et al. (2020), more than one-third of firms that switched workers to remote work believe that distant work will remain common after the COVID-19 situation. Another paper by Dingel and Neiman (2020) examined how many jobs can be done remotely in the USA and other places, and most of the developed countries fell in the range between 30 and 50%. Since work can be done in the suburbs where traffic and taxes are lower, the negative growth in the major metropolitan areas might increase even more. This is especially true for such work as programming and software development that can retain similar productivity levels. Facebook CEO Mark Zuckerberg already claimed that within the next five to ten years, around 50% of employees would do work remotely (Bloomberg, 2021). It is reasonable to expect that other companies will follow this strategy since office rent costs can be reduced by holding virtual conference calls instead of physical ones. Construction activity outside the cities might rise, and homes with a dedicated workroom will become common. Some speculate that the COVID-19 virus might stay with society for the upcoming five years; thus, the remote work trend might be more prominent than at first was thought to be. If this is the case, it might help deal with the tremendous stress of urban density issues for policymakers and companies just shifting building activity from the city center to suburban areas. Nonetheless, remote work is much more common in industries with better educated and better-paid workers that can retain high productivity levels in distant environments. Thus, some portion of jobs will remain in the physical realm.

Furthermore, the developed regions will carry the agenda of sustainable development. European governments, as well as other countries, are doing all they can to popularize sustainable building practices that can contribute positively to the environment. The construction industry will need to be focused on net-zero building strategies that generate all energy required for consumption on-site and integrate innovative energy-saving technology. The general housing shortage problem might be reduced if more people start working from home and unused office space will be converted by construction companies into apartments or live work communities. Additionally, some architects are focusing on high-density future housing that is planned to accommodate around 4000 people per hectare in areas that today only accommodate 1500 people. The latter kind of structure will require construction companies to be more digitalized, flexible, and innovative to accommodate new building shapes. This might require using bent-active splines and textile membranes with tensioned bamboo nodes draped in fabric, which later can be cast in concrete and turned into single-family structures or shared housing. Smart or integrated homes are becoming more prevalent which allows controlling house energy use from a smartphone with ease. Other building configurations trends are focusing on conservation and sustainability as well. Houses are becoming more self-sufficient by using solar panels or being better integrated into the micro-grids.

Nevertheless, the sustainability agenda may fit the developed world, but for the least/less developed parts, problem solving should be done from a different angle. It is essential to understand that a compromise between net-zero buildings and a population increase of magnitudes like in Mumbai or Lagos must be achieved. Otherwise, climate catastrophes might arise in the future. It is calculated that every person emits two tons of CO_2 per year and on top of that construction industry is responsible for around 35–45% of CO_2 released into the atmosphere of which construction itself produces 11%, thus accommodating Mumbai or Lagos population increase without fighting CO_2 emissions is hardly an option (Muñoz et al., 2010; WEF, 2020). It is unreasonable to assume that less developed regions will have every single home equipped with solar panels in practice. Nevertheless, a prefabricated construction powered by digital technologies can help to create sustainable and high-quality housing at a speed that fits both the developed world and less/least developed regions and has immense AI adoption capabilities.

The idea of prefab is as follows: in contrast to traditional building methods that require massive labor force and material creation on-site, prefab apartments are assembled using different components (like the roof, walls), which are produced in a factory and transported to the construction site. The benefits of such production create a win–win situation for almost every party involved. First, as noted by Fluxus and Arcadis, companies can expect around 30% of net savings (WEF, 2020). In many cases, worker movement and accommodation are costly operations, thus having a permanent factory location helps workers and companies avoid unnecessary issues. More importantly, since most equipment parts are being made inside the factory, bad weather conditions are circumvented without interruption, leading to more predictable timings and higher overall efficiency.

Additionally, AI is the highlight of Industry 4.0, and so much product improvement and management can be achieved with big data. Companies that fail to adopt such tools might lose a competitive edge later on. In the prefab context, AI technology integrates smoothly with assembly lines or using data analytics to deliver insights for stakeholders. The material delivery using big data can be scheduled to minimize traffic or avoid peak times. Furthermore, simulation models at the factory level can help optimize, design, and test products, or even find new ways of making them. Additionally, if product standardization can be maintained, the speed at which the construction products are created can increase immensely. In general, a cheaper, faster, and more sustainable product, such as prebuilt construction material or smart housing equipment, could be delivered worldwide. Secondly, around a 90% reduction in construction waste can be achieved, and approximately 70% savings in CO_2 emissions can be expected (WEF, 2020). Heavy machinery transportations at low speed, constant worker arrival, and general material delivery are major problems that contribute to high CO_2 emissions, while prefab implications in the construction industry considerably reduce emissions and waste footprints. The factories can build most of the building components in the suburbs. This, in turn, can also create new jobs in new regions and reduce traffic. The speed, quality, and precision of prefab come from automated assembly lines, which human hand-built products cannot outpace. The latter is very important for less developed regions that will have to fight the population explosion (Howick, 2020).

Other alternatives for a more sustainable future are additive manufacturing or, more precisely, 3D printing technology. In layman's terms, using automated machinery, the building is built bottom-up, layer by layer. At first, it was considered a prototype building technology, but it is becoming an effective building tool in recent years. A project by the name of "Prvok" is the first 3D printed house in the Czech Republic. The project was estimated to complete in 48 h, and construction costs decreased up to 50%, while the CO_2 emissions were claimed to be reduced by 20% (PRVOK, 2020). Other engineers postulate that 3D printed concrete produces roughly 50% less emissions (All3dp, 2015; Malek et al., 2020). Although these numbers are smaller compared to prefab claims, both technologies are very young, and significant improvements can arise.

The beauty in 3D printing is that AI can create energy-efficient geometries that will consume less material (this process is sometimes called dematerialization) or even create new products that were never seen before. Simultaneously, any broken parts can be replaced on demand with no spare parts needed, thus creating less or no waste at all. Some authors like Sevenson (2015) or Van Wijk and Van Wijk (2015) even demonstrated 40–64% savings in materials that could be achieved. Another benefit is that limited logistic space is needed because products can be created on demand in any shape or form and are stored in a virtual warehouse. The latter benefit extends further to combat the tremendous energy usage in transportation, which according to the US energy information administration, around 28% of all energy was used for transportation alone in 2019. Since the production is local, less transportation is used, and even in the case of transportation, because material weighs less, energy is considerably saved. Additionally, 3D printing has immense capabilities for recycling. In many cases, plastic can be remelted and used again. Thus, the implication of additive manufacturing technology across the construction industry fits the concept of the digitally enabled circular economy perfectly. Lastly, 3D printing technologies reduce the need for labor, plant, or formwork.

At the moment, also some drawbacks exist with regard to 3D printing. Van Wijk and Van Wijk (2015) in their case study pointed out that the 3D technology impact on the environment comes mostly from electricity use. For a fused deposition printer, the heating element that heats up and melts the plastic consumes most of the energy. In the case of PLA (polylactic acid), the precise heat is between 1.5 and 2.0 kJ/kg for the temperature range of 50–200 °C, and in aggregate, the heating operations account for around 66–75% of total energy use. Furthermore, Van Wijk and Van Wijk (2015) created a case study where a hypothetical townhouse was built using 3D printing and conventional building methods. The size of the house was 100 m^2 of floor space, even roof, and was estimated to require around 50 m^3 (120 ton) of concrete conventionally, while for 3D operation, the PLA layers were used and around 5.4-ton PLA, 15 m^3 (36 ton) concrete, and 15 cubic meters of sand were needed. The final embodied energy and CO_2 emissions for the traditional building were at 133 GJ and 19.2 tons of CO_2, while for 3D printing, 186 GJ and 7.3 tons of CO_2. In this concrete example, it is evident that energy consumption is tremendous for 3D printing even though the CO_2 emission is slashed more than half. Consistently, having cleaner and preferably renewable energy input sources is indispensable for the industrial application of 3D printing technology in the construction sector. If the energy is generated sustainably, then the higher cost of energy consumption is not a problem. However, one must keep in mind that the case study by Van Wijk and Van Wijk (2015) had many limitations and assumptions about house building and insulation layers. Various other forms of bulk construction processes, like contour-crafting of walls, may not necessarily require such energy needs. Malek et al. (2020) have already noted that three-dimensional concrete printing has significantly reduced environmental outcomes in terms of global warming potential, acidification potential, eutrophication potential, smog formation potential, and fossil fuel depletion, thus, there are many nuances at play.

Another issue relating to construction, population, and Industry 4.0 is the labor force. Due to the declining labor force, it is difficult to tell if enough labor for the conventional building will exist in the future. Historically, a practice existed to allow emigration flows from donor states to compensate for population decline. However, due to tightening border control because of COVID-19 or changing government attitudes, it can be unreliable to expect a cheap labor force from abroad. This might disrupt building operations for some companies operating on small margins, meaning automation, simulation, continuous improvement, and the practical use of AI should be at the forefront of any company. An excellent example of how machine compensates worker shortage is a corporation in Japan called Shimzu. Due to aging population in Japan, three robots were developed to weld steel columns, install ceiling panels, and carry materials and were deployed to build a 24-story hotel in Osaka. The latter company claims to reduce its labor force up to 70–75%. In a prefab scenario, automated machinery requires less labor force as well (BBC, 2018; Shimz, 2017).

At the same time, another process from the opposite direction exists. Due to automation, many workers might be displaced from the construction sector. A research paper by Smith (2019) went into detail, claiming that around 2.7 million US construction workers will be displaced by 2057, the majority of them being blue-collar workers. According to Manzo et al. (2018), robots nowadays can lay bricks faster, build more yards per day, and construct buildings faster than human labor. It is estimated that around 49% of construction activities can be automated. Manzo et al. (2018) elaborate the automation potential is 35% for manual workers, 50% for carpenters, 42% for electricians, 50% for plumbers, and 88% for operating engineers.

For this reason, companies should work alongside the governments and begin thinking long term, since to have high-skilled labor that can use machine learning will not be easy to find. Thus, re-skilling current employees is a must. Some reports suggest conducting vocational training for current employees to work with the machines in the future. Also, government migration policies should be consulted with business community representatives. Otherwise, vast migration flows into the country might leave more people unemployed, thus increasing the homelessness problem. Smith (2019) also warns that sustainable development goals with companies, labor unions, or other governmental institutions will have to be unified. If not, an extreme redistribution scenario might occur, where robots will be taxed, or companies will be forced to pay stipends to workers for work displacement. As such, a sustainable approach is more beneficial for both companies and workers alike.

Finally, the workers' health in business has always been a priority in the social sustainability domain. The construction sector is one of the most dangerous fields to work in. As noted by the Occupational Safety and Health Administration (OSHA, 2020), one in five deaths annually occur in the construction sector. The governments have emphasized the "Fatal Four" primary causes of sector working fatalities, which are the following: falls, being struck by an object, electrocution, and being caught in something or between two objects. In essence and consistent with the technical assistance principle of Industry 4.0, the use of robotics and automation can reduce the majority of deaths relating to the latter situations, although still malfunction can exist, where assembly robot arm can accidentally harm a worker. Thus, robust and reliable systems have to be developed and implemented (ISO, 2016).

4 Future-Proof Construction Industry: The Need for Crisis Resilience

To become resilient to future crises, a healthy and productive construction industry matters more than ever. From the emergency construction of hospitals in just a few days to addressing the prevailing housing crisis, the construction industry plays a critical role in responding to future challenges and prompt recoveries from crises. Unfortunately, the construction sector has been significantly hit by the COVID-19 pandemic (CHAS, 2020). The construction industry is generally much more volatile than other industrial sectors, given any economic disturbance, reduction of income, and lack of consumer purchasing power massively reduce the demand for commercial or industrial facilities. On top of that, supply chain disruptions, labor shortages, and operational restrictions are causing the extra suffering of the construction industry. These issues have negatively impacted the financial performance of construction companies worldwide.

It is vital for the construction sector to mitigate the risks of the current pandemic and to become resilient for any future issues that might arise. Some speculate that the COVID-19 virus might stay with us for up to five years or more. Indeed the building projects cannot stay in a frozen state until the virus is over as urbanization and many other problems await. Obviously, the construction sector is not a software development business that can easily be done from a distance, as it is in a physical realm that requires manual labor. However, and as previously mentioned, building methods like prefab and 3D printing fit nicely into the picture. First, as prefab can be done at any location, workers can avoid the hotspots of the city center, where the majority of people reside, and infection is more likely to occur. For most factories, it is more reasonable to be located in the suburbs and avoid high traffic. Second, as automation increases, more labor can be put into 3D modeling or programming fields. This would reduce person-to-person contact and the virus spread. Boston Dynamics has already presented "the spot" robot that can go to dangerous places to inspect structures or issues that occur during the construction process. Similarly, other remote monitoring devices like drones could be useful in managing risks.

Construction projects are generally complicated and slow, involving lengthy planning, piecemeal financing, cumbersome approval processes, detailed material and resource planning, and integrated execution phases. Under such circumstances, the disruptive force of the COVID-19 pandemic will manifest in the large-scale delivery disruption throughout the construction sector, whereas other industries may experience the disruption caused by the pandemic differently, such as swift and severe market disruptions within the airline industry or small-scale manufacturing interruptions across automobile sector. Therefore, the construction industry is expected to strongly feel the COVID-19 crisis's full disruptive impact within the next two to four years. It is important to note that the construction industry is the backbone of any economy, and the shrinking of this sector will negatively affect other industries in the near future. Thus, policymakers are expected to proactively address this crisis and come up with countermeasures such as strategically planned construction-economic stimulus programs that may prop up the construction industry. While devising the supportive strategies, either at the corporate or government levels, the development of digital progression and maturity strategies should be prioritized, given the construction industry is considerably lagging behind other industries in digital transformation. Interestingly, more digitally mature industrial sectors such as the automobile, distribution, or even energy industries have endured less during the COVID-19 crisis. The construction industry should ensure that digitalization investments and efforts are aligned with the strategic priorities to deliver the intended return on investment. Value chain integration is an integral part of the Industry 4.0 transformation, and identifying digitally mature partners and striving to develop the hyper-connected construction ecosystem should be equally emphasized, given this level of integration and collaboration is vital for construction companies seeking an adjustment to the new market realities and proactively reacting to disruptions.

2020 was an unfortunate year for many, including the construction industry. The COVID-19 crisis may have permanently changed the world, and many believe that the occurrence of unpredictable changes and crises would be accelerated in the future. The residential and non-residential construction outlook for the upcoming years seems to be volatile. Although mega constructors and industry leaders might be able to absorb the impact of market volatility better due to their unparallel absorptive capacity, construction companies with limited balanced portfolios, smaller companies particularly, are expected to face significant turbulence interacting with the market. Under such circumstances, digital and connected construction and application of advanced digital technologies present valuable opportunities for developing new business models and strategies that favor resiliency and adaptability. The communication and information sharing capabilities of digitalization would further allow construction companies to consider new business models such as digital alliancing or public–private partnerships that may improve their absorptive capacity and crisis resilience significantly. Looking at the micro-level implications, digitalization would also allow construction firms to deal with the restrictions caused by COVID-19 pandemic efficiently. The vertical integration of equipment, personnel, processes, and resource planning systems, facilitated by the organization-wide implication of sensors, Internet of things, networking infrastructure, and smart gadgets, would allow the virtual accessing of worksite whenever possible. Coupled with virtual meetings, remote mapping, and robotics, firm-level digitalization would minimize the physical interaction of human labor while maintaining productivity without sacrificing employment opportunities. More importantly, the rising construction material costs, as the side effect of the COVID-19 pandemic, can be significantly alleviated with benefits offered by digitalization to the construction operations, such as streamlined off-site and modular construction, the improved value proposition of smarter buildings, optimized construction management, resource management efficiency, informed decision making and project selection, better market sensing, and improved stakeholder collaboration.

5 Conclusions

The construction industry is in the middle of a radical change. The present chapter explained how the dramatic shifts in the population growth and dispersal patterns and the resulting turbulence in the housing market, along with the global crises such as the COVID-19 pandemic and the ongoing digital transformation known as Industry 4.0, are reshaping the future of the construction industry. Overall, changes in the market and technological environment are introducing major disruption into the construction industry. Fluctuating housing demand, ever-shrinking employee pool, supply and delivery chain disruptions, and the emerging social trends have made it even more challenging for the construction industry to meet the quality, time, safety, and budget limitations of construction projects. The chapter explained how interactions between these disrupting forces have dramatically pushed the modernization of the entire construction industry. Under the Industry 4.0 scenario, the construction industry needs to shift toward automation and digitalization and draw on disruptive technologies such as additive manufacturing, AI, smart wearables, autonomous vehicles, robots, the Internet of things, extended reality, big data, and smart materials to streamline the constructions operations, improve communications across project stakeholders, facilitate modular construction, increase the safety of operations, and enhance the flexibility and sustainability of construction operations. The modernization of the construction sector demands industry leaders and policymakers to recognize the enabling role of Industry 4.0 technologies in navigating through the ongoing crises and responding to the emerging social trends.

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Chapter 4
The Circular Construction Industry

Seyed Hamidreza Ghaffar, Mina Salman, and Mehdi Chougan

Abstract This chapter defines circular construction, and how the construction industry should prepare and make interventions to promote the transition from a linear model to circular and sustainable ways of designing, constructing, maintaining and dealing with waste. Circular construction is an emerging business strategy that promotes the reuse and recycling of as many raw materials as possible in a bid to minimise CO_2 emissions and waste to landfill. The chapter focuses on construction and demolition waste (CDW) and how potential new technologies developed for other applications can be utilised to bring circularity to CDW management. CDW alarming impacts have caused increased public concerns. Aiming to boost resource exploitation efficiency, circular construction should improve CDW waste management practices. However, transition and implementation of circular construction practices are slowed down by technical, social and legislative barriers. Circular construction, as an important component of sustainability, is a new business model that promotes the maximum reuse and recycling of raw materials and products to reduce waste and CO_2 emissions. Reduce, reuse, recycle and recover are essential interventions for a circular construction, with a systemic shift in the culture and mindsets of stakeholders.

Keywords Circular construction · Circular economy · Demolition waste · Recycling · Recovery · HS2

1 Introduction

The construction industry is responsible for more than 30% of natural recourses extraction, as well as 25% of solid waste generated worldwide due to its linear

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_4

economic model of "take, make, dispose" (Benachio et al., 2020). The built environment accounts for 39% of global energy-related CO_2 emissions (Orr et al., 2019). As a result of recent progress in reducing operational energy and implementing stringent standards for near-zero energy buildings, embodied energy is one of the most critical features of whole-life energy consumption in buildings. Adopting a circular construction model and utilising raw materials efficiently are a crucial step in reducing emissions. Buildings use structural material inefficiently, while generating nearly 50% of waste (Orr et al., 2019). This could be due to individual misconceptions among engineers or cultural phenomena in which engineers unquestioningly repeat previous techniques without examining their sustainability.

Worldwide policies indicate a recognition on rapid actions which are required to mitigate resource depletion, greenhouse gas emissions and climate change in the construction industry. These actions should be focused on implementing a circular economy approach, where construction materials are used in a sustainably (Ghaffar et al., 2020). Circular economy in Europe may generate a net benefit of EUR 1.8 trillion by 2030, while also solving rising resource-related concerns, creating jobs, fostering innovation and providing significant environmental advantages (Kirchherr et al., 2018).

The demand for using eco-friendly resources, coupled with advances in digital technologies and waste materials valorisation, is leading to unprecedented opportunities in the construction industry. With an eco-design concept, the construction industry must bring environmental aspects into consideration through eco-efficient design (minimising negative impacts) and eco-effective design (maximising positive effects, including profit). Waste has always been and continues to be a major issue for the construction industry. In 2019, the UK, approved legislation aimed at reducing its contribution to global warming by 2050. The G7 followed suit in June 2021, pledging to lay up a plan to achieve net-zero greenhouse gas emissions by 2050.

2 Principles of Circular Economy Concept

Circular economy (CE), a regenerative system, in which growth is gradually decoupled from the consumption of finite resources, offers a response to global challenges. EC is an economic system based on business models that substitute the paradigm of "end-of-life" with "reduce, reuse, recycle and recover" resources in production, distribution and consumption processes. The circular economy is founded on three principles: (1) waste and pollution should be designed out: today's products should be transformed into tomorrow's resources and the negative effects of economic activity on human health and environmental resources should be eliminated (e.g. the use of hazardous and toxic compounds, greenhouse gas emissions, air, land and water pollution). (2) The materials and products should be kept in use: prioritising operations that increase product utilisation and reuse to preserve the embedded energy, labour and materials. (3) Natural systems should be restored: adopting practises that not only avoids natural resources degradation but also enhances their availability over time. CE models are supported by concepts such as reverse logistics, cradle-to-cradle design, eco-efficiency and the hierarchy for waste management—reduce, reuse, recycle and recover (Ogunmakinde et al., 2021). CE enables economic growth without increasing resources' consumption and is a concept that implies the redesign of industrial systems, and deep transformations on production chains and consumption habits. Thus, CE strategies are clearly aligned with the United Nations Sustainable Development Goals.

Several countries, including the UK, China, Japan and all members of the European Union, have embraced CE concepts into their policies and legislation (Smol et al., 2017). However, the implementation of CE in different industrial sectors has followed diverse approaches, and the lack of common strategies and instruments has limited the desired widespread of CE (Singh & Sung, 2021). CE models are supported by concepts such as reverse logistics, cradle-to-cradle design, eco-efficiency and the hierarchy for waste management—reduce, reuse, recycle and recover (Ogunmakinde et al., 2021). Several countries, including the UK, China, Japan and all members of the European Union, have embraced CE concepts into their policies and legislation (Smol et al., 2017). However, the implementation of CE in different industrial sectors has followed diverse approaches, and the lack of common strategies and instruments has limited the desired widespread of CE (Singh & Sung, 2021).

At present, there are no available measurements or indications that can be employed to verify that a structure is circular. It is challenging to establish the magnitude at which circular transformation occurs in the construction industry without a robust mechanism to benchmark and monitor circularity efforts and interventions. Material lifespan, urban mining and circular design are examples of indicators that should be developed with specific user and data needs in mind. Analysing industrial design standards and tools is imperative in order to investigate the possibilities of establishing adapted or new indicators for monitoring circularity throughout the chain value. The Ellen MacArthur Foundation defines four important parameters for achieving a circular economy: (1) circular business models, (2) circular design, (3) reverse logistics and (4) enablers and favourable conditions (i.e. public policy). Without addressing circular business models and new engineering processing it will be impossible for the built environment to fully move towards a circular economy. Therefore, it is critical that commercial leaders from all tiers of the supply chain work towards new business models.

The goal of the circular construction industry is to promote sustainable development for present and future generations through economic success, environmental quality and social equality (Kirchherr et al., 2017). Despite the fact that CE has grown in relevance among policymakers, academics and entrepreneurs, the conceptual correlation between sustainability and CE remains unclear. This may have a negative impact on scientific advancement in terms of sustainability and the spread of CE-based practices. The CE and sustainability both need the integration of non-economic characteristics into development that requires the cooperation of different stakeholders where business model innovations are key for transformation of industry (Geissdoerfer et al., 2017). It is important to note that technological innovations are crucial for further developments of CE and sustainability but often pose implementation problems. On the other hand, differences between sustainability and the CE are in their respective main motivation; i.e. for the CE concept the goal is better use of resources, valorisation of waste (from linear to circular), whereas the sustainability concept is a balanced integration of economic, social and environmental performance (Geissdoerfer et al., 2017). Moreover, the responsibilities are shared, although not clearly defined in the concept of sustainability, while for the case of CE the responsibility of implementation lies with the private business and regulators/policymakers. Most of the research efforts focus on the environmental performance improvements of the CE rather than taking a holistic view on all three dimensions of sustainability.

The principles of circular construction could be summarised in the following major and generic categories:

(1) Constructing and developing in harmony with nature, considering the climate emergency;
(2) Using waste as a resource where construction materials and products should flow in a closed loop;
(3) Resilience through diversity where infrastructure development with multi-components are more resilient;
(4) Use energy from renewable resources such as solar, wind, hydro and tidal power;
(5) System approach and system implementation is key, e.g. considering multi-factors, multi-actors and multi-stakeholders.

Circular construction, in line with sustainable development, is a guiding principle for expansion and growth based on environmental quality, economic prosperity and social equity, which should be achieved without jeopardising future generations' potential. When it comes to circular construction, the focus on economic prosperity is predominantly noticeable among practising engineers while environmental aims are most important for the academics, without investigating the economic feasibilities of their lab-scale developed solutions. The circular construction can improve the competitiveness of stakeholders by protecting businesses against shortage of resources and unstable prices, and this will then create innovative business opportunities and efficient methods of production and consumption (Kirchherr et al., 2017). To achieve circular construction, two of the main bottlenecks are: (1) changing the mindset of industry stakeholders towards cleaner production of raw materials, (e.g. promoting secondary raw materials recovery from different waste streams), (2) overcoming the technical issues, where there could be a low market acceptance (e.g. prices, legal barriers and regulations) for recycled construction materials and products (Ghaffar et al., 2020).

3 Innovative Technologies for Circular Construction

Innovative technologies are the real game-changers for delivering circular construction, which promotes reactive decision-making, i.e. what happened in the past; and being proactive, i.e. what can be done better.

Digital networks, intelligent robotics, digital image analysis, robotics for waste separation, sensor-based infrastructures for waste collection, geographic information systems, global positioning systems to assist waste disposal and data sharing to support product lifecycle analysis are all examples of innovative technologies used to bring the circular construction vision to life (Kabirifar et al., 2020; Sarc et al., 2019). For example, smart interconnected assets can provide predictive maintenance to extend the life of the asset, blockchain can reduce waste by creating traceability and transparency in the supply chain and 3D printing makes the repairs of spare parts easier. As a new emerging technology, artificial intelligence (AI) has the potential to support and accelerate human innovation in product design, bring together elements of successful circular business models and optimise the infrastructure required to loop materials and products back into the economy. AI capabilities could assist in constructing an effective economic system that is regenerative by design, resulting in a step-change that goes beyond incremental efficiency increases. Design innovation is required in the circular economy to keep materials, products and components at their highest utility and value at all times, recognising the distinction between technical and biological cycles. ZenRobotics is an example of industry enterprises contributing to circular construction, they were one of the first companies to use AI and robots in a demanding waste processing environment. To extract recyclables from waste, the company uses combined AI and robotics technologies. ZenRobotics's technology enables increased waste sorting flexibility, which leads to enhancing the efficiency of secondary material recovery and purity. Cameras and sensors coupled with AI technology were employed to monitor the Waste. ZenBrain, an AI software, examines sensor data to produce a precise real-time analysis of the waste stream. The heavy-duty robots make autonomous decisions on which pieces to remove based on this analysis, which leads to a rapid and precise separation of waste and it enhances the secondary raw materials recovery efficiency.

The potential value unlocked by AI in helping design out waste for food will be up to USD 127 billion a year in 2030. This is achieved by opportunities in farming, processing, logistics and consumption phases (Artificial Intelligence and the Circular Economy, 2013). Using image recognition to detect when fruits are ready to pick, better matching food supply and demand, and increasing the value of food by-products are some of the specific applications. This is an example from different sectors to the construction; however fundamental similarities between the prospects imply that AI's potential to generate value in a circular construction is huge. Integrating the capabilities of AI in the construction sector creates a substantial and unexplored possibility to support efforts to fundamentally transform the construction industry into a resilient, regenerative and long-term solution for combating the global challenges.

To encourage applications that cover and go beyond the domains of circular design and circular business models, it is vital to raise awareness and understanding of how AI and other innovative technologies may be utilised to support the transition towards circular construction. AI could be used to redesign entire networks and systems in any industry, such as reorganising supply chains and enhancing global reverse logistics infrastructure (Chiaroni et al., 2021).

Recent advances in AI-based data analysis techniques, especially in smart sorting systems, provide a solution for automated on-site classification methods. On-site sorting has many advantages and developing mobile machines and plants that can operate on-site is one of the innovative developments that have potential in contributing to circular construction. Since on-site operations require less workforce and resources than sorting at recycling facilities, it can also improve the reusability and recyclability of CDW and therefore contributes to production of high-quality products (Bao & Lu, 2020). Wang et al. proposed simultaneous localisation and mapping (SLAM) technology and the instance segmentation method, which enable the robot to deal with complex site environments, resulting in enhanced on-site CDW sorting accuracy (Wang et al., 2020). Blue Phoenix Group, established in 2008 in the Netherlands, provides a patented solution called Advanced Dry Recovery (ADR) method, for recovering and upgrading fine non-ferrous metals from municipal waste-to-energy ash. In the ADR method, the wet mineral fraction is separated from the coarser ash fraction comprising the precious small metal particles. This fraction can then be separated from the mineral aggregates using conventional eddy current separators to extract non-ferrous metals. The ash fraction less than 12 mm includes the most valuable percentage of non-ferrous metals (Advanced Dry Recovery (ADR), 2008). The heating air and classification system (HAS) works in conjunction with the ADR system. The HAS technology uses a combination of ADR's air knife (1–4 mm) and rotor (0–1 mm) products as its input material. HAS is developed to expose the fine fraction aggregates to hot gas in order to dry them out and remove unwanted small CDW impurities, such as plastic shards and wood. The procedure consists of a particle–gas interaction in a fluidised-type reactor, wherein the air is employed to convey the heat while classifying fine aggregates depending on their particle size. Heating is used to dry the material and activate the ultrafine particles, mostly comprised of hydrated cement.

Figure 1 illustrates our developed concept diagram for an integrated innovative solution which could deliver circular construction. It starts with smart dismantling as opposed to complete demolition, where the chances of recovery of secondary raw materials and reuse of components are higher. Combining new technologies with advanced sensors and robotic sorting, recycling systems offer a unique upcycling approach that can be utilised for a selection of input materials whilst consistently maintaining the ability to produce high-quality outputs, i.e. circular products. Pre-demolition audits and mobile on-site operations can be critical to the success of circular construction, while remanufacturing process aligned with modern methods of construction, such as prefabrication and 3D printing can assist with the circular product developments (Chougan et al., 2021; Ghaffar & Mullett, 2018). Issues around

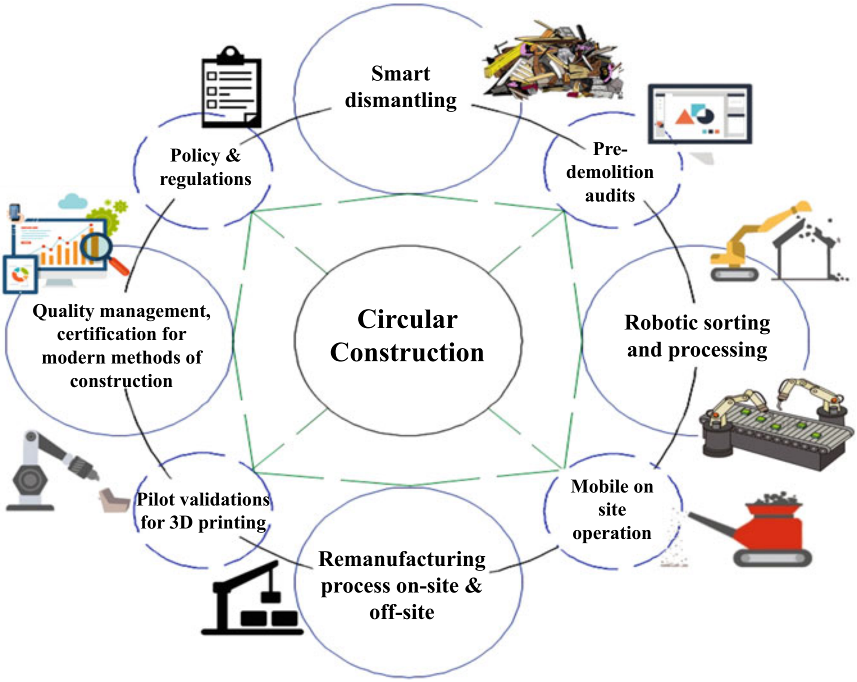

Fig. 1 Circular construction concept (author's original)

quality management and certifications require policymakers, scientists and practitioners to come together and make responsive policies and regulations that allow and enforce circularity within the construction industry.

More specifically, practitioners in the industry must be inspired and encouraged to be passionate about changing the mindsets of stakeholders and the public and showcase the potential of new paradigms. This can be driven by a combination of: (1) creative design, (2) focused academic research and applied technology, (3) external industry engagement and (4) flexible, responsive regulation.

4 Construction and Demolition Waste Management

CDW consists of bulky and heavy materials, such as concrete, wood, asphalt, gypsum, metals, bricks, glass, plastics, soil and rocks. Approximately, 333 million tons of CDW (except for soils) were generated in the EU in 2014, consisting of 300 million tonnes of inert waste, 30 million tons of non-inert waste and 3 million tons of toxic waste (Eurostat, 2018). Nearly 11 billion tons/ year of solid waste are produced globally, implying that each individual produces over a ton on average, and this amount is increasing. In 2025, waste generation is expected to double compared to 2000 (Tons

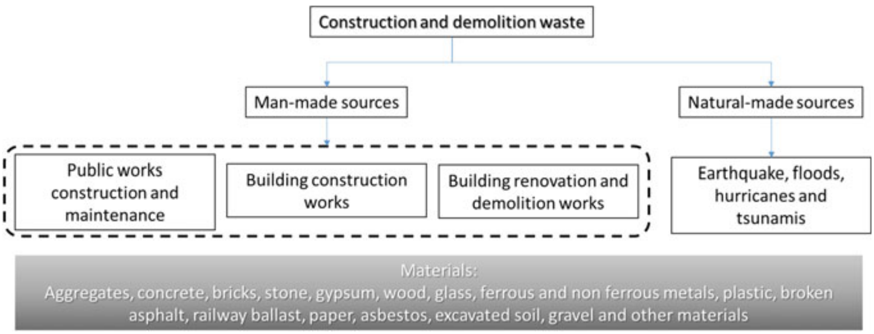

Fig. 2 CDW generic classification based on the source of origin (Menegaki & Damigos, 2018)

of Solid Waste Generated, 2020). Furthermore, by 2050, solid waste generation is predicted to be approximately twice comparing to 2016. CDW, municipal solid waste (MSW) and commercial and industrial waste are three major forms of solid waste (Global Waste Generation, 2018).

The sources of CDW origin are depicted in Fig. 2.

In 2018, China had the largest CDW production (i.e. around 2360 million tonnes). Ma et al. visited 10 different recycling plants and interviewed 25 industry practitioners in China and to produce a list of the challenges in the Chinese CDW management: (1) no tracking and accurate estimation of the CDW (where it comes from, how much is generated, and where it will be used), (2) insufficient waste minimisation design, (3) unregulated landfill practices with high cost, lack of financial or political support and (4) lack of cooperation from the government for the CDW management (Ma et al., 2020).

The USA (i.e. around 600 million tonnes) followed by India (i.e. around 530 million tonnes in 2016) are known as the second and third largest CDW producers in the world after China (Wang et al., 2021). Governments, researchers and businesses have all made efforts to mitigate CDW's negative environmental and economic effects by recycling and reusing it.

The CDW recycling is mainly hindered by, not only, technical and economic aspects, but also political and social aspects. The technical aspects are the lack of background information of CDW (e.g. the origin and amount of CDW) (Ma et al., 2020; Yuan, 2017), the constraints of the project and construction site (Zezhou et al., 2019), the lack of support from off-site recycling (Bao et al., 2020) and the lack of advanced technologies in recycling processes (Chi et al., 2020). The economic aspects include the lack of interaction and coordination in the CDW recycling and supply chain (e.g. nonexistence of platform for trading and information sharing of recycled products) (Aslam et al., 2020) and immaturity of recycling market (Chi et al., 2020; Ma et al., 2020). The absence of audit and oversight from authorities as well as insufficient recycling incentives are amongst the political factors (Chi et al., 2020; Ma et al., 2020). The social aspects, on the other hand, include insufficient

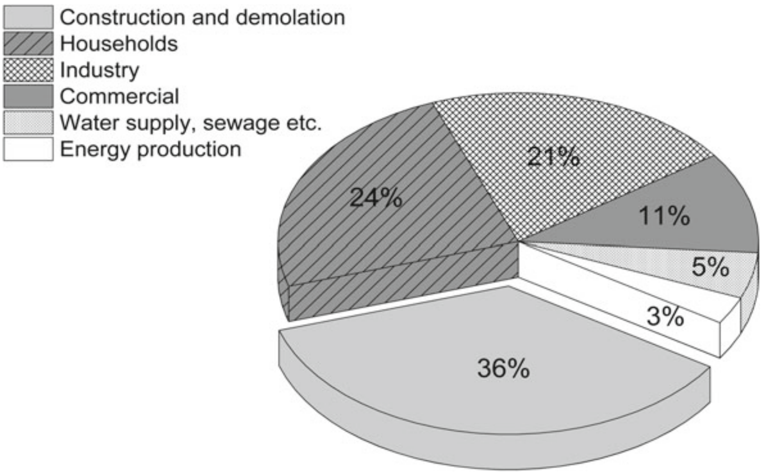

Fig. 3 Categorised sources of global solid waste generation (2020) (Ferdous et al., 2021)

awareness and acceptance of the products from recycled materials by public (Chi et al., 2020).

Figure 3 shows the various classifications for the global generation of solid waste, where CDW is shown to be responsible for the majority of solid waste generation, which will be disposed of in landfills.

Taking into consideration waste disposal facilities, policies and regulations, the amount of CDW created and the corresponding management procedures vary from country to country. For instance, Singapore recycles 99% of CDW each year, whereas China recycles only 5% of the total 2.36 billion tonnes of CDW generated (Lv et al., 2021). Europe also successfully recovered around 90% CDW of the total 870 million tonnes annually (Bonoli et al., 2021). According to the Environmental Protection Agency of the US, 600 million tonnes of CDW were generated in 2018, with 24% ending up in landfills (EPA, 2020).

Circular economy models and 4R framework of reduce, reuse, recycle and recover present as a major gateway to solving the issues with CDW management. Practical, feasibility and technical challenges in CDW management must be addressed and resolved to facilitate the transitioning to a circular construction in practice (Ranta et al., 2018). Reuse of CDW refers to the practice of repurposing building materials, either for the same or a different application. This necessitates efficient CDW collection and sorting techniques, which may be difficult to implement. Recycling of CDW, on the other hand, requires waste collection and sorting technologies, where the high cost of procedures reduces the economic advantage of recycled materials over original materials. Moreover, effective recycling of CDW requires the existence of an organised market for secondary materials to uptake recycled waste. Despite the extensively documented environmental advantages of reuse and recycling of CDW, linear-based processes are still the dominant rule in the construction industry (Ogunmakinde et al., 2021). Nevertheless, based on the principles of circular construction, CDW practices of reduction, reuse, recycling and recovery of secondary raw materials could have positive impacts on the amount of disposed waste, while preserving the natural resources used in the construction industry.

Apart from imposing stringent legislations and fiscal policies, using incentives and tax breaks is crucial for reducing construction waste. These incentives and tax breaks could be funded by penalties and fines for poor sustainable practices, which can be an effective way of achieving sustainable practices in the construction industry. Unlike government that is mainly concerned about environmental aspects of waste minimisation, the contractors are more influenced by financial benefits of waste minimisation (Ajayi & Oyedele, 2017).

Despite the understanding that design stage is decisive in construction waste minimisation, most strategies target construction stage where preventive measures are already late. Well-known, sustainable design appraisal systems such as Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) have not yet considered options for designing out waste, despite covering various design practices for environmental sustainability.

A study conducted by Mahpour (2018) evaluated the environmental impact of on-site sorting, off-site sorting and direct disposal of construction waste. They discovered that the trend towards off-site sorting and direct landfilling was an obstacle to severe environmental problems, but on-site sorting resulted in net environmental advantages. Moreover, they realise that, compared to the existing cradle-to-grave model, construction participants are hesitant to undertake on-site sorting due to space and financial constraints, tight timetables, and more labour and administrative efforts (Mahpour, 2018).

An implementation strategy that incorporates circularity and constructability could help to build on apparent achievements such as the UK Statistics on Waste report (2019), where the overall recovery rate from non-hazardous CDW is reported to be 90%, which is 20% more than the objective of the EC Waste Framework Directive by 2020. However, overall statistics may not be as impressive as they appear; according to the same report, the UK construction industry accounts for more than 60% (130MT/year) of all waste generated in the country. Furthermore, between 2010 and 2016, the rate of CDW generation increased gradually, with no notable increase in recovery rates.

CDW minimisation is the waste management strategy with the lowest negative environmental impact; hence, it should be given top priority in waste management practices. CDW minimisation is highly reliant on resource efficiency measures created during the design stage. Prefabricated modules, for instance, can reduce CDW by 80%, and there are additional solutions, such as building information modelling (BIM) and lean construction, that could have a significant influence on waste reduction (Kabirifar et al., 2020). Approximately one-third of construction waste is resulted from design decisions (Yuan et al., 2011). However, design for waste minimisation has not received sufficient attention, potential due to the lack of training and awareness of industry practitioners, or their lack of interest to environment protection or the absence of regulations on waste reduction (Ma et al., 2020).

There are various barriers to moving to circular construction in terms of CDW management. Some of the more significant ones are listed below:

1. Ineffective CDW dismantling, sorting, transporting and recovering processes.
2. Preferring off-site CDW sorting and landfilling over on-site sorting due to lack of incentives.
3. Inadequate policies and legal frameworks to manage CDW.
4. User preference for new construction materials over reused/recycled ones.
5. Lack of clearly defined national goals, targets and visions to move towards circular economy in CDW management.
6. Inadequate awareness and understanding about circular economy and its potential for the construction industry.
7. Lack of funding to implement circular economy in CDW management, where there is a tendency to manage cost and time rather than CDW.

4.1 Construction and Demolition Waste Valorisation

Recent investigations have proven that employing CDW recycled aggregates (RAs) as a replacement of natural aggregates (NAs) in new construction applications as recycled aggregate concrete (RAC) showed both economic and environmental benefits. According to estimates, utilising RAs instead of NAs in concrete construction saves 10–20% of material costs (Zheng et al., 2017). Moreover, a study conducted on the life cycle assessment of RA and its environmental effect showed that its use in concrete can lead to a reduction of 58% in non-renewable energy consumption and 65% of greenhouse gas emissions compared to use of NA (Hossain et al., 2016). Nevertheless, the mechanical properties of RAC are inferior to the corresponding natural aggregate concrete (NAC), which limits RAC's applications for structural concrete (Wang et al., 2021). In addition to the reduced mechanical performance of the RAC, the process for recycled aggregates production has also limited its widespread utilisation. In the past 20 years, the number of publications on RAC has exponentially increased (Gao et al., 2020; Ismail & Ramli, 2013; Mukharjee & Barai, 2014). A review by Wang et al., (2021) comprehensively investigated RAC and recycled aggregates in terms of their background, recycling, reuse and manufacturing processes, intrinsic defects (e.g., the presence of additional interfacial transition zones (see Fig. 4)) and material characteristics (Wang et al., 2021). They offered techniques aiming to improve the mechanical and long-term performance of RAC based on (i) porosity refinement of recycled aggregates, (ii) old mortar layer reduction on the surface of recycled aggregate and (iii) improving performance without any modifications on recycled aggregate such as the incorporation of reinforcing fibres.

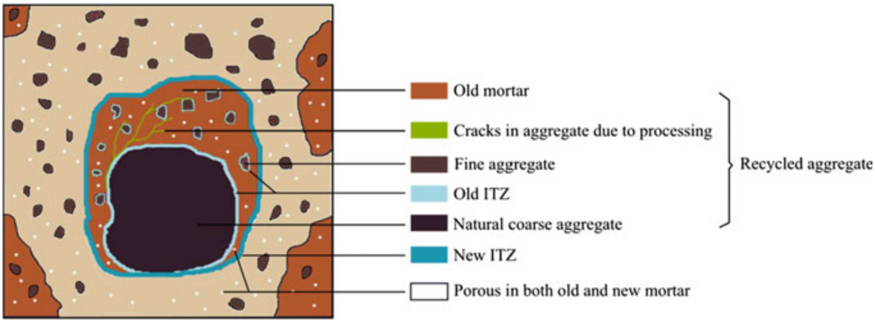

Fig. 4 Schematic of recycled aggregate in recycled aggregate concrete (Wang et al., 2021)

Crushing concrete waste, screening and removing contaminants such as steel reinforcements and plastics are common methods for producing recycled concrete aggregate (Devi et al., 2020). Recycled aggregate accounts for approximately 8% of aggregate use in Europe, with substantial differences between countries. The greatest users are the UK, the Netherlands, Belgium, Switzerland and Germany (Aslani et al., 2018).

The incorporation of recycled coarse aggregate, with the size of 4 mm and higher, in new concrete, has been proven to have compressive strengths that are comparable to natural aggregates, and in some conditions, even higher (Lotfi et al., 2014; Malešev et al., 2010). As a result, suggestions for the use of coarse recycled aggregate in concrete can be found in the European concrete standards, EN 206:2013, annex E and EN 13,369:2012 (Müller et al., 2015).

In general, recycled aggregates include three constituents: original aggregate, adherent mortar (AM) and an interfacial transition zone (ITZ) between AM and original aggregate (Juan & Gutiérrez, 2009). The quality and quantity of AM determine the final performance of recycled aggregates. Considering the concrete source, strength grade (the porosity of the original paste), crushing procedure, particle size distribution and test parameters, the quantity of AM in recycled aggregate concrete can range from 25 to 70%. Moreover, the quality of AM is influenced by the cement strength grade (Liu et al., 2011) and the original aggregate characteristics. Recycled aggregate has a rough morphology with a poor physical and mechanical performance which is attributed to the presence of AM. However, numerous pre-treatments have been carried out to enhance the low quality of recycled aggregate (Shaban et al., 2019). The application of appropriate pre-treatment techniques can yield significant technical benefits at a low cost. Most recycled aggregate pre-treatment approaches have either targeted on eliminating or enhancing the AM. Several standard procedures, including microwave removal, mechanical grinding, thermal processing and pre-soaking in acid, have been employed for an effective removal of AM (Shi et al., 2016). In addition, other techniques such as pozzolanic slurry immersion, polymer impregnation, bio-deposition and accelerated carbonation curing have also been proposed to strengthen the AM by enhancing the weak areas of the RA caused

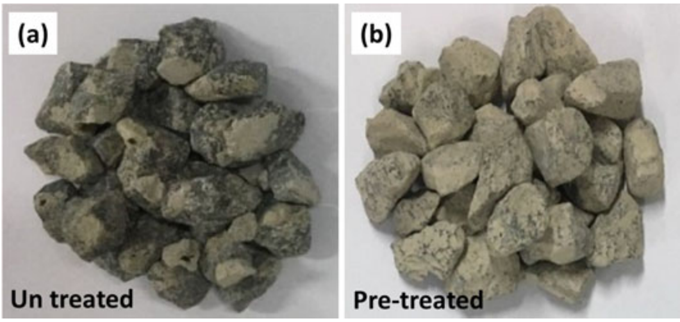

Fig. 5 RCA and pre-treated RCA coated by sulphoaluminate cement (**a** and **b**) (Zhang et al., 2018)

by filling capacity and/or chemical reactions (see Fig. 5) (Shi et al., 2016). For instance, Zhang et al., (2018) suggested that the sulphoaluminate cement surface-treatment improves RA quality (Fig. 5a, b), leading to improved apparent density and reduced crushing value and water penetration. The RAC's mechanical performance and the aggressive materials resistance (i.e. chloride and sulphate) were consequently improved (Zhang et al., 2018). In addition, polymer coating using Sika Tite-BE polymer (Fig. 5c, d) revealed a promising effect on the quality enhancement of RA particles.

While concrete recycling is a well-studied topic, brick waste recycling has been primarily employed as a replacement for natural aggregate. The use of waste bricks (WB) in the form of (i) recycled aggregate, (ii) partial cement replacement and (iii) alkaline activation for precast block manufacturing has all been explored and proven as viable recycling scenarios for waste bricks on small laboratory scale (Fořt & Černý, 2020).

The use of WB as a natural aggregate replacement is the most common scenario in the EU, owing to its simplicity and minimum of additional material processing and treatment requirements. Processed WB is commonly utilised in road construction, which needs large quantities of natural aggregates with low specifications. WB aggregates have also been utilised to make lightweight concrete with a bulk density of less than 1800 kg/m^3 (Zhao et al., 2018). Improved thermal and acoustic insulation were among such material benefits, apart from a lower environmental impact. WBs with a high amount of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and a relatively smaller proportion of CaO have a suitable chemical composition that makes them ideal to be used as supplementary cementitious materials if their grain size distribution is fine enough (Afshinnia & Poursaee, 2015). Given the large quantity of crystalline phase, the pozzolanic reaction of brick powder was found to be less intense than that of conventional supplementary cementitious materials such as metakaolin or ground granulated blast furnace slag (GGBS). However, a good grinding process can enhance the specific surface area and, as a result, improve the pozzolanic activity (Komnitsas et al., 2015). Based on the investigation conducted by Vejmelková et al., (2012), 20% of the cement could be successfully replaced without causing significant material performance deterioration (Vejmelková et al., 2012). WB powder was proven to be suitable for partially replacing cement in lime–cement mortars, resulting in substantial enhancements in compressive and flexural strength (Kočí et al., 2016). Brick waste fine particles (fine fractions with D50 ~50 μm) can also be utilised as a binder material for alkaline activation employing a variety of alkaline solutions such as sodium hydroxide or sodium silicate. This method has the advantage of completely replacing Portland cement, making the use of WB powder more effective than when only partial cement replacement is used (Fořt & Černý, 2020).

5 Circular Construction Practices in the Industry

This section highlights examples and real cases of circular practices and strategies adopted in the Skanska, Costain and STRABAG Joint Venture (SCSJV) sites. SCSJV is working in delivering 26.4 km of High-Speed 2 (HS2) railways, known as the London Tunnels. HS2 is a 140 miles high-speed railway line to serve around 30 million people from London to West Midlands, Manchester, Glasgow, Liverpool, Preston and Wigan. It is assumed to be operational between 2029 and 2033. There are over 200 HS2 construction sites working on delivering variety of structures such as 150 bridges, 110 embankments, over 50 viaducts, 4 stations and over 70 cuttings, making it currently the biggest railway project in UK and Europe. Therefore, it is likely that the construction of the HS2 railway will generate significant amount of construction and demolition waste (CDW) and around 130 million tonnes of excavated earth. Due to its size, complexity and importance, the HS2 project could be a great example of implementing circularity in practice, and therefore, some of its case studies have been chosen to be covered in this chapter.

The government had introduced the High-Speed Rail (London -West midlands) Act 2017 and the Environmental Minimum Requirements (EMRs) documents supported by a series of papers to cover the high-level environmental and sustainability commitments, including (1) Annex 1: Code of Construction Practice; (2) Annex 2: Planning Memorandum; (3) Annex 3: Heritage Memorandum; (4) Annex 4: Environmental Memorandum; (5) Register of Undertakings and Assurances. These documents set out the expected approaches and outcomes when handling excavated materials and waste that arises from the construction of HS2. An estimated value of 130 million tonnes of soil needs to be excavated to enable the HS2 railway line construction. However, over 95% of the excavated soil will be reused, recycled or recovered and the unsuitable materials will be classified as waste and sent to landfill. Therefore, the waste producers, i.e. construction contractors, are obligated under the law to apply the appropriate waste hierarchy method in relation to reducing the waste and applying circular construction waste management methods.

SCSJV is one of the JVs working in delivering the final 26.4 km of the HS2 route from Northolt to Euston via Old Oak Common Station, including 21 km of twin bore tunnels for the construction of which SCS will be running seven tunnel boring machines (TBMs).

This part covers how the SCSJV are implementing circular economy practices on site. Below are a detailed list of interventions towards circularity and reduction of waste.

- **Area West—West Ruislip Portal (WRP): Reusing temporary works concrete**

West Ruislip Portal used approximately 4800 tonnes of concrete for piling platform and pile breakdown as part of their temporary works which means, the concrete will be removed once the work is completed. Therefore, in order to minimise the construction waste and reduce material transportation, it was decided to crush the concrete as 6F5 (which is an unbound, coarse recycled aggregate) and reuse it for other purposes. This led to 26tCO2e carbon emissions savings from transportation, and there was no additional need to order 6F5 for the other works on the West Ruislip Portal.

- **Area West—Northern Sustainable Placement Area (NSPA): Reused excavated materials from Copthall**

Copthall Green Tunnel is a 550 m of cut and cover tunnel, and it is one of the areas that will generate significant volume of excavated materials, approximately 852,000 m^3 of soils which had to be reused in line with the environmental and sustainability commitments of the project. In order to successfully manage the potential impacts of waste and materials, it was decided that the arising soils will be used as an embankment fill for a road embankment, approximately 80,000 m^3 which will later be landscaped with trees and shrubbery, for the construction of NSPA, approximately 140,000 m^3. Another 140,000 m^3 of the arising soils will be used on the spot to cover the Copthall tunnel walls and cover slabs, as a required layer on top of the concrete box structure.

To comply with the High-Speed Rail (London-West Midlands) Act 2017, an area was created approximately 3 km away from the actual working area where the inert waste would be placed and conically mounded for up to 18 m. Excavated materials that will be stored in the NSPA are mainly London clay, and once completed it will be used to enhance the local ecosystem by providing a rich diversity of woodland and a variety of types of grassland habitats. The habitats created will consist of broadleaved woodlands, wet woodlands, wood pasture, parkland, scrubland, scattered trees, seasonal and permanent ponds. Northern sustainable placement area will also be used as a natural flood management method to control the rainwater and reduces the risks of flood and support water filtration through proposed wet woodlands in the low-lying areas. The NSPA is an effective way of reducing the transportation of the large volumes of the arising soils and materials on public roads. The materials from Copthall Tunnel will be transported to the NSPA using conveyors to save over 21.8t of CO_2e from HGV movements between the sites and blocking narrow roads within the area. This will also help to save over 21.8 tonnes of CO_2.

- **SCS logistics Hub—Willesden: transporting materials by trains to facilitate the construction of residential buildings**

In September 2021, SCS launched its first logistics hub in Willesden, which is used to transport approximately 5.6 million tonnes of inert excavated materials. To be able to transport these materials, it has been estimated that around 34,000 sets of lorry movements would have been required to carry out this operation. Instead, the SCS team will utilise 4,150 wagon trains with 20 T capacity to transport the materials to Barrington in Cambridgeshire, Cliffe in Kent and Rugby in Warwickshire. The materials will be reused for redevelopments of residential buildings. This will not only help to minimise the landfill waste, but it also cuts lorry movements on the road, thus reducing the carbon emissions by 40%.

- **Transformation of London clay into construction resources**

A feasibility study to explore the possibility of producing useful construction resources from excavated material is being led by SCS. The project named Re-purposed Excavated Arising Loop (REAL) (Papakosta et al., 2020) aims to assess the potential to transform excavated London clay spoil into calcined clay for use as Supplementary Cementitious Material (SCM) in concrete; and expanded clay for use as Lightweight Aggregate (LWA). Successful implementation and uptake of this circular economy approach could result in minimised waste streams to landfill, improved resource efficiency and reduction of imported materials. However, there is a wide range of literature on the suitability of several clays for use in concrete, there is little information specifically for London Clay as a potential SCM.

London Clay could also be utilised as expanded clay pellets serving as lightweight aggregate for different uses such as infill, insulation or in low-grade lightweight concrete. While several clays are used worldwide to produce expanded lightweight aggregate, there is only one documented study to manufacture clay aggregate using London Clay as part of Crossrail project (Boarder & Owens, 2014), where excavated London Clay was converted into expanded clay aggregates in the laboratory and used in concrete. The study indicated that the resulting aggregates led to low compressive strengths concretes, which suggests that while the expanded London Clay aggregate may not be suitable for structural concrete, non-structural applications could be considered, such as mass concrete fills and concrete blinding.

- **Carbon savings**

As well as minimising waste to reduce the environmental impact, SCSJV has also been implementing and changing the traditional construction methods to contribute to carbon savings. Some of these are listed in Table 1.

Table 1 Interventions for carbon savings across SCS sites

What	Benefits/Savings
Replacement of plant and vehicles to low impact hybrid machines including use of renewably-powered equipment	Solar pod station that can be used to charge radios and handheld tools. 20% fuel saving per annum compared with diesel counterparts (i.e. for hybrid dozer and excavator). The hybrid excavator is saving over £9000 in fuel costs per year. The dozer has an electrical drive system which offers up to 25% more fuel efficiency translating to a saving of about 4.5 L of fuel per hour. Approximately 22,000 kg of CO^2 saved from one solar pod charging station in 4 months (roughly £5000 fuel costs savings)
Cement replacement in concrete works	The concrete mix was prepared by replacing the cement content with 70% of GGBS (Ground Granulated Blast Furnace Slag) in capping beam and slab. This led to a saving of around 157 T of carbon emissions
Carbon savings by cutting road movements	As for the Earthworks tasks, there are high volume of materials importing and waste materials removal, approximately (25,000 T materials import) and (34,000 T of muck away); therefore, to reduce the lorry movements on roads and cut down on carbon emissions, SCS agreed with the contractor to implement a single holistic approach, which means, the same lorry that offloads the materials, takes the waste materials, reducing the carbon by 1240 trips
Low carbon piling mat	The concrete piling mat chosen is an environmentally friendly mix which uses GGBS and fly ash. Additionally, a 6F5 layer was installed underneath the concrete slab to avoid the use of mesh. This led to 79% of carbon savings as opposed to the traditional method

6 Conclusions and Prospective

In the shift to net-zero carbon, circular principles play a critical role in meeting carbon emission targets. Embracing circular strategies in the construction industry will prove pivotal in driving financial and environmental opportunity to design out waste, enhance asset productivity and achieve sustainable development goals. In order to fulfil all the possible economic opportunities, the circular economy approach should be considered not only as a sustainability consideration but also as a business factor. In the construction industry, circular economy pillars such cradle to cradle, regenerative design, eco-efficiency, eco-effectiveness, reverse logistics and zero emissions can enhance closing material loop by reuse and recycling. Closing the loop implies that no material is left hanging in the cycle. Material reuse as is key methodology for closing the loop. Similarly, recycling of products or their component parts could ensure their continuous use over time. This would enhance material recovery and maximise the product value. Most construction materials (e.g. steel, concrete, aluminium and wood) can be recycled at the end of their useful lives suggesting that recycling is important in closing the material loop. Repair and refurbishment of materials can also be considered in ensuring closed loop. Broken materials or structures can be repaired while old materials can be restored. Furthermore, it is critical not to restrict circularity to the reuse and recycling of construction materials but rather to keep the wide scope of circular concepts in mind. For instance, there is a critical need to address life cycle impacts across various factors, which would necessitate dynamic impact models that account for technology advancement and innovation. Prefabrication of materials or component parts can be a strong approach in closing material loop in the construction industry. With prefabrication, building components are produced of-site and are assembled on site. This allows for appropriate inventory of materials and waste materials emanating from the production process can be returned into the system thereby ensuring no material leftovers. Therefore, it is important that materials or products are designed for ease of conversion, reuse and recycling. This would reduce the amount of waste that is sent to landfill. The implication is for construction professionals to incorporate into their design the circular economy pillars identified to enhance closing material loop in their design and to ensure that durable materials are specified for construction projects.

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Part II
Innovation in Construction: A New Future for the Construction Industry. Areas of Focus for a Step Change in Construction

Chapter 5
Fundamentals of Innovation

Paul Mullett

Abstract This chapter explores the definition of innovation and through the use of well-known examples from the aviation industry, dispels frequently held assumptions about the use of cutting-edge technology as a prerequisite for innovation and instead explains that innovation is simply the intersection of novelty and the creation of value. The chapter then identifies seven key actions that are fundamental to the development of an innovation culture across businesses and teams including: developing the 'why?', setting big goals, planning resources, promoting diversity, creating proximity, giving permission and driving adoption. These actions are discussed in general terms and with a passing reference to the construction industry, explaining how each is an integral component for the success of businesses, teams and projects.

Keywords Innovation · Technology · Transformational · Incremental · Culture

1 Introduction

The world of business and government is seemingly obsessed with the idea of innovation. It is considered an ultimate panacea to the many challenges of surviving and thriving in a capitalist economy; feeding growth, developing brand, creating competitive advantage, helping retain staff, avoiding irrelevance and preventing commercial decline.

Indeed, there are courses, institutions, standards and awards associated with the implementation of innovation across fields as diverse as management, economics, art and design, technology and even politics. Whilst these resources are naturally welcome, there is a risk that the more complex and studied the concept of innovation, the more misunderstood and out-of-reach it becomes. There is the danger it becomes a specialism in its own right rather than embedded in everything we do.

The AEC industry is no exception and in the modern era has struggled to understand and benefit from innovation. The number of published articles, government-

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_5

and industry-sponsored reports and textbooks continues to grow on the subject; describing an urgent need to innovate, the potential of emerging technologies, the challenges and opportunities of digital transformation and a need to re-think construction. The next chapter attempts to distil some of these ideas and explores some of the specific challenges facing the AEC industry.

This chapter does not seek to repeat or replicate the wealth of material written about innovation but simply to provide a timely reminder of what innovation is and to highlight a few of the factors that help contribute to its successful implementation, in the hope that when looking at some of the excellent examples of innovation presented elsewhere in this book, it will help readers remain focused on real and tangible benefits and practical opportunities.

2 Definition

We would all be able to name products that we thought were innovative without perhaps understanding exactly what makes one thing innovative and another thing not. And, herein lies the first challenge in understanding and applying innovation; real innovation can be quite different to assumed innovation. The world is full of assumed innovation—products that are marketed as being innovative, look innovative or are simply believed to be innovative by virtue of their status, brand or level of applied technology. Some of these are the deliberate consequence of smoke and mirror marketing strategies, and others are not, but from a practitioner's perspective, assumed innovation is failed innovation.

The first challenge must, therefore, be to remove our bias in adopting technology for technology's sake, finding an excuse to use the latest shiny toy in the R&D department or simply trying to be cool and 'cutting-edge' to sell and instead to look more deeply at what needs to be done and how we can do it better. Great care must be taken when assessing the appropriateness and readiness of technology, and significant research must be undertaken to ensure expectations and outcomes are realistic. The Gartner Hype Cycle (Blosch & Jackie, 2018) is a useful evolving reference providing an overview of emerging technologies and their anticipated timelines for measurable benefits.

It is, therefore, important to attempt to define innovation so that we can have an awareness of the fundamentals that underpin what makes something truly innovative. There are many definitions of innovation, and too many to list here; however, a quick search on Google will reveal a few recurring themes;

1. Using cutting-edge technology/knowledge
2. Applying a creative idea/concept
3. Being the first to do something
4. Adding value for the benefit of stakeholders or society.

There is, however, no consensus on these fundamental themes, and so, we are left to ponder how they relate to our context—that typically of a commercial enterprise in the AEC industry endeavouring to be successful and hopefully bringing a benefit to society.

The idea of innovation somehow being the result of cutting-edge technology or the application of new knowledge (often scientific) is perhaps the most common preconception. Technology is certainly a significant factor in the potential to innovate, but it is not by any means essential or a guarantee of success.

In fact, many innovations take existing or well-established technology and apply it differently to realise a previously unrealised benefit. We often see examples where the first commercial application of technology is a failure as the technology is immature, the value offering is undeveloped, the commercial model is wrong, or society/industry is simply not ready. Subsequent attempts (often by competitors) frequently succeed by learning from the failings of the original pioneers. Alternatively, innovation can be successful by taking established or proven technologies from one industry and modifying them for specific applications in other industries.

Institutional definitions often refer to innovation in terms of its ability to generate value or economic benefit. Indeed Drucker (2002) viewed innovation as an entrepreneurial activity stating 'It is the means by which the entrepreneur either creates new wealth-producing resources or endows existing resources with enhanced potential for creating wealth'. Drucker goes further in saying that 'Purposeful, systematic innovation begins with the analysis of the sources of new opportunities'. Emphasising the point that successful innovation is first and foremost dependent on defining an outcome that meets a need or addresses an opportunity previously not realised.

There are other perspectives that believe innovation must be new, or perhaps even the first, in order to be considered innovative. In his book 'Diffusion of Innovation', Rogers (2003), communication theorist and sociologist, describes innovation as 'An idea, practice or object that is perceived as new….' without specifically referencing economic value. This perhaps plays to the idea of innovation being somehow separate to its commercial application—a notion which is ultimately meaningless in a corporate context unless it represents a stepping stone on which to build future innovations.

The word innovation is often used interchangeably with creativity, and whilst it is important to understand the role of creativity in the innovation process, it is equally important to recognise that creativity is not necessarily commercially led or outcome focused, and therefore, a systematic process of innovation needs to be effective in channelling and guiding creativity to achieve a value-oriented outcome. Art is undoubtedly creative, but it is rarely innovative. There are exceptions. Banksy's concept to shred his own artwork on completion of sale at auction (Banksy, 2020) is innovative, leveraging both the creativity of the traditional artwork but more-so the creativity of delivering an unanticipated uniqueness and artistic value through the art's own destruction (which was of course an artistic statement in its own right).

We often assume that innovation must always be transformational; however, innovation can take different forms. The implementation of innovation generally follows the shape of an S-curve with each part of the curve defining a phase in the life

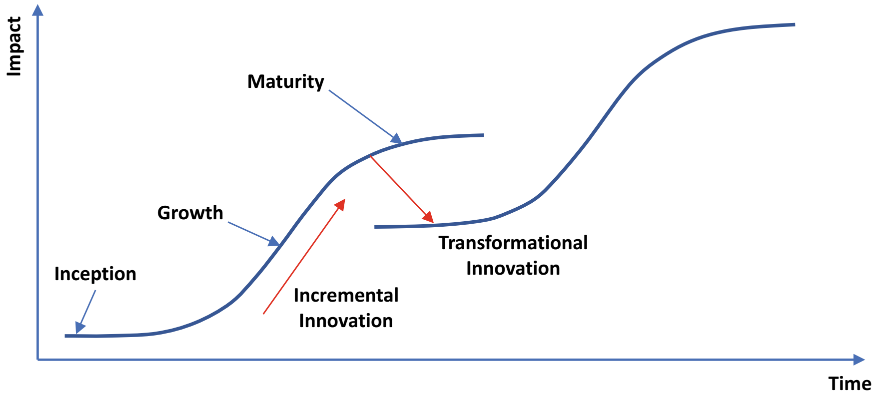

Fig. 1 Innovation S-curves (author's original)

cycle of any particular industry paradigm (see Fig. 1). The lower portion of the S-curve represents the early stages of research and trials where returns are yet to be established, the middle phase represents the zone where the idea is developed and becomes widely adopted and where value is rapidly gained, and the upper portion of the curve shows diminishing returns as the paradigm reaches maturity. So-called transformational innovations often kick-start the formation of a new S-curve which, if successful, results in returns throughout the life cycle. Incremental innovations, which usually refine or build on existing paradigms, occur typically in the mature part of the curve and may prolong or increase returns in the upper part of the curve. Both types of innovation attract different levels of risk and reward and have their place depending on the circumstances and desired outcomes.

There are many examples to be found in literature and on the Internet of innovative practices; however, over the last century, the aviation industry, which has seen significant levels of innovation throughout the previous century, has delivered some useful and relatable case studies on which we can reflect on the definition of innovation;

3 Case Study 1—The de Havilland Comet

As mentioned previously, being the first to do something does not necessarily guarantee successful innovation outcomes, indeed it comes with the potential for unforeseen risks, either technical, commercial or social.

An example of this is the de Havilland Comet which was the world's first commercial jet liner. It featured numerous technical innovations and design features which differentiated it from any other aircraft in the market at the time, offering much quieter and comfortable air travel with flights approximately 50% faster than piston-engine airliners which were its only competition.

Fig. 2 The de Havilland Comet (n.d.) (left) and Boeing 707 (n.d.) (right)

The Comet entered service in 1953 and throughout its first year of operation appeared to be a technical and commercial success. However, in 1954, the Comet was hit with two catastrophic in-air failures (BOAC Flight 781 and South African Airways Flight 201) resulting in the death of all passengers and crew. An extensive enquiry was launched, and the failures were found to be due to the uncontrolled propagation of fatigue cracks resulting from repeated compression and decompression of the passenger cabin. The impact on de Havilland was significant with all Comet 1 aircraft grounded for modifications, all orders for the Comet 2 cancelled, and a major re-design required for the upcoming Comet 3. The result was that commercial Comet flights did not resume until 1958.

In the intervening time, the Boeing 707 and Douglas DC-8 both entered service and, learning from the Comet's failures and featuring a more efficient 6-abreast design with podded engines, both quickly set the standard for intercontinental jet airliners. Production of the Comet was discontinued in 1964 with just 114 produced (compared to 556 for the Douglas DC-8 and 856 for the Boeing 707) (Fig. 2).

The Comet was a world first, entering service four years before the Boeing 707 and Douglas DC-8; however, in commercial terms, it was unsuccessful, and its technical innovations were overshadowed by its tragic failures. Putting aside the questions over the long-term commercial viability of the Comet, the story is primarily one of innovation risks. It could be argued that the same tragic consequences could have be fallen either the Boeing 707 or the Douglas DC-8 if they had been the first jet airliner to see operation. This case study is particularly pertinent for the construction industry where public safety is of prime importance, and there is a very low appetite for technical risk.

4 Case Study 2—Concorde

Taking its maiden flight in 1969, Concorde was not the first supersonic transport aircraft to take flight (this honour fell to the Russian Tupolev TU-144 which flew 2 months earlier); however, Concorde was a fine example of applied cutting-edge technology, applying technologies never-before utilised in a non-military aircraft including delta wings, supersonic afterburners, fly-by-wire systems and on-board digital computers. When it entered service in 1976, it could fly at over twice the speed of sound and reduced the potential travel time between London and New York to just over 3 hours, pushing the envelope of commercial air travel well beyond anything that had been experienced previously.

However, what is not well publicised is that despite its technological prowess, Concorde was a commercial failure; it cost an estimated GBP 1.3 billion to develop, failed dismally to reach its sales targets and ultimately required a UK government subsidy to realise a viable commercial operating model. Other operational factors also hindered its commercial success including its high relative fuel consumption (brought sharply into focus by the 1973 oil crisis) and a ban on supersonic flight over populated land. Only 20 Concordes were ever built, of which 6 were prototypes.

The Concorde case study is one that demonstrates that even the prestige of cutting-edge technology is no guarantee of successful innovation. If the commercial model is inappropriate or poorly developed, then it is likely that any premium associated with technological Research and Development will be very difficult to recoup.

It can be argued that Concorde's non-commercial successes outweigh its shortcomings; however, there is no doubt that it did not achieve its objective to lead a transformation of air travel, and its value to stakeholders or wider society is highly debatable. Before rushing to an emotional defence of the British and French engineering pioneers and reminiscing the symbolism of Concorde, we should perhaps reflect on its antithesis, the Boeing 737.

5 Case Study 3—Boeing 737

The Boeing 737 made its first flight in 1967 and entered service in 1968, a few years earlier than Concorde. Unlike Concorde, the Boeing 737 targeted the competitive short-haul market, and was to be a successor to an existing aircraft, the Boeing 727. As with most designs of the day, the original design featured the engines either sides of the rear fuselage; however, a simple design innovation relocated and 'podded' the engines underneath the wings. This modest modification resulted in simplification of the fuselage design facilitating 6-abreast seating as opposed to 5-breast which was the industry norm at the time. These design approaches, also adopted earlier for the Boeing 707, were driven by a practical consideration of operational efficiency and have become the norm in air travel ever since.

The Boeing 737 was the dominant short-haul airliner in the market until the introduction of the Airbus A320 in 1988. Operated by over 500 airlines worldwide, over 14,500 units of Boeing 737 variants have been ordered with circa 4500 in active service. Whilst development costs of variants have continued, the initial development budget was a modest US $150 million. The 737 remains in production 54 years after its first flight incorporating multiple incremental innovations during that history (Fig. 3).

Fig. 3 Concorde (n.d.) (left) and Boeing 737 (n.d.) (right)

Comparisons are perhaps subjective; however, it could easily be argued that the Boeing 737, with its simple but effective design and modest initial innovations, was more innovative than the technically advanced Concorde, which fundamentally failed to deliver the value expected by its investors and the wider industry.

Looking at these examples of innovation, it becomes clear that in a commercial sense, the primary purpose of innovating must be to generate some value or to provide benefit to society that can deliver financial returns—a must for a commercially viable enterprise. This value can be found in either what is delivered (the product or services) or how it is delivered (the processes).

However, accepting that this definition falls short in identifying what it is that *specifically* makes innovation special, and we also acknowledge that it must include the adoption of something novel. The word ‘novelty’ is chosen carefully, suggesting something interestingly new or original. Indeed, it is this novelty that often provides the basis for the commercial value, rather than simply the adoption of something new or technologically advanced (Fig. 4).

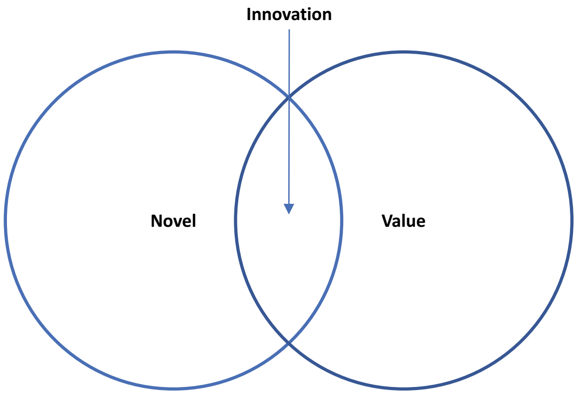

Fig. 4 Definition of commercial innovation is something novel that provides practical benefit or value (author’s original)

6 Fundamentals

Having settled on a broad definition of what makes something truly innovative and of particular value in a commercial context, we will next reflect on some of the fundamental actions that underpin successful innovation.

This chapter does not delve into the details of business models, ecosystems or cultural shifts to catalyse innovation in a corporate setting (this can be found in Chap. 15), nor does it explore the somewhat hit-and-miss discipline of entrepreneurism or business start-ups; however, the following seven fundamental actions aim to frame the reader's thinking as we explore some of the general challenges facing implementation of innovation in the AEC industry in particular in the next chapter (Fig. 5):

1. Develop the 'Why?'

   We regularly hear about the importance of business goal-setting and the need to communicate strategic direction, give clarity of purpose and gain buy-in from key stakeholders. Sinek's (2011) golden circle is synonymous with this idea—demonstrating that those businesses that are supremely successful have a very clear picture of their overriding purpose. Of course, we want staff to feel energised and to come to work for a reason; however, developing the 'why?' is fundamentally important for innovation; otherwise, the automatic tendency will be for technological fads and 'shiny newness' to fill the void left by an absent or poorly defined purpose. With a clear direction and purpose, innovation can be targeted towards goals which meet organisational objectives and are in line with its values. If it does not already exist, the process of innovation should,

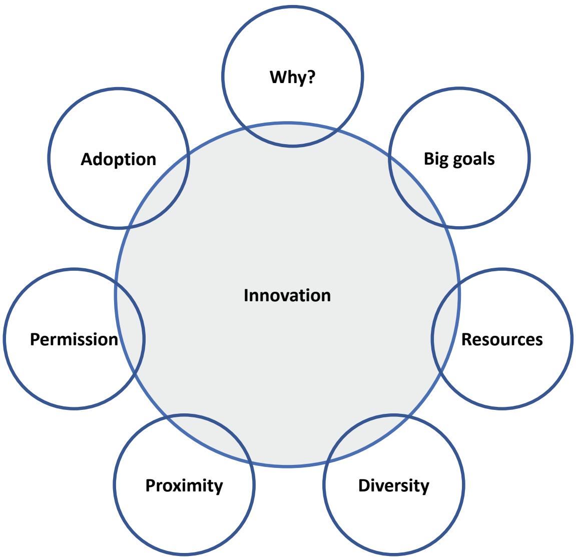

Fig. 5 Seven actions that underpin successful innovation in a commercial environment (author's original)

therefore, commence with a step to develop the 'why?'. Getting the intended innovators involved in this process also assists in building personal engagement with the goals and to drive outcomes.

2. Set big goals

   Many successful technology companies and research organisations choose to set big goals to drive innovation (Google X Head on Moonshots, n.d.). This technique is controversial as a means to drive and encourage practical innovation (Turpin, 2017) with many favouring the less risky incremental innovation as a means to drive beneficial change in already well-established paradigms. It is fair to say that innovation can happen on many levels including both transformational and incremental; however, the mindset required for transformational innovation is quite different, and whilst the goals themselves may not actually be achieved, both the tangible and intangible benefits of considering problems that cannot be solved through orthodox approaches can be significant and can flow through to support the achievement of smaller goals.

3. Plan resources

   Innovation can happen in many guises; in dedicated R&D laboratories, solving problems on specific projects or impromptu experiments; however, it *never* happens for free. Whether it is at the point of innovation, at some time prior or even in the development and adoption phase afterwards, at some point, a resource investment is required; be it technology, training or staff resources. In the AEC industry, it is often said that the best place for innovation is on projects, and it is certainly true that real-world projects often provide the sort of problems that would benefit from innovative solutions. It is also true, however, that innovation on projects is no shortcut to the dedication and groundwork required to enable such innovation to be successfully realised. Projects are also not typically the place for transformational innovation which requires a higher degree of risk and resource. The success of project-led innovation can only come via a strategic commitment to the resources required so that once a project team is faced with a problem, they and their support teams are ready and have the ability to solve it innovatively. Resources must, therefore, be planned so that they can be mobilised to support reactive innovation activities when opportunities arise or to proactively deliver strategic, purposeful innovation.

4. Promote diversity

   There is a view that changes in any complex system can be linked to evolutionary theory (Beinhocker, 2007) and that in order to increase the chances of success, an evolutionary system (such as a business) should improve its ability to adapt by increasing diversity. Intuitively, this approach seems to have merit; a group of people with similar backgrounds and similar ways of thinking are more likely to come up with a narrower range of ideas, thus reducing the probability of success in finding an appropriate innovative solution. Bringing together a diverse range of people to solve problems or to identify innovative solutions is, therefore, important including different ages, genders, cultures and levels of education. More broadly, such strategies can also include getting engagement from specialists, the use of external agents or collaboration with industry partners. Such diversity can also come from crossovers with other industries; bringing technologies and concepts that are tried and tested in one industry and applying them for a different application in another industry.

5. Create proximity

Diversity works if people can exchange views and exchange ideas without boundaries. Siloed working, whether diverse or not, is unlikely to result in an optimum environment for innovation to flourish. To break down barriers and create open communication pathways, both physical and non-physical proximities must be created. This can be as simple as helping to build interdepartmental or interdisciplinary relationships though secondments or workshops or creating dedicated outcome-focused working groups. Thanks to the constraints imposed by the global pandemic, digital collaboration platforms are now more familiar, and in a post-pandemic world it is likely that the emphasis on non-physical proximity will continue.

Of course, the concept of personal proximity can also be applied at an organisational and project level and can manifest physically, digitally, culturally, commercially and contractually. To maximise innovation outcomes, mechanisms should be developed in all of these areas to encourage project teams to work closer together and communicate more openly.

6. Give permission

It may seem so obvious that it does not need to be said; however, people need to be given permission to innovate. Leaders and managers too often *assume* that the people they are responsible for have already been given permission; however, the reality is that this is not what is understood or felt by those who are expected to do so. Indeed, the act of innovating relies on the behaviours of the people involved, and unless an individual works in an R&D department or has a specialist role where key performance indicators (KPIs) for innovation are defined, it is likely that both individual and team goals will be counter-productive to encouraging behaviours conducive for innovation. Normal business-oriented KPIs are commercial or delivery focused, and the burden of risk sits with the holder of the KPI who will often have no incentive to take risks or do something different to the last time. In fact, most KPIs will encourage safe behaviours that give surety of outcome. Ideally, KPIs should be aligned with an accepted and agreed range of success metrics including those that encourage innovation, R&D and the adoption of technology. Regardless, clear and explicit permission from a business leader or manager to innovate and try new ideas is incredibly valuable.

Similar to the concept of proximity, the giving of permission also applies at an organisation level. Procurement and risk/reward structures should be put in place to ensure that all relevant stakeholders have the permission they require to drive or contribute to innovation.

7. Drive adoption

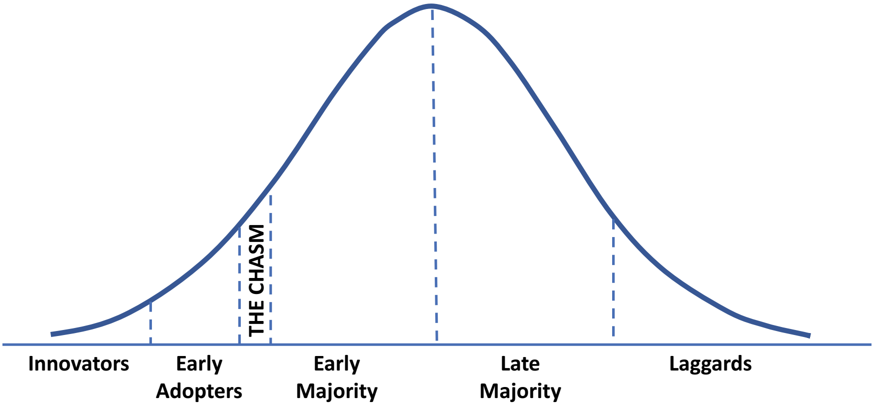

Fig. 6 Everett Rogers concept of diffusion of innovations and the so-called chasm or tipping point

> It is all too easy to think that the job of innovation stops once an idea has been created or released into a business or market place; however, this is a part of the process that is often overlooked, particularly for internally focused innovations. Many ideas underperform or have a significantly less impact that predicted simply because they have not been adopted by the target population. Rogers's Diffusion of Innovations theory explains that the innovation itself is only one of four elements that influence the adoption of innovation or the spread of a new idea. Other factors include communication, time and the social system. The theory points to a critical tipping point or 'chasm' that must be passed for an idea to diffuse from Innovators and Early Adopters to the Early Majority (usually identified as being 16% of a target population). By doing so, innovations become self-sustaining and spread to the population as a whole. Rogers outlines five stages in the adoption process; Knowledge/awareness, persuasion, decision, implementation, confirmation/continuation and these all need to be included in any strategy for the implementation of innovation (Fig. 6).

The concept of the diffusion of innovations applies not just externally with buyers or target clients, but also (and perhaps most importantly) within a business. Making sure that ideas or innovations are successfully diffused throughout a business; both vertically and horizontally is absolutely critical to improving the likelihood of success.

7 Conclusion

This chapter has explored some commonly held beliefs and misconceptions regarding innovation and has looked at several case studies that reinforce the view that, in a commercial context, innovation is a specific combination of both novelty and value.

Seven fundamental actions have been presented that underpin successful innovation. These actions look to address issues such as purpose, goal-setting, resources and investment, diversity and proximity of teams, the giving of permission and driving adoption.

This chapter hopefully succeeds in framing the key issues in successful innovation as we look to understand some of the challenges facing the AEC industry in the next chapter.

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Chapter 6
Challenges to Innovation in Construction

Paul Mullett

Abstract This chapter reviews the recent history of the construction industry's stagnation, referencing key reports and milestones in the identification of the industry's challenges and the changes proposed at industry level to improve performance. The chapter then proposes that there are underlying challenges that are specific to the construction industry that relate to the nature of the industry's product, the nature of the art and the science and the nature of the system. The nature of the industry's product is viewed in the context of lifespan, re-use and embodied carbon, unique complexity and the influence of time and trends. The chapter then explores the nature of the art and science of construction through scale, materials and methods and deemed-to-satisfy design versus performance-based design. Finally, the chapter considers the nature of the system, looking at the concept of industrial lock-in (in the form of asset legacy and process legacy), fragmentation and value ownership, regulation, life safety and risk aversion and drivers for change. The chapter concludes by affirming that global sustainability mandates will likely force the industry to change, requiring greater vertical integration, the adoption of digital platforms and the rise in collaboration and enterprise agreements; however, these structural changes do not obviate the need to strive for innovation at every level throughout projects, teams and businesses.

Keywords Construction · Challenges · Innovation · Productivity · Opportunity

1 Introduction

Most industries will claim they are unique. They will claim that their particular products, processes and service offerings have been either deliberately tailored or organically shaped over time to uniquely respond to marketplaces that have grown to provide for society's hierarchy of needs. For some industries, this has been a slow

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_6

and steady process, but for others, such those that are digitally centric, this change is happening with an increasingly unsettling pace.

Industries vary considerably in their nature; for example aviation to petrochemicals or telecommunications to agriculture, yet there is something uniquely challenging about the very particular differences of construction compared to other major global industries. Practitioners in the industry may have a biased perspective; however, in recent years, this view has become widely accepted by many observers, analysts and agencies and is consistently borne out in data that compares the levels of productivity in the construction industry against those in other industries (Teicholz, 2013).

The industry holds a very special place alongside agriculture as one that serves humankind's most fundamental needs. Indeed, two of humankind's basic physiological needs from Maslow's Hierarchy of Needs (Maslow, 1994) are provided by the construction industry, namely the direct provision of shelter and water (both potable and sewerage). It also provides critical supporting infrastructure that serves almost all humankind's safety and social needs. Going further, construction and its semi-permanent embodiment in architecture are fundamental to our sense of place, culture and history. In recent years, the importance of construction in supporting the drive to halt and reverse climate change, and to protect against its consequences, has become abundantly clear. No other industry (again except perhaps agriculture) has the potential to have such a significant impact on future of the planet.

The construction industry is as big in economic terms as it is in scale. A significant proportion of global GDP is accounted for by the construction industry, for example 6.5% in the UK (Infrastructure & Projects Authority, 2016) and higher for developing nations. Despite being susceptible to global and regional economic fluctuations, continued investment in infrastructure is vital for economic growth, oftentimes delivering far more to an economy over the long-term than is invested (IMF, 2014). Well-planned, well-delivered and sustainable construction makes economic sense. Ironically, however, construction has very low profit margins and attracts few large external investors.

As a discipline, construction is almost uniquely old, sharing its ancient origins with humankind's gradual domestication of plants and animals during the Agricultural Revolution when the first permanent settlements and places of worship were formed around 9000–8000 BC. Whilst the first few millennia represented a modest start, humankind's ability to build gathered remarkable pace delivering notable monuments including the Pyramids of Giza, the Acropolis of Athens and later innumerable architectural accomplishments such as the Santa Maria del Fiore of Florence. However, it was the Industrial Revolution in the late eighteenth century that led the industry into a glorious era which continued unabated through to the late twentieth century; driven by technological developments, economic growth, war, post-war recovery and an almost insatiable cold-war appetite for bigger, better and faster. But, it is here in the 1980's when the expectations of society began to exceed the ability of the industry to deliver, and questions started to be asked.

In the UK, construction's first official 'could do better' report card came in the shape of the Latham Report (1994) published in 1994. The report was prepared in response to concerns about industry-wide performance, efficiency, fairness and teamwork. Whilst the report was not concerned with technical (or technological) issues, the findings of the report were a landmark in challenging the status quo of how the construction industry had traditionally functioned and centred on encouraging better quality and efficiency via collaboration and teamwork. The title of the report 'Constructing the Team' was very deliberate. Recommendations were wide-ranging and included new industry roles, clarification of responsibilities, mechanisms to provide research funding, changes to forms of contract, cost reduction initiatives, changes to dispute resolution processes, industry-wide registration, quality initiatives, changes to regulations and government taskforces.

The Latham Report was followed in 1998 by the Egan Report (2003), which built upon the core themes. The report reviewed challenges in the construction industry including a need to modernise and identified key drivers for change including; committed leadership, a focus on the customer, integrated processes and teams, a quality-driven agenda and commitment to people.

The report proposed challenging targets, including a 10% reduction in construction costs and time, and a 20% reduction in project defects. It recognised that in order to meet these targets, radical changes would be necessary in the processes through which the industry delivers its projects and proposing an integrated project process around four key elements; product development, project implementation, partnering the supply chain and production of components. It notably emphasised the recommendations of the Latham Report in replacing competitive tendering with long-term relationships based on measurement of performance and sustained improvements in quality and efficiency.

The Egan Report was followed up in 2002 by the report Accelerating Change (Rardin, 2011) which updated the targets and reviewed progress with reference to demonstration projects that had adopted some of the recommendations of the Egan Report. All the demonstration projects showed marked improvements across a range of KPIs which included client satisfaction, quality, safety, cost, time and profitability. The report notably acknowledged the future importance of 'e-business and virtual prototyping'.

These three reports effectively provided a manifesto for change in the UK construction industry and, despite the significant progress of technology in the intervening twenty five years or so, remain largely relevant today. Table 1 of the Latham Report from 1994 compares the motor industry against the construction industry and is recreated in Fig. 1. In many respects, the gulf between the automotive industry and construction industry has only increased over time, with the automotive industry now providing better than ever quality and value for money, whereas the construction industry has continued to fall short in meeting the demands of clients and society.

Innumerable other reports and articles in the last two decades have furthered the debate and sought to bring greater clarity on the challenges facing the industry and, in particular, shine a spotlight on how the rise of technology can be an effective catalyst for change. More recent publications such as the WEF's Shaping the Future of Construction (Agenda, 2016) and MGI's Reinventing Construction (Mckinsey Global Institute, 2017) have reviewed the industry's shortcomings and

Wants	Modern Motor Car	Modern Buildings		
		Domestic	Commercial	Industrial
Value-for money	●●●●	●●●●●	●●●	●●●●
Pleasing to look at	●●●●	●●●●	●●●	●●●
(largely) free from faults	●●●●●	●●●	●	●●
Timely delivery	●●●●	●●●●	●●●●	●●●●
Fit-for-purpose	●●●●●	●●●●	●●	●●●
Guarantee	●●●●●	●●●●	●	●
Reasonable running costs	●●●●	●●●●	●●	●●●
Durability	●●●●	●●●	●●	●●
Customer delight	●●●●●	●●●	●●	●●

Fig. 1 Recreation of Table 1 of the Latham Report 1994, showing comparison of the motor industry and construction industry

provided a multi-pronged call-to-arms incorporating the adoption of digital technology, future-focused skills development, changes to industry procurement and increased partnering and an increase in off-site or pre-manufactured solutions.

Yet, another UK government-promoted report, the Farmer Review (2016) commissioned by the UK Construction Leadership Council in 2016, incorporates many of the same themes as these independent reviews. The UK Government's Construction 2025 Report (Janton, 2020) has a more forward-looking agenda and presents its vision built around people, smart application of technology, sustainability, economic growth and industry leadership.

With so much already published in this area, the purpose of this chapter is not to repeat or attempt to summarise this information. The reports speak for themselves and demonstrate a recurring and compelling story of an industry caught in a desperate and persistent rut, one which Mark Farmer described as being in 'survivalist' shape. This chapter seeks to view the debate from the perspective of innovation and identify some of the specific underlying reasons for the industry's failure to embrace innovation. Many reports to date list a lack of innovation and R&D as a contributing cause to the industry shortcomings, whereas the reverse can also be argued; the industry is fundamentally incapable of improving innovation whilst systemic barriers persist. So, whilst recognising that some of these issues are systemic and overlap considerably with, or are caused by, the industry's fundamental shortcomings, this chapter focuses specifically on barriers and challenges. It is intended that, alongside the positive examples of innovation given in other chapters, it invites readers to consider how the challenges can be met and overcome at a project and practitioner level.

The chapter presents the challenges to innovation in terms of three categories;

- The nature of the product—what is it about the product of construction that makes it inherently resistant to the application of cross-industry innovation?

- The nature of the art and science—what is it about the materials and methods of construction that create particularly difficult constraints to innovative solutions?
- The nature of the system—what is it about the systems and processes involved in construction that reduce the ability of the industry to innovate effectively?

2 The Nature of the Product

The product of the construction industry is very different to that of other industries for a variety of reasons.

In fact, to understand this, we must first consider the term ‘product’ which is synonymous in many industries with a repeatable and mass-produced artefact, often produced directly for generalised categories of consumers, which has a short, limited lifespan.

This definition is different in almost every respect to the output of the construction industry. Buildings often have a lifespan of over 50 years and, including all buildings systems and interior fit-out, contain tens of thousands of components. Built assets are also inherently unique in terms of both geography and client and, therefore, are typically unique by design (and also in construction).

2.1 Lifespan, Re-use and Embodied Carbon

We are surrounded by examples of products in our everyday lives ranging from the simple to the complex and the small to the large. Motor vehicles, which are probably the closest example in size and complexity to modern buildings, typically contain approximately 30,000 parts and have a lifespan of circa 10 years (although admittedly cars can often be used much longer). An iPhone on the other hand has approximately hundreds of parts and would be expected to have a lifespan of only 2–3 years. Indeed, most products are deliberately designed to be disposable rather than re-usable (a concept known as ‘planned obsolescence’); to be either sent to landfill or recycled at the end of their short useful life.

Lifespan is one of the key differences between consumer products and that of the construction industry. Most built assets are designed with an intended service life of 30–100 years, with residential property at the lower end and critical infrastructure at the higher end of this scale. An important reference here is ‘service life’ which does not equate to ‘end of life’. Built assets are typically designed on the premise of being non-disposable, an unusual concept for most products which are replaced after a few short years of use. Buildings are not designed to cease functioning at the end of their service life. Service life is the point at which the asset will require significant maintenance or repairs, and an important part of the design and specification of the building and its components is making sure this life can be achieved, with many built assets actually able to continue to provide a valuable contribution to society and the economy well beyond this point. We only need to consider the number of Victorian and Georgian buildings still in use across the UK to appreciate just how long buildings can remain valuable.

Often at the end of their service life, or even before, buildings are re-purposed to continue to provide value. For example we often see old schools and industrial buildings renovated to be used as residential buildings. Modern, sustainable design practices now require us to consider carefully the potential for future use in the design so that buildings constructed now can be modified for a variety of possible future scenarios. The re-purposing of existing buildings is also becoming an increasingly important area of design, particularly so following societal shifts that are anticipated to follow the COVID-19 pandemic. The idea of re-purposing and re-use of either whole buildings or building components is an important part of the concept of circular construction, an idea discussed further in Chap. 4.

An important consideration here is the concept of embodied carbon. Buildings account for 38% of the world's carbon emissions (UN Environment Programme, 2020) of which 10% is embodied—or in other worlds, the carbon emissions associated with the materials and processes used to construct, maintain and ultimately demolish an asset throughout its life cycle. Using less embodied carbon is clearly a good thing for the environment and to preserve natural resources, and the industry continues to strive to produce designs that reduce embodied carbon; however, if we can maximise the lifespan of a built asset and its components, through re-purposing, de-construction or recycling, then the embodied carbon remains purposefully embodied rather than inviting more embodied carbon to be generated through premature or poorly planned replacement.

Interestingly, the question of renovation, repair and re-use is one that has yet to be solved for most consumer products. As the world wakes up to the reality of a climate emergency, the concept of planned obsolescence is being challenged. An example is the 'right to repair' regulation which is currently being proposed across Europe for various categories of consumer products. This will give consumers the right to be able to take apart, repair and modify their products without limitations imposed by manufacturers.

From an innovation perspective, this idea brings significant opportunities but also great challenges for the construction industry. The vast majority of built assets are not designed to be simply 'taken apart'. Concrete sets with reinforcement embedded within and steel beams cannot be re-shaped or re-sized. Interiors and facades are designed and constructed to precisely fit the building they were intended for. As we will see, each built asset is also unique in terms of its location and purpose, meaning that sometimes modification is just not viable. The innovation challenge requires a complete rethink of how buildings are put together so that they can either be readily modified in situ or deconstructed and re-used.

2.2 Unique Complexity

For an iPhone or a motor car, the end-user and their needs are usually very clear, developed through decades of consumer research and customer feedback, as are the market norms and expectations associated with any product competing in the marketplace. The needs are categorised and form the basis of a fixed product range tailored to provide for the generalised needs of a population.

Each product in the range can be extremely complex; however, the range is usually limited and is typically based on a standard set of suppliers and components that can be integrated across multiple products through a well-developed design and manufacturing process. Some industries use this to provide a degree of customisation which allows individual customers to tailor their own products using pre-selected components. An example is ordering a car with a particular specification: colour, engine, sunroof, interior and exterior trim and wheels can all be modified. Many car manufacturers have websites or apps where this can be done by the customer and the vehicle can be visualised as intended.

The range of end customers for the construction industry is diverse. Whilst a large proportion is for private consumers, for which the purchase of a property will be the single largest purchase in their lives, most significant built assets are for governments or large corporations and developers. Such assets are either built for the purposes of providing long-term social or industrial infrastructure, or as a part of an investment portfolio, generating long-term wealth through rental income and increasing asset value. This diversity brings about a range of often conflicting value perspectives including: quality, durability, capital expenditure, operational expenditure, sustainability performance and social capital. Each and every construction project may, therefore, have a unique client with, rightly or wrongly, its own particular value perspective that needs to be considered in the design, delivery and operation.

In addition to the uniqueness of the customer, construction projects also have to contend with the uniqueness of location. Consumer products are generally the same across multiple geographies. An iPhone or car in the USA is essentially the same in Europe. Products need to consider the cultural expectations and preferences within each region (e.g. small hatchback cars are preferred in Europe, whereas larger saloon cars are preferred in the USA); however, this is reflected more in the regionally available product range. Geographically, products have to comply with regional regulations and climatic differences—for example motor vehicles have to accommodate varying emissions limits and modify systems such as air-conditioning and paint specification to be suitable for regional climates.

In construction, built assets are geographically unique. Most sites are defined by the geometry of the site boundary which, in built-up locations, can often be additionally constrained by adjacencies, underground services, tunnels or other obstructions (e.g. in London, there are multiple underground obstructions that must be avoided or not overloaded) and previous site use. Previously used brownfield sites may require demolition, avoidance of old foundations and treatment of contaminated land. Every site also has its own geology, topography and groundwater which will influence not just its foundation solution but also the nature of any sub-structure and the relationship between the architecture and the surrounding environment.

Regional variations also take the form of climatic conditions and seismic risk both of which are usually defined in codes of practice. Where these are significant (e.g. in areas of cyclones and high seismic activity), they can both fundamentally affect the form of the structure—which can significantly influence the architectural solutions. Projects are increasingly being asked to consider the impact of climate change to ensure that they can accommodate higher temperatures, water levels and extreme climatic events. Regional climatic conditions can also drive environmental control systems and the types of finishes used.

Other national or municipal regulatory requirements can have an impact on many aspects of design including: building appearance, allowable floor areas, height limitations, types of occupancy, site boundary set-backs, fire protection, vertical transportation, parking capacity and layout, minimum sustainability performance, entry/exit and circulation and interfaces with public transport.

With such a depth and breadth of variation, it, therefore, becomes very difficult to develop 'cookie-cutter' design solutions for different scenarios and clients. Doing so often results in customer dissatisfaction and ill-fitting solutions which fail to meet the long-term needs of the customer or society. This comes with increasing risk that an asset will be prematurely replaced, leading to increased waste and embodied carbon.

Indeed, there is a reason why we generally refer to construction *projects* rather than construction *products*. The latter has little relevance when every product is different, and the specific set of actions required to deliver it may also be unique.

From an innovation perspective, the challenge remains one of balancing the benefits of construction systems and processes that provide potential for re-purposing/re-use with that of the inherent uniqueness of every project. Any such construction innovation solution must be flexible and adaptable to a range of geometries, regulations and client needs. One of the biggest limitations of industry forays into modularisation and componentisation to date has been an inability to accommodate architectural freedoms and specific client needs.

2.3 Time and Trends

Architecture and its implementor, construction, have a unique role in the fabric of our societies and cultures. Architecture endures and is emotionally intertwined with our sense of place and belonging. When we think of places we have lived or grown up, it is often the architecture and places that feature: its sense of permanence integral to our perception of the passing of time and evoking feelings of nostalgia. There are few comparisons in other industries that can provide the same connection.

As mentioned previously, built assets have a lifespan far in excess of products from most other industries. Many other products are designed with current trends and fashion in mind. Motor cars and consumer electronic devices are an example of this. It is not difficult to identify a car or device that is more than a few years old;

even though it is the internal features and performance that define its purposefulness, it is the external design and appearance of the product that is most apparent in determining its ‘newness’. This is of course quite deliberate, as it is fashion that often drives consumer purchases rather than a genuine need (a key part of planned obsolescence), and it is this continued turnover which keeps shareholders satisfied (and unfortunately keeps our landfills growing).

Whilst the construction industry is different in terms of both timescale and types of clientele, its products are still susceptible to the effects of fashion. Indeed, the negative consequences of ’out-of-fashion’ architecture or out-of-date functionality can be significant. History has shown how architectural trends change and buildings that were once considered to be state-of-the-art modern design can quickly become despised by society. An example is the plethora of concrete shopping centres and residential complexes built during the 1950s and 1960s in the brutalist architectural style, many of which (such as Portsmouth’s Tricorn Centre) have now been demolished to make way for modern replacements. Some, such as The National Theatre in London remain as functioning architectural and cultural mementos, are nevertheless still divisive.

The invisible aspects of architectural design are just as susceptible to trends as the visible. Societies and cultural norms change as does state-of-the-art architectural planning. For example the post-war utopia of dense, high-rise communities were largely deemed to have failed by the 1980s with many tower blocks being demolished and replaced. Although there were technical failings (the Ronan Point disaster being the most significant), it was not high-rise, apartment living per-se that was the contributing factor (indeed Le Corbiseur’s original Unite d’Habitation is considered very successful), more-so poor design and a lack of social understanding that encouraged a disassociation with society rather than generating a sense of community (Fig. 2).

Whilst classic architecture is timeless, modern architecture is subject to trends, which places an additional challenge on architects to develop designs that are less sensitive to the coming and going of architectural fashion. In addition, architects and engineers have an increasing responsibility to ensure that aesthetic and functional refurbishment can be accommodated by both interior and exterior spaces during an asset’s service life. In some cases, as mentioned previously, complete re-purposing is the best way to purposefully continue to use the embodied carbon in a built asset.

It may be tempting to dismiss architectural matters and the trends of society when considering innovation in construction; however, this is done at great risk. Architecture is enduring and its impact lasts for generations. If the solution to innovative construction solutions is a functional or aesthetic compromise, then the result will be a legacy of failed buildings and a huge missed opportunity.

This further increases the challenges in construction innovation; buildings must be inherently re-usable, adaptable to the needs of clients, society and geography and able to accommodate architectural trends and future aesthetic and functional changes.

Fig. 2 Unite d'habitation, Marseille, France. *Source* https://commons.wikimedia.org/wiki/File:Unité_d%27habitation_Marseille,_France.jpg

3 The Nature of the Art and Science

In the previous section, we have seen how the nature of the construction industry's product is quite dissimilar to that of other industries, and we touched on some of the ways these unique challenges impact on industry innovation. In this section, we will explore the nature of the art and science of construction, and how there are some specific factors about the application of engineering and science to the built environment that are quite different to other industries.

The first observation is that a structure is at the very heart of every building. It is the skeleton for the architecture, the building services and the building envelope, providing form, creating space, standing firm against gravity and helping to protect against the forces of nature. It is also, by far, the most significant contributor to volumetric material required to erect a completed building. The performance and behaviour of structure are wholly dependent on the laws of physics; in particular, those that determine strength, stiffness and mass. It is a common mistake to assume that strength is the only consideration. Stiffness is equally important in determining deflections under static loads, and both stiffness and mass are important factors in the dynamic behaviour of a structure or its elements—a critical issue for buildings subject to earthquake loads, tall buildings subject to wind and the response of floors to human-induced vibration.

This chapter is not intended to be a technical review of engineering materials, indeed references such as Gordon's The New Science of Strong Materials (Gordon, 2006) still serve as an excellent summary, explaining the fundamental science behind how materials perform. However, these fundamentals also define their inherent limitations. Much research and development have focused on the incremental improvement of engineering materials to improve quality, strength and durability. There have been many incremental innovations over the previous century that underpin the engineering feats we see today, notably increasing the strength and corrosive resistance of steel, improving the strength and workability of concrete through additives and mix constituents, and the development of products and composite systems that seek to maximise the benefits of the materials available. This continued incremental innovation of existing technology is, however, a sign that the industry has struggled to identify transformational innovation opportunities that will create the next innovation life cycle. Whilst we see consumer electronics, aviation and the automotive industry being transformed by the innovative development and use of new, better materials, the fundamental materials and processes used in construction remain the same as those from over a century ago.

There are a few reasons why this is the case.

3.1 Scale

The first and perhaps most glaringly obvious is a simple matter of scale. The construction industry relies on the bulk use of high-carbon materials which must be mined from the upper layers of the earth's crust. The volume of this mined material used to develop our built environment is astounding. Globally, there are 30 billion tonnes of concrete produced per year (York & Europe, 2021). By way of example, a typical mid-rise apartment block built from reinforced concrete, including foundations, comprises 10–20,000 tonnes of concrete alone including sand, aggregate and cement. This scale is apparent even in some of the world's most ancient constructions. For example the Great Pyramid in Egypt constructed over 4000 years ago used an estimated 2.3 million blocks with a total weight of nearly 6 million tonnes (Fig. 3).

Construction has always required the mass sourcing, movement and processing of material. We can look at material innovations and efficiencies in other industries, for example aircraft built from carbon-fibre composites rather than steel, but it is difficult to envision how the magnitude of material needed to meet society's needs could ever be reduced by an order of magnitude or how it could be replaced by an alternative that does not require similar mining, movement and processing. The industry has, therefore, focused on continuous improvement of current materials to increase performance, improve reliability and reduce environmental impacts.

Recent examples are graphene and its tubular counterpart, carbon nanotubes (CNTs). CNTs have been researched for some time to understand their potential benefits for concrete, and more recently, research has been carried out on the use of

Fig. 3 The Great Pyramid, Egypt. *Source* https://upload.wikimedia.org/wikipedia/commons/e/e3/Kheops-Pyramid.jpg

graphene flakes (Chougan et al., n.d., 2020a, 2020b; Lamastra et al., 2021). Experiments have shown that both CNTs and graphene (Greener & Cheaper, 2021) have the potential to enhance the physical properties of concrete including compressive and tensile strength which could result in a reduction in material volumes. It is unclear, however, whether these benefits are scalable, differ significantly from other available concrete technologies or come with associated negative impacts such as reduced service life performance or health and safety implications (Hassan et al., 2019).

There are also some myths to dispel in terms of the potential for material reduction. For example whilst the impact of high-strength steel was transformative to the industry and further incremental increases have been welcomed, the arrival of a much stronger material would be unlikely to transform *what* we built considerably. As mentioned, mass and stiffness are also important factors to consider, and whilst only of current relevance to particular structures or types of problems, stiffness and mass would very quickly become a critical issue if, say, we needed 10× less structural steel for strength purposes. This is separate to the discussion on efficiency—which is complex when considering the overlapping context of design and construction. What is often efficient in terms of design and material volume is oftentimes more difficult, time-consuming and expensive to build. This conundrum is discussed later.

Scale effects also come into play when we consider the importance of self-weight. This is because self-weight is proportional to volume which increases cubically relative to linear dimension. It is, therefore, a far greater constraint for built assets than it is for, say, automobiles or consumer goods. At smaller scales of engineering, self-weight is a much lesser consideration—other load effects are generally much more significant. It is, therefore, an important factor in the design of built assets and a constant consideration when finding optimum design and construction solutions. It is, for example, the reason why flat slabs are only efficient up to an absolute dimension.

Self-weight is also a factor, however, for not just the permanent works, but also the process of how things are built. Our traditional construction systems and processes are designed to accommodate and overcome the challenges that self-weight presents at scale. At smaller scales, materials are able to be self-supporting much more easily, whereas at the scale of built assets, other measures are required to maintain temporary stability such as formwork, temporary towers, temporary shoring or propping. Indeed, the challenge of maintaining stability and sufficient factors of safety during construction under self-weight should not be under-estimated in its complexity; methodologies should be developed to ensure it is fully considered. The balanced cantilever approach for the construction of bridges is an example, and other large and complex structures (e.g. stadium and airport roof structures) also require very special consideration. Nonetheless, it is still too often the source of tragic failure. Quebec Bridge collapsed under construction in 1907 (Pearson & Delatte, 1907) as did the footbridge in Florida, USA (Hansford, 2019), in 2018.

The effects of scale and stability at scale are one of the challenges facing the adoption of new and innovative construction techniques, for example 3D printing.

3.2 Materials and Methods

As noted, construction materials are extracted from the earth, processed, moved and then shaped and erected at site. The methods and practices associated with these design and construction process are tailored specifically to the nature of the materials used and have been developed and refined over hundreds of years. Concrete and steel are the most commonly used materials in modern construction (although timber is seeing a renaissance for environmental reasons); however designing and building with one is quite different to designing and building with the other.

By far, the most common material used in construction is concrete. Concrete is an ancient material having its first origins in 1500–800 BC and was extensively used by the Romans from 300 BC onwards. Many of the great Roman construction achievements still standing today used concrete extensively including the Colosseum in Rome and of course the Pantheon which is still the largest unreinforced concrete dome in the world.

Concrete is a composite material comprising aggregates, cement and water. When mixed, the water reacts with the cement creating a paste that hardens over time to bind the component materials together. Until the concrete hardens, it is fluid and is incapable of supporting its own weight or even holding a given form. Some of the earliest uses of concrete were for floors; however, the idea of using formwork to hold the concrete into a pre-defined form was used extensively by the Romans to construct walls, columns and arches. The Pantheon dome for example was constructed using temporary formwork and wooden propping. On other occasions, the Romans would use masonry to provide permanent formwork into which the concrete was poured.

After a decline in use during the Middle Ages, concrete eventually saw a renaissance in the industrial era of the eighteenth and nineteenth century. Concrete is a material that is good in compression; however, its lacks tensile strength and ductility which means that it cracks easily under tension and flexure. In the latter half of the nineteenth century, the concept of adding iron or steel bars was developed and implemented in buildings and bridges to provide tensile strength and ductility to concrete as a composite structural material. This has defined the paradigm for the use of reinforced concrete that we know today.

This paradigm is fundamental to the whole construction supply chain. At the beginning of the design process, the design team will review options, and if concrete is preferred, this will set the course for the remainder of the whole project, influencing numerous other design decisions and project procurement. Oftentimes, project programme, regional supply chains or other factors will influence the choice of material. In the case of concrete, the off-site batching and supply of concrete, delivery, pumping, formwork systems, back-propping methodologies and testing regimes are all part of the process of producing cast in situ concrete elements, not to mention all the roles associated with the oversight and quality inspection of the works.

There have been numerous incremental innovations in the previous century to make these processes more efficient, to optimise delivery, improve quality and increase performance. Concrete materials technology has increased significantly, with concrete technologists able to provide an ever-increasing range of concrete to meet different needs, with strengths now readily able to exceed 100 MPa. Technology has also advanced the performance and quality of reinforcing steel, where high-strength and high corrosion-resistance steels are now also readily available. Alongside advances in the material itself, batching, delivery and pumping technologies have also improved, and there is now a range of smart re-useable formwork systems in addition to wireless IoT systems for monitoring concrete temperature and strength.

Other innovations including precast, composite and hybrid forms of construction aim to overcome some of in situ concrete's shortcomings by eliminating formwork or moving processes off-site. These innovations have significant benefits but also require consideration throughout the supply chain including the design phase.

The use of precast columns and walls for example reduces the need for vertical shuttering and accelerates site operations, however, requires special care during design. The use of composite floor systems eliminates formwork and reduces back-propping, however, is compatible with only certain types of floor construction and requires a one-way spanning floor design. The use of hybrid concrete (e.g. lattice planks or twin wall) again eliminates formwork and reduces back-propping but requires very special consideration in the design at an early stage, an issue that we will review later.

As with concrete, there is a similar story for structural steel. Cast iron has its origins as far back as the fourth–second century BC in China and was used as a structural material from the late eighteenth century, primarily for non-flexure applications (such as struts and columns) due to its poor tensile strength and brittleness. Examples include the Iron Bridge in Shropshire, UK, built in 1781 and the Ditherington

Flax Mill, Shrewsbury, UK, built in 1795. Wrought iron became popular during the nineteenth century as puddling and rolling processes-enabled purer composition and more consistent properties to be achieved. In the latter part of the nineteenth century, due to introduction of the Bessemer process, steel started to replace wrought iron as the preferred material—being used for ship building and structural applications.

Up until this point in time, wrought iron and steel were either hammered or rolled into shape and then joined together using rivets. Elements were cut to size in the factory, transported to site, lifted into place and riveted to form larger assemblies. Temporary works, sometimes complex, were required to support and lift structural assemblies until final erection was complete. Achievements using this method of construction were impressive including examples such as the wrought iron Royal Albert Bridge completed in 1859 which required the on-site fabrication, floating and lifting of two 140m main-span trusses (Fig. 4).

At the beginning of the twentieth century, the development of welding technology permitted the simplification of connections and pre-assembly of more complex components using arc welding. Later in the twentieth century, high-strength steel bolts replaced rivets as being easier and less labour intensive to install. Nevertheless, the design and erection of steel structures remain, to this day, based on the same fundamental processes used for wrought iron construction in the mid-nineteenth century. Steel elements are rolled and cut to pre-defined sizes and shapes, followed by a degree of pre-assembly and then lifted into place using cranes where bolting, or less commonly, on-site welding is carried out. Temporary works are used to maintain stability until the structure is complete and able to carry its own weight and any other temporary loads.

Fig. 4 The Royal Albert bridge, Saltash, UK. *Source* https://upload.wikimedia.org/wikipedia/commons/d/de/Royal_Albert_Bridge_%2842132162584%29.jpg

As with concrete, the whole supply chain is aligned with this particular construction paradigm. Starting with the design team, the decision to adopt structural steel will impact the future direction of the project, affecting numerous other design decisions, project procurement strategies and logistics. In the case of structural steel, steel suppliers, steel fabricators, transport and logistics planners, lifting and cranage strategies, site erection teams and temporary works engineers are all part of the process of delivering the completed structure. Again, there are also many other roles throughout the supply chain to ensure the process is carried out safely and in accordance with the requirements.

Whether it is concrete or steel, changing the way we build is a collective challenge that impacts the whole supply chain and touches on a wide range of interrelated issues including design, materials and methods. Opportunities exist in the adoption of off-site modular and componentised construction, and whilst these continue to gain greater traction in parts of the world, supported by increased digitisation, these approaches expose difficulties in the very way the industry is structured, how risk and reward are shared and how motivation for innovation is generated. We will review these underlying issues later.

3.3 Deemed-to-satisfy Design Versus Performance-based Design

The design and construction of built assets is one industry where deemed-to-satisfy approaches to design are still regularly used. In many areas of design and specification, overall compliance is achieved if the building or its component parts meet specific pre-defined criteria rather than demonstrating a particular level of performance overall.

The criteria used are often embedded into national codes and standards and originate from a range of sources including previous experience, empirical data, physical testing or analytical studies.

The deemed-to-satisfy approach is a logical response to a fragmented design and construction process where, as we have seen, any one project can be unique in terms of its constraints and client requirements which necessitates not just a unique design response but also a very particular specification of materials and products sourced from the locally available supply chain. This very project-specific mix of loads, design, materials and product specification makes it extremely difficult to predict performance and, therefore, compliance, against over-arching requirements (such as safety, service life, occupancy comfort) from fundamental principles.

The downside of a prescriptive deemed-to-satisfy approach is that it is generalised and, by not incorporating a fundamental analysis of project-specific parameters or behaviours, can result in inherently conservative designs and little understanding or transparency with which to adapt solutions to varying project needs.

Performance-based design is, therefore, the 'gold-standard' that allows designers to predict building performance based on a set of input parameters that are specific to the project. Such methods often employ advanced nonlinear computational methods to predict the behaviour and response of the building to physical and environmental loads and are commonly used in other industries such as the automotive and aeronautical industry to continually refine and optimise design solutions. The benefit of this approach is twofold; firstly, load effects can be modelled more accurately oftentimes resulting in a net decrease in severity, and secondly, significant benefit can often be gained from nonlinear behaviours and hidden factors that may not otherwise be accounted for in deemed-to-satisfy approaches.

Whilst computational power has increased significantly in recent decades, enabling easier access to high-power nonlinear analytical methods, such techniques are still time-consuming and complex to implement correctly, a luxury that most clients are unwilling or unable to accommodate for one building, even if there may be significant project benefits.

An example of the deemed-to-satisfy approach is the design and specification for fire resistance. A key issue for the design and specification of structural solutions is the ability of structural elements to resist fire for sufficient time for the building to be safely evacuated or the fire contained. From a structural perspective, this is usually achieved through the provision of suitable fire protection; either through the use of a minimum concrete cover to reinforcement or the addition of intumescent paint or other protective materials added to structural steel. Given a generalised location, exposure and type of element, the standards typically specify the level of protection required (e.g. 2 hours) and stipulate the means by which it should be achieved, for example by specifying a minimum concrete cover to reinforcement or the type of steel protection board or paint. This approach is generalised and does not include many project-specific factors that may enable the same overall outcome at a reduced cost.

In contrast, performance-based fire design will look at the nature of the fire, the way it spreads, areas of high and low heat and the performance of the structural materials when exposed to the fire, incorporating nonlinear, heat-dependent material properties that inform the behaviour during a fire and predict the time to failure. The evaluation of performance will then inform specific, localised protective measures that can then be tested in the model subsequently to achieve the stipulated time required.

Because of the way that deemed-to-satisfy approaches are formulated, it can, therefore, become very difficult to incorporate the impact of novel methods or new technologies. Performance-based design, however, provides full transparency and understanding of the effect of each and every parameter, allowing better design decisions and providing data on the effectiveness of new technologies or different design approaches. Unless the industry moves towards a wider adoption of performance-based design approaches, opportunities to identify and integrate innovations will be missed.

By way of example, performance-based design is at the heart of the digital twin concept. Being able to understand and predict the behaviour of an asset or system from input data and constraints (either from a physical asset or digital prototype) is a key part of a functioning digital twin. The continued reliance on deemed-to-satisfy approaches will limit the extent to which digital twins can be adopted by the industry.

4 The Nature of the System

In the previous sections, we have looked at some of the inherent reasons why innovation in construction is difficult. This has looked at product life cycle, unique complexity, scale, fashion and permanence, materials and methods and design approaches.

The focus has been very much on the unique magnitude of the challenges facing construction and outlining the need for transformational innovation in addition to incremental if the industry is going to find solutions to the issues of productivity and sustainability that are increasingly prevalent and urgent. In this section, we will explore some of the underlying reasons why unlocking innovation at the transformative scale necessary has proved elusive, delving into some of the more intangible aspects of the industry that exist today. These are complex, interrelated issues; however, we will consider these under the following broad headings:

1. Industrial lock-in
2. Fragmentation and value ownership
3. Regulation, life- safety and risk aversion
4. Drivers for change.

4.1 Industrial Lock-in

The term 'lock-in' as applied to innovation was coined by the virtual reality pioneer Jaron Lanier. The term is used to describe a barrier to innovation that exists due to well-trodden paths within an industrial or societal ecosystem that continue to reward mediocre groupthink solutions. In his book You Are Not Gadget (Lanier, 2010) the example Lanier uses is that of the MIDI file format which was particularly unsuited to the representation of music in a digital environment, yet became an industry standard nonetheless because its format was embedded into hardware and software solutions so deeply that it was almost impossible to replace.

This concept rings true for the construction industry for good reason. As opposed to Lanier's digital points of reference that are (to a degree) transient and relatively fast moving, the construction industry is, as we have seen, a lumbering giant that treads a well-worn path based on historically what has provided comfort and predictability (although the latter could be argued to be a false bias). A suitable example would be the use of standard modern railway gauges which have their historic roots in the width of chariots and ancient carriages (Ogatai et al., 2006). Like the ruts for horse-drawn wagon wheels of the past, the standard railway gauge ensures everyone stays on course; however, it also inadvertently discourages challenges to convention. No matter how promising or transformational an idea is, a wagon of a different width simply will not fit, and therefore ideas are cast aside without even getting through the first gateway.

Lanier compares the concept of lock-in to the scientific method stating '*Science removes ideas from play empirically, for good reason. Lock-in however, removes design options based on what is easiest to program, what is politically feasible, what is fashionable, or what is created by chance*'.

When we look at some of the specific challenges around permanence, scale and materials and methods, we can see why this is such a significant issue for construction. It follows that industrial lock-in for construction comes in two forms.

The first is through asset legacy, or the difficulty of dealing with existing physical infrastructure. Aptly using the railway analogy, we cannot rip up and replace thousands of kilometres of railway infrastructure even for the promise of a transformational step change in our transport paradigm; hence, why high-speed rail, and more recently hyperloop concepts, rely on new parallel infrastructure rather than the re-use of legacy systems. When we look at our city centres, we are surrounded by lock-in on a grand scale; legacy buildings and infrastructure representing countless millions of tonnes of embodied carbon with outdated mechanical and electrical systems, sub-performance facades, outdated architecture and increasing durability challenges. Building a new city in parallel is not an option for most societies; therefore, we are left with the challenge of navigating the boundaries of asset legacy to make the most of what we have. From an innovation perspective, this presents not just challenges but also opportunities, as we endeavour to find ways to use the assets of yesterday to meet the needs of today, without compromising our ability to provide for tomorrow (Fig. 5).

The second form of industrial lock-in for construction comes in the form of process legacy, or how our built environment is delivered. We have seen how our materials and methods have been developed and refined throughout previous centuries, and all members of the supply chain have been trained and fine-tuned to intimately understand what is required to deliver a particular form of construction. In this instance, the 'wheel ruts' of lock-in are there to ensure everyone in a project plays their part and knows exactly what to expect from all the other parties in the project team. Although process legacy is manifest in materials and methods, it is not a physical constraint but rather one that is embedded into the very framework of the industry; the roles, responsibilities, contractual relationships, funding and governance which all collectively serve to reinforce lock-in by inadvertently creating barriers to innovation. If the industry is to overcome the challenges presented by societal shifts and climate emergency (whilst meeting the challenges of asset legacy), then it must work harder to overcome lock-in due to process legacy. This will only be achieved by addressing the reasons it exists in the first place.

Fig. 5 Lock-in via asset legacy is a major issue for the transformation of our cities such as London, UK. *Source* https://upload.wikimedia.org/wikipedia/commons/3/3a/01_London_cityscape_-_Aerial_view_of_London_UK_-_free_stock_photo_with_attribution_.jpg

4.2 Fragmentation and Value Ownership

The term fragmentation is used frequently and loosely when referring to the construction industry. It is used as an umbrella under which we can conveniently gather all the discontinuities that collectively prevent cohesiveness, efficiency and simplicity. These have been discussed extensively in many of the reports referenced at the beginning of this chapter, however, generally fall into the two following categories:

1. Project discontinuities

As we have previously examined, projects are unique in almost every respect, and this has historically necessitated delivery using bespoke teams that are brought together often for a specific, one-off purpose. Putting aside supply chain discontinuities that make this issue even more complex (discussed below), there are still immense disadvantages in this approach. On larger projects, project teams often work together for months, collectively identifying problems, developing solutions and overcoming challenges in order to achieve an overall aim. During this process, they often develop close personal relationships, a strong mutual understanding, a collaborative culture and efficient ways of working. When the project comes to an end, the business entities part ways and, oftentimes, individuals within these entities also move on to other projects with new employers. Many of the ideas, innovations and efficiencies are lost as the tacit knowledge of the project team is dispersed and effectively diluted.

This trend is exacerbated by the industry's obsession with project utilisation which actively encourages a project delivery focus at the expense of all other activities. Staff are moved from one project to another to reduce overheads and, once on a project, have little incentive or opportunity to cross-pollinate ideas to other projects even within the same organisation. People working on projects, particularly contractors, therefore, often find themselves feeling a greater sense of belonging and commitment to the project than to their own organisation.

2. Supply chain discontinuities

The traditional supply chain for construction projects still holds strong, as do its many discontinuities. The industry is still largely divided into those that own and operate, those that plan and design, those that supply labour and build and those that supply materials and products. Over the years, traditional methods of procurement have been supplemented by different delivery vehicles such as Design and Build (D&B) and Design, Build, Finance and Operate (DBFO) to encourage more integrated approaches and adopt different risk strategies. New contract forms such as the NEC have been adopted to encourage a more collaborative approach to risk and reward and a focus on project outcomes; however, these measures have still failed to overcome the fundamental discontinuities wherever they may be drawn in the supply chain.

The problem is that construction is inherently a risky business. At the commencement of any project, there are uncertainties that need to be identified and managed. These risks do not disappear without action, and often the right solution requires a holistic approach that spans across supply chain discontinuities. Unfortunately, such is the nature of capitalist enterprise that wherever a discontinuity exists, it is natural to want to pass this risk to another party, whether or not they are best placed to manage and mitigate it. We therefore continue to see projects with huge technical risk, unreasonable budgets and programmes being competitively tendered and won based largely on price. Such projects inevitably end up confrontational and more than often fail to deliver the clients expectations. Notably, the larger the project, the greater the likelihood of failure, with mega projects having a particularly poor record of delivery success due to political interference and inherent optimism bias (Zahariadis, 2004).

Furthermore, despite the unique nature of construction projects, many of the risks (and opportunities) are similar. Project-based procurement does not unfortunately encourage long-term relationships between entities in the supply chain which limits the ability to invest in research and development or take strategic decisions. Such ideal relationships, built on trust, mutual understanding, sharing of risk and reward and defined common goals, are, therefore, extremely difficult to forge unless there is a strong, specific and immediate commercial benefit in doing so. Concepts such as the ICE's Project 13 (n.d.) aim to provide the framework for creating such relationships throughout the supply chain by promoting enterprise agreements rather than transactional and oftentimes confrontational contracts. Trials of Project 13 continue with an early focus on framework agreements for clients with multiple infrastructure assets; however, it remains to be seen how the concept can be adapted for one-off commercial or residential projects.

The concept of so-called vertical integration attempts to close the supply chain discontinuities by bringing the component parts of the supply chain closer together in terms of both knowledge and delivery process. The aim of such systems is to provide a standardised approach to construction, thereby mitigating the loss of knowledge from one project to another and reducing the impact of project discontinuities. In recent years, modular and componentised construction has been touted as a potential solution for the industry's woes and could address long-standing issues such as health and safety, material wastage and quality. However, the engagement of supply chain-specific solutions early on in a project is currently fraught with both technical and commercial challenges and hence the interest in vertical integration as an alternative. There have been a number of relatively new ventures into this area, but perhaps the most well-known is Katerra, whose approach was to fully integrate the supply chain through acquisitions. Katerra envisaged a kit of parts that could be designed, sourced, manufactured and implemented all in a one-stop shop.

However, if the issues of risk and reward are successfully managed through appropriate procurement methods, we can see that fragmentation is not, in itself, a problem. Many industries are fragmented, and it can be argued that the expertise, variety and flexibility provided by a specialist supply chain provides a much-needed antithesis to the opposing trend of multi-national, multi-disciplinary corporations. There is a reason why Katerra was ultimately unsuccessful—car manufacturers do not typically own their supply chains, rather they work more closely with their supply chains to overcome the technical challenges in managing any discontinuities.

The heart of any scheme to close supply chain discontinuities is data flow and a common digital platform on which to exchange design information, specifications and performance data. The industry has seen a number of initiatives to encourage greater access to supply chain knowledge in the design stages of construction. Aside from specific contractual mechanisms to get Early Contractor Involvement (ECI), the industry is starting to see the adoption of digital tools that bring supply chain information to the fingertips of designers, planners and clients. An example is Prism (n.d.) which allows the quick development of costed building solutions based on a range of pre-fabricated construction options. Such applications are already starting to evolve into fully fledged construction system platforms that connect design feasibility through to manufacture and assembly. Such platforms are Katerra's Apollo (n.d.) and Lend Lease's Podium (n.d.).

These tools enable better risk management and the adoption of holistic value principles at the appropriate time in the construction life cycle. With standardised approaches and supply chain knowledge, designers and clients can take more informed decisions for better economic and sustainability outcomes rather than focusing on siloed benefits. It is, therefore, an area that is expected to continue to grow in the coming years.

4.3 Regulation, Life Safety and Risk Aversion

Sadly, we are occasionally reminded of the tendency for risk aversion in the industry. Structural failures are thankfully rare, but the consequences can be catastrophic, and despite greater technology and insights into structural behaviour and materials, incidents do still happen. The moral and professional obligations to society are engrained into engineers from day one, with a strong emphasis on health and safety, risk management, reliability and quality procedures all wrapped up with an overriding personal commitment to not cause injury or loss of life.

Whilst the fundamental basis of this mindset is obviously sound, there are downsides. Structures are often over-designed, loads over-estimated and materials over-specified. Often under significant time and cost pressure, it is easier to add extra conservatism than it is to justify a design to be closer to the line. Aside from the obvious sustainability challenges this presents, the outcome is often poor value for money for the ultimate client.

Worse still, as we have already mentioned, due to the high personal and commercial consequences of failure, some parties in the construction life cycle have historically tended to push accountability for risk onto others. Thankfully from a health and safety perspective, government regulations such as the Construction, Design, and Management (CDM) Regulations in the UK (2015) include provisions, for example the Designer's Risk Assessment, to ensure that risks are identified and managed by those best to deal with them. Notably, recent amendments to the CDM regulations have put an increased onus on clients to take responsibility for health and safety risks where appropriate.

From a commercial perspective, because of the oftentimes huge commercial consequences of failure, there is also a continuous struggle for risk accountability. However, with no regulations to define the obligations of those involved, risk continues to get passed around in contracts; buried in models, drawings, scopes of services, programmes, bills of quantities, specifications and other documents—sometimes shockingly so. As we have mentioned, this then serves to enhance the discontinuities in supply chains, resulting in a focus on self-servitude (and even self-preservation) rather than what is best overall for the project, client and society.

In this environment, the idea of 'trying something new' causes a multitude of conflicts. Each individual stakeholder typically has little interest in innovating unless it has some self-serving benefit. Clients may like the idea of innovation—but only after it has been demonstrated elsewhere and the risks eliminated. Innovation never becomes tried and tested until it is tried. Faced with project deadlines and tight budgets no one wants to try, and this mindset percolates through the entire supply chain.

Under such conditions, it is quite easy for designers and specifiers to point the finger at national codes and standards as a barrier to change. Many such documents are developed over decades and incorporate research going back over half a century. Standards committees are dependent on a flow of quality research and testing which can take many years to find its way from industry inception to funding and then to academia and peer-reviewed publishing. Even then, it can take many more years for good quality research to be collated and consolidated into codified rules or guidance. The approach is methodical, conservative and risk averse for very good reason.

However, we are starting to see signs that this slow and methodical process cannot keep pace with the advancement of technology and materials. The use of additive manufacturing (or 3D printing) in construction is an example where material and construction technology is advancing far ahead of the ability of standards committees to keep up. Whilst there are a number of ASTM standards for materials, testing, terminology and design (primarily for metals and plastics), there are no specific standards for use in construction. By way of example, the ACI committee ACI 564 3D printing of cementitious materials (n.d.) was set up in 2018; however, technology has advanced considerably in the years since, and proof of concept projects continue to evolve, becoming increasingly elaborate and demonstrating value potential. The very combination of new methods of delivery, new materials and different design concepts that makes 3D printing in construction so enticing is also creating a growing disconnect between the expectation of the industry and what is codified and technically justified.

The industry needs to reconsider how research and development can be funded and fast tracked to offer benefits at a practical and accessible level. This once again asks questions of the nature of procurement and a switch to enterprise-based relationships that could include funding of targeted, outcome-focused research and development.

4.4 Drivers for Change

When the Latham Report was published in 1994, it was already recognised that the construction industry had significant inefficiencies, serious problems with quality and suffered from unreliable delivery. The reports that followed have continued to emphasise the issues and have updated stakeholders; however, the problems have largely remained unresolved. The supply chain seems happy to drive down its own profit margins, whilst clients continue to play a game of chance and the legal system remains delighted to sort things out retrospectively when things go wrong.

There was an expectation that the industry would solve the problems itself. It has largely failed to do so for many reasons (many of which we have discussed), but perhaps the biggest oversight is the lack of a real driver for market change. In other industries, change is generally imposed via governmental or societal forces; for example in the automotive industry, the use of seatbelts, lower emissions and reduced fuel consumption were all driven by regulation or operational cost. Other changes come from market expectations in the form of product competition and a search for competitive advantage; for example performance, appearance, build quality, features.

To date, the construction industry has had no reason to change other than its own desire to improve itself. Clients have continued to demonstrate apathy towards the problem simply because they have not felt sufficiently impacted, although the real impacts often remain unquantified. This may be about to change as measures required to address the climate emergency become increasingly important in how projects are designed and delivered.

Mandated building energy efficiencies, tenant sustainability expectations and measures such as embodied carbon tariffs are going to force clients to take the issues far more seriously. This challenge will be passed onto the industry supply chain; however, it will not be achievable without more drastic changes to the way projects are delivered. The industry will, therefore, be forced to adopt more collaborative and innovative ways of working; moving towards vertical integration, digital platforms and enterprise agreements.

5 Opportunities for Change

Many of the more recent industry reports, for example Ribeirinho et al., (2020) present an opinion on the major industry shifts that are to be expected to drive change in the coming years. These include:

- Increasing sustainability drivers
- New technologies, materials and products
- Off-site manufacturing and vertical integration of supply chains
- Increased digitisation and the rise of digital platforms
- Collaborative frameworks and enterprise agreements.

There is a risk that reports and lists such as these fail to motivate or engage change on the shop floor, presenting mega shifts in a way that is inaccessible to most that work within the industry. Whilst it is important to acknowledge the challenges and scale of change needed, it does not take away the real and present opportunities for innovation that exist on every project and within every business. Looking back at the seven fundamental actions to drive innovation which were proposed in Chap. 5 and looking forward to the following chapters, we can see that innovation is within the reach of everyone and can leverage a range of technologies. Despite the constraints and difficulties imposed by the nature of the industry, we can still create environments that encourage innovation, share knowledge and explore new ways of doing things.

The industry, and everyone working in it, needs to take accountability for driving change—and, there is no better time to start than now.

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Chapter 7
Cutting-Edge Practical Research on Generative Design, IoT and Digital Twins

Kean Walmsley

Abstract This chapter explores two areas of research undertaken by Autodesk over the last decade and how they both have the potential to impact the construction industry. The first area relates to the Internet of Things and the possibilities around integrating sensor data from smart buildings into a 3D context for exploration and visualization. This has the potential to drive interesting workflows related to understanding and optimizing the performance of the built environment, but more broadly will have the potential to impact design and fabrication processes. The other area of research described in this chapter relates to generative design, particularly in the context of the AEC industry. Autodesk's work in this area started in 2010 with a project named Dreamcatcher. It was further accelerated in 2014 with the acquisition of The Living, an architectural studio which had—under the guidance of its principal David Benjamin—started exploring the application of multi-objective optimization through the use of genetic algorithms for architecture, engineering and construction industry (AEC) workflows. Looking to the future, real-world performance data captured via IoT—and hosted in Digital Twins—will increasingly influence the Generative Design process, as Autodesk and other software providers start to complement algorithmic exploration of the design space with machine learning systems trained with data from prior projects and captured using physical sensors. This has the potential to drive "closed-loop" processes where performance increases with each design iteration or system re-configuration.

Keywords Generative design · Computer vision · Evaluation metrics · Design generation · Data capture

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_7

1 Introduction

This chapter explores two areas of research undertaken by Autodesk over the last decade and how they both have the potential to impact the construction industry. The first area relates to the Internet of Things and the possibilities around integrating sensor data from smart buildings into a 3D context for exploration and visualization. This has the potential to drive interesting workflows related to understanding and optimizing the performance of the built environment, but more broadly will have the potential to impact design and fabrication processes. Autodesk Research started investing in this area in late 2009 and has since been developing Digital Twin technology—with the primary focus of integrating sensor data with BIM—via Project Dasher.

The other area of research described in this chapter relates to Generative Design, particularly in the context of the AEC industry. Autodesk's work in this area started in 2010 with a project named Dreamcatcher. It was further accelerated in 2014 with the acquisition of The Living, an architectural studio which had—under the guidance of its principal David Benjamin—started exploring the application of multi-objective optimization through the use of genetic algorithms for architecture, engineering and construction industry (AEC) workflows. They have since delivered projects at varying scales—from manufactured aerospace components, to office and exhibit hall layouts and even up to the urban scale with studies on the layout of residential neighbourhoods—that demonstrate the potential for Generative Design in the AEC space.

Both Digital Twins and Generative Design are not only useful for architecture: this chapter will show concrete examples of how they are also being applied to both engineering and construction.

Looking to the future, real-world performance data captured via IoT—and hosted in Digital Twins—will increasingly influence the Generative Design process, as Autodesk and other software providers start to complement algorithmic exploration of the design space with machine learning systems trained with data from prior projects and captured using physical sensors. This has the potential to drive "closed-loop" processes where performance increases with each design iteration or system re-configuration.

2 Early Applications of Project Dasher in Building Operations

When Project Dasher (Autodesk, 2021a) was conceived, back in late 2009, the vision was to create a "building debugger" to help people explore data captured from the built environment and allow them to make appropriate changes to drive efficiency, so they might better understand how the building was performing and discover any unexpected ways in which it was not behaving as intended.

The project became possible because of two overall technology trends: the increasing ubiquity of low-cost (and low-power consumption) sensors and the decreasing cost of cloud-based data storage. Proper instrumentation of the built environment will require not only a significant number of sensors but also cheap, accessible storage for their readings: a central thesis was that the value of the data would continue to be high (and potentially increase) as it helps build an overall impression of how performance changes over time. This thinking predated much of the current focus on big data and machine learning, but these are two examples of how this focus on data has proven to be valuable. Another central notion of the data capture was that it be generic: that the sensors be as sensitive as possible and collect higher than average frequencies of data to enable experiments in data mining and sensor fusion that would emerge over time in the style of a living laboratory.

It did indeed turn out that the data collected and made accessible was of significant value in optimizing a building's performance. One example of this was in Autodesk's former Toronto office at 210 King Street East, which was one of the first buildings to be instrumented and feed its data into Project Dasher. It was noticed that 3D prints left to run overnight in the office were often failing, while similar print jobs run during the day would succeed.

The team used Project Dasher to explore the issue and helped uncover the fact that the air conditioning would shut off every day at 6 pm, leading to the temperature in the room housing the 3D printers to spike upwards of 30°C that, coupled with the very low humidity that was exaggerated by the door to this very noisy room always being closed, led to a significant change to the ambient conditions that were at other times favourable to 3D printing with PLA plastic filament.

Beyond just helping people running facilities to optimize performance, Project Dasher always had sustainability as a core goal: as buildings contribute roughly 40% of global CO_2 emissions (UN Environment Programme, 2020), anything that can be done at a wide scale to optimize performance and reduce this impact would have a significant effect on humanity's use of the planet's resources.

2.1 NASA Ames Sustainability Base

When Autodesk Research embarked on a project alongside NASA to instrument their Ames Sustainability Base in California, it was at least partly with this vision in mind. The building was already equipped with an extensive system of sensors, some of which were built into the HVAC system. It also incorporated smart water management both inside and outside the building, with flora that was carefully selected for the local microclimate.

When the project started, there was no holistic view of the various data being captured from the building's disparate systems: a large part of the initial effort was to feed the data from more than a thousand sensors into a centralized, cloud-based, time series database.

This data could then be visualized in a 3D context with the Dasher client—originally a desktop application (Attar et al., 2010) but more recently web-based (Autodesk, 2021b), taking advantage of Autodesk's Forge platform (Autodesk, 2021c)—to allow more intuitive exploration of the building's performance data. The readings for individual sensors could be displayed in graph form, or the data for a particular zone or floor could be displayed as a heat map, showing the variations between multiple sensors. All this data could be animated via a timeline that enabled targeted and interactive exploration of a historical time period.

The graphing system—known as Splash (Glueck et al., 2014)—made use of multiple levels of detail onto the data, allowing the user to see years' worth of data and then quickly zoom into (say) an interval of just minutes or even seconds.

When the visualization shown in Fig. 1 was originally shared with NASA, a member of their team of scientists quickly pointed out an area of the building—highlighted in red—that performed differently from the rest of the floor. He immediately explained that this room was being used to perform a glazing study but that the results had not yet been analysed. In seconds, the results were clearly visible in the contextual 3D visualization. This was an early indication that this kind of explorative visualization tool could provide benefits to people operating a building.

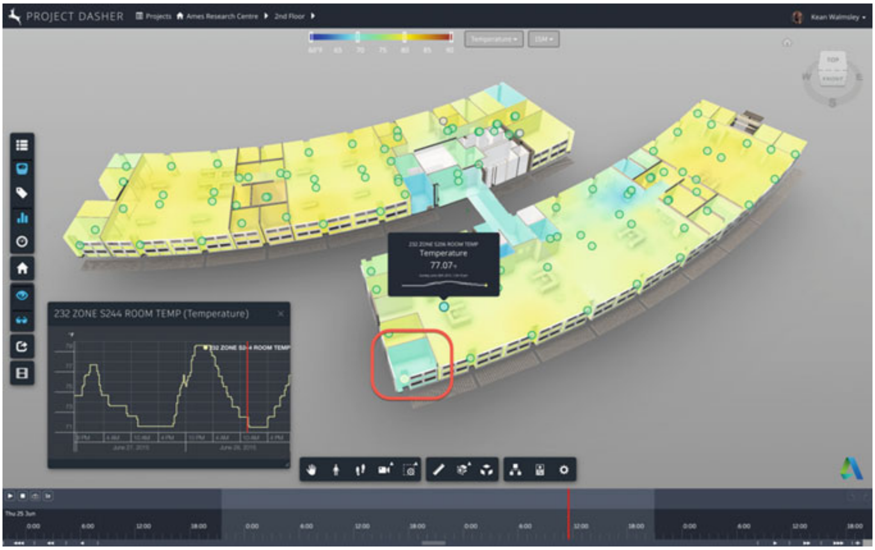

Fig. 1 Project Dasher displaying data captured from NASA's Ames Research Center (author's original)

2.2 Schneider Electric's GreenOValley HQ

Another interesting building-centric pilot project was for Schneider Electric, for a building on their GreenOValley campus in Grenoble, France. Schneider Electric had developed and installed a new occupancy sensor in their building which provided information on the approximate relative (and anonymous) locations of the building's occupants. The data displayed locations of people in the building at moments in time—so Dasher was unfortunately not able to plot the movement of people through a space—but it was certainly enough to be able to plot occupancy against CO_2 levels for a space.

Figure 2 illustrates how Project Dasher allows the correlation of sensor data, highlighting how high occupancy of a particular conference room for an extended period caused the CO_2 levels to spike. Dasher allows quick exploration of such problems, providing the ability to zoom out of the more granular data for the CO_2 sensor for that room, looking at weeks, months or even years of data at a time in order to assess how frequently this situation arises.

Fig. 2 Project Dasher displaying data from a building in Schneider Electric's GreenOValley campus (author's original)

3 From Buildings to Infrastructure: Applying Dasher to Bridge Monitoring for Pier 9 and MX3D

The potential for this technology clearly goes beyond the operation of buildings. The opportunity to explore such possibilities came out of a collaboration with Netherlands-based Joris Laarman Lab.

The laboratory had worked with Autodesk Research via a partnership with the Autodesk Technology Center in San Francisco, where they explored the possibilities for using industrial robots to 3D print large-scale metal objects and structures.

They came up with the idea of using this technique to “print” a generatively designed bridge over a canal in Amsterdam. The bridge would be a metaphor for connecting the city’s rich history with its bright technological future.

This was the birth of MX3D, a spin-off from the Joris Laarman Lab that would explore this and other use cases for this innovative technique. Autodesk Research was initially involved in the project to help prototype some initial design options. The final design, shown partially in Fig. 3, was generated and developed by MX3D, but Autodesk remained involved, ultimately shifting focus away from its design to consider possibilities for monitoring the bridge’s performance.

Being the first of its kind, constructed via a novel manufacturing technique—shown in Fig. 4—there was clearly no information available on how the bridge would perform when under load or across temperature extremes. A significant amount of effort was put into analysing the performance of the material, of course—primarily by project partners Imperial College, the Turing Institute and Arup—and the recommendation was made to perform structural monitoring of the bridge for a period of time.

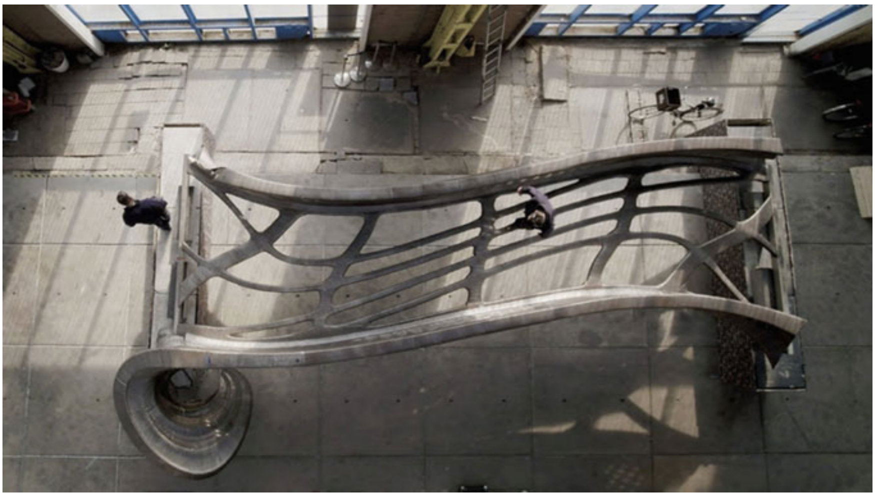

Fig. 3 MX3D smart bridge under construction (photo © Joris Laarman Lab)

Fig. 4 Industrial welding robot depositing material for the MX3D smart bridge (photo © Olivier de Gruijter)

Understanding this as an opportunity for gathering deeper insights from the bridge beyond the structural implications, a group at Autodesk identified the role that smart infrastructure could play within future cities. The idea was to integrate a "nervous system" into the bridge, allowing for constant monitoring, which could unlock the ability to gain insights into how the bridge gets used and performs.

This nervous system would come in the form of sensors on the bridge's surface that would measure temperature, load, strain, acceleration and incline, passing the readings into a cloud-based, time series database for storage and analysis.

To be useful, the data coming from some of these sensors needed to be read at a much higher frequency than in the previous contexts explored by the research team: in a building, one might read the temperature or CO_2 values from a sensor every 5 minutes or so, while an accelerometer on a bridge might be read as often as 1000 times per second (10 Hz is probably more realistic, but that is still significantly more data to marshal and store than had previously been tested with the system).

Rather than waiting for the MX3D bridge to be completed, the decision was made to install sensors on a raised pedestrian walkway connecting areas of Autodesk's Pier 9 office in San Francisco, a bridge of comparable size and function. This would allow the research team to make sure the system was able to deal with the volumes of data generated by a bridge with sensors being sampled at higher frequencies.

The Pier 9 project was an invaluable stepping stone to be able to add a nervous system to the MX3D bridge. A network of 30 sensors was installed on the Pier 9 bridge, as shown in Fig. 5, enabling the collection of data for structural movements

Fig. 5 Raised walkway in Autodesk's Pier 9 office inside Dasher (author's original)

through strain and acceleration, as well as pedestrian motion, sound levels and atmospheric information such as temperature, pressure, humidity and CO_2 levels in the indoor space. Visitors to the space were able to see their impact on the bridge in real time via screens displaying the sensor data inside Dasher.

The Pier 9 project provided Autodesk Research with knowledge that was highly valuable when instrumenting the MX3D bridge with its sensor network. The goal for the smart bridge project was not only to understand the bridge's performance, but also for it to sense its environment beyond the immediate. Alec Shuldiner, who helped initiate the project and drive it to its conclusion said: "I am very interested in what's happening on and around the bridge, and what the bridge can tell us about that. I'm interested in this as a sensor for the neighbourhood.".

A big piece of enabling this was a computer vision system allowing the system to "see" people using the bridge and understand how they engage with the bridge and its environment.

4 Enhancing Privacy: Using Computer Vision to Anonymize Data Capture of Occupants and Passers-By

To "feel" activity on the bridge, Autodesk tried different machine learning approaches. Early results were promising, but the team concluded early on that the best results would be obtained with a properly labelled data set for pedestrians crossing the bridge. In order get as close as possible to "ground truth" with the labelling of the dataset, a key component was the integration of synchronized video

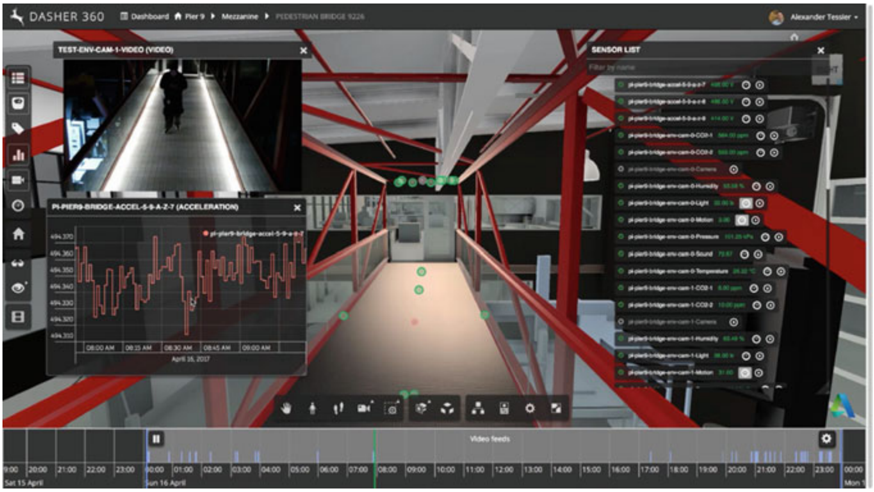

Fig. 6 Pier 9 bridge inside Dasher showing synchronized video content (author's original)

camera footage as shown in Fig. 6, allowing the team to make sense of the performance data relative to what could be seen on and around the walkway. By integrating video into the data set, new possibilities emerged for data correlation and sensor fusion beyond simple annotations.

While it was extremely valuable, the amount of video data was significant but more importantly was also highly sensitive. This led to a project—code-named Ajna—being started to explore the possibilities that modern computer vision algorithms (which effectively allow the computer to "see" real-world objects) could introduce into the context of a 3D visualization system.

Initial phases of the project required reliable pedestrian motion detection to only store video of salient events on the bridge, such as pedestrian crossings, instead of being triggered by the machine movement or lighting changes within the machine shop. These events were integrated into the timeline navigation also shown in Fig. 6. Combined with cloud storage and video compression, the motion detection events proved to be even more useful in understanding where people were on the walkway during traversals and were an integral part of data set labelling for training machine learning human presence, gait and position on the bridge.

The use of integrated video footage quickly became a highly sensitive topic within Autodesk Research. To maintain employee privacy, access to the system was extremely limited. Initial efforts at automatically blurring faces—as shown in Fig. 7—at the hardware level proved insufficient in the perception of anonymization of the data. It was also desirable to derive more complex loading conditions from the data for analysis, such as when people walked in lock step, carried heavy objects or leaned on the handrails along distinct parts of the bridge. To get at the data that was needed, yet remove sensitive individual traits, the research team turned to extracting

Fig. 7 Person with a blurred face crossing the Pier 9 bridge (author's original)

pedestrian skeletons as shown in Fig. 8, with the potential of negating video storage altogether, storing only the skeleton data.

Part of the project was to map this data into a 3D context to allow visualization of people walking through a space and correlation with other types of data. The initial implementation of this approach allowed mapping of skeletons into a plane that was parallel to a standard (non-depth, non-stereo) camera frustum: essentially

Fig. 8 Extracted skeletons overlaid onto video of people crossing the Pier 9 bridge (author's original)

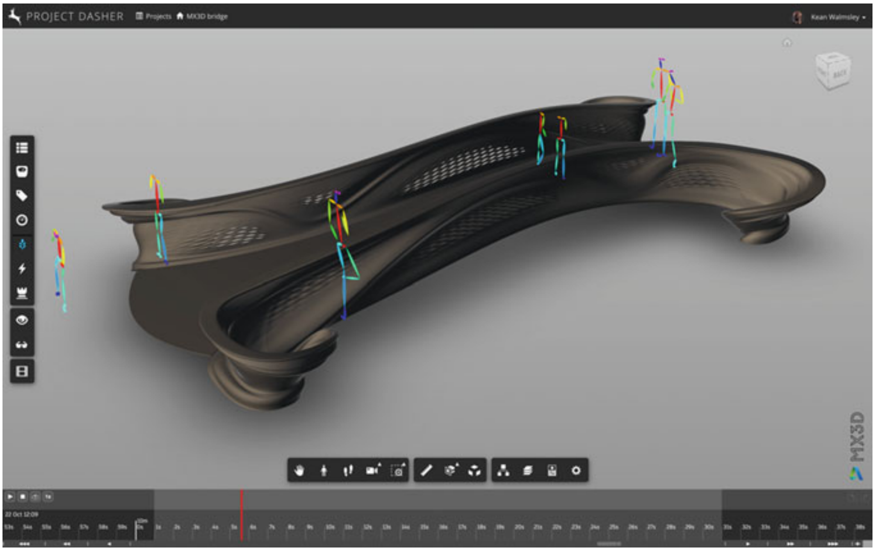

Fig. 9 Displaying 2.5D skeletons extracted from video footage inside Dasher (author's original)

giving 2.5D, in that flat skeletons were positioned correctly in 3D space, as shown in Fig. 9.

A more recent phase of Project Ajna harnessed machine learning—in that it used a library that was trained against various typically body configurations (Kocabas, 2019)—to extract and display full three-dimensional skeletons, an important milestone in the project.

While there was clearly sensitivity about employee privacy in the context of the Pier 9 project, the concerns around privacy of people crossing a bridge placed over a canal in the red light district of Amsterdam were much higher. It was essential that the project complied with GDPR, of course, but also that it met the privacy needs of people who would use the bridge.

The opportunity this kind of positional data provides is significant: firstly, it is possible to compare what is known about people crossing the bridge—as detected by the cameras—with the information from sensors about how the bridge is behaving structurally. Correlating this data inside Dasher, it is possible to understand the specific impact of people crossing the bridge on its performance. See Fig. 10 for an example of how positional information can be correlated with strain information via the combination of skeletons and surface shading.

Secondly, it is now possible to analyse the flow of people across the bridge and the kinds of behaviours they exhibit—anonymously. One can start to reason on how people in Amsterdam move around the city and interact with their infrastructure. The MX3D bridge is ultimately an art exhibit—which does mean that people will engage with it very differently from a more functional piece of infrastructure—but this type

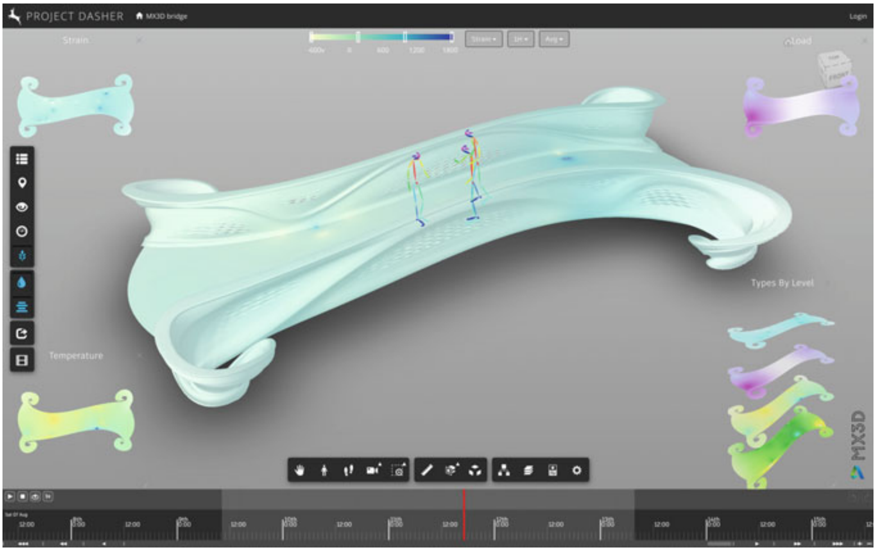

Fig. 10 MX3D bridge displaying 3D skeletons and strain data shaded onto its surface inside Dasher (author's original)

of project paves the way for a future of smart infrastructure that helps the city of the future better meet the needs of its inhabitants and visitors.

5 First Steps with Generative Design: The Airbus Bionic Partition

Autodesk Research started exploring the potential for Generative Design in 2015, shortly after The Living—a New York-based architectural studio headed up by David Benjamin—was acquired by the company.

Generative Design is a methodology where the power of computation is used to explore a solution space for a particular design problem. The performance targets for a design are described in some way, and the system will generate design variants that are measured against these goals.

The project with Airbus was in many ways the beginning of Autodesk's exploration of applications for generative design.

Each A320 airliner currently sports a 65 kg partition at the back—separating the passenger compartment from the galley—that supports two crew seats and can be opened to make space for a stretcher to navigate around the tight corner leading out of the plane in the case of a medical emergency.

The aim of this project—a collaboration between Airbus group's APWorks and Autodesk Research's The Living—was to design a partition that was 50% lighter

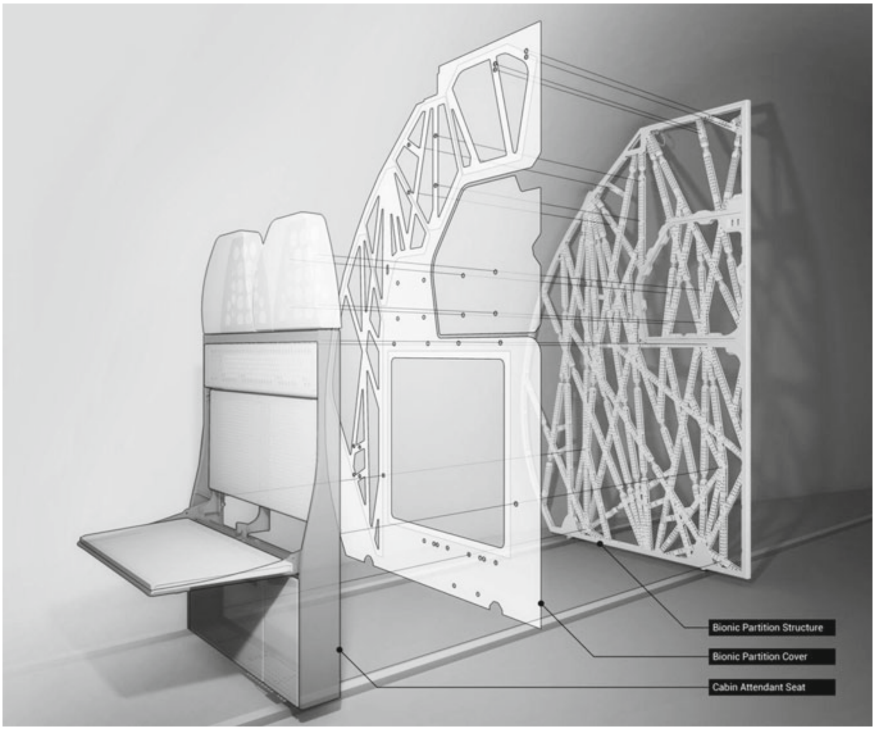

Fig. 11 Airbus A320 Bionic Partition (author's original)

while maintaining or improving its structural properties (Nagy et al., 2017a). The structure and purpose of this partition are shown in Fig. 11.

In October 2020, there were more than 9000 A320s in active service, making it the highest-selling airliner. Reducing the weight of this partition by 50% across all A320s would reduce the amount of fuel needed and—in aggregate—save 1 million tons of CO_2 emissions each year.

For this project, there were two primary metrics used to evaluate each design option: weight and displacement under structural load. The aim was to minimize both of these metrics.

The parametric model used to generate the various options encoded an algorithm inspired by nature: physarum—a type of slime mould—creates efficient, redundant networks while seeking (and linking) its food sources, as shown in Fig. 12.

Physarum sends out tendrils seeking food: those finding it are strengthened, while those that do not wither away. This basic mechanism—coded as a software algorithm—was used to generate many different design alternatives and effectively explore the solution space for this problem. The system was deliberately designed to evaluate options that were outside the space a human designer would typically consider.

Fig. 12 Physarum (slime mould) tendrils connecting food sources. Source: https://en.wikipedia.org/wiki/Physarum_polycephalum#/media/File:Physarum_polycephalum_plasmodium.jpg

The results of this generation process could then be explored by considering the trade-off between weight and displacement: as demonstrated in Fig. 13, it is easy to reduce displacement while increasing weight and vice versa.

It is here that the designer places a key role in the process, once again: using their intuition to guide the appropriate trade-off between how the designs meet the stated objectives.

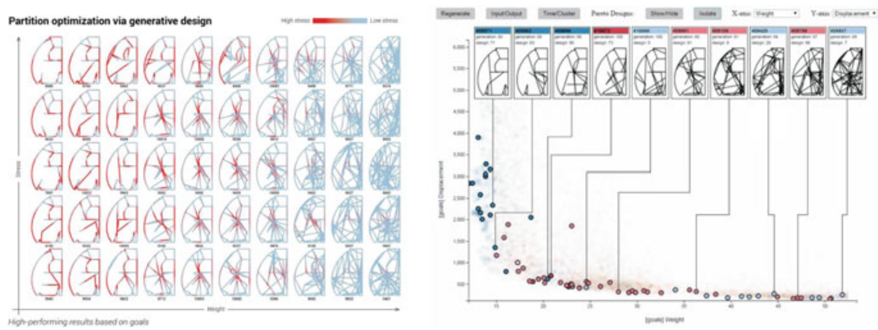

Fig. 13 Generated designs mapped based on their performance (author's original)

When a particular design was selected, a secondary optimization process started: each of the “macro” bars in the design had its topology optimized, replacing each with a set of microbars of varying thickness and strength depending on the load they needed to support.

Of course, extensive testing was performed, both virtual (via finite element analysis) and physical. The results were consistent: the physical objects failed in highly predictable (and predicted) ways.

At the time of the project, the technology did not yet exist to 3D print the entire partition in one piece, so it was divided into 122 parts that were printed in Scalmalloy, a high-performance aluminium–magnesium–scandium alloy designed for metal 3D printing. These parts could be printed in batches, of course, as shown in Fig. 14.

Figure 15 illustrates how these 122 parts were then assembled into a single object using 40 titanium connectors.

These connectors only added 2–3% to the overall weight and allowed the partition to be crated up and transported to Las Vegas for display in the Autodesk University Exhibition Hall, as shown in Fig. 16.

The question remains—longer term—of the appropriate fabrication granularity for this partition: having it all in one piece is likely to be desirable, structurally speaking, but any damage would then mean the full panel would probably need replacing, rather than a smaller component. This is ultimately a manufacturing decision rather than a drawback of the design process, of course (Fig. 17).

The finished partition ended up being 45% lighter—at 35 kg—while being slightly stronger—it had a displacement of 99 m rather than 108 mm—and otherwise

Fig. 14 Parts of the Bionic Partition printed together from Scalmalloy (author’s original)

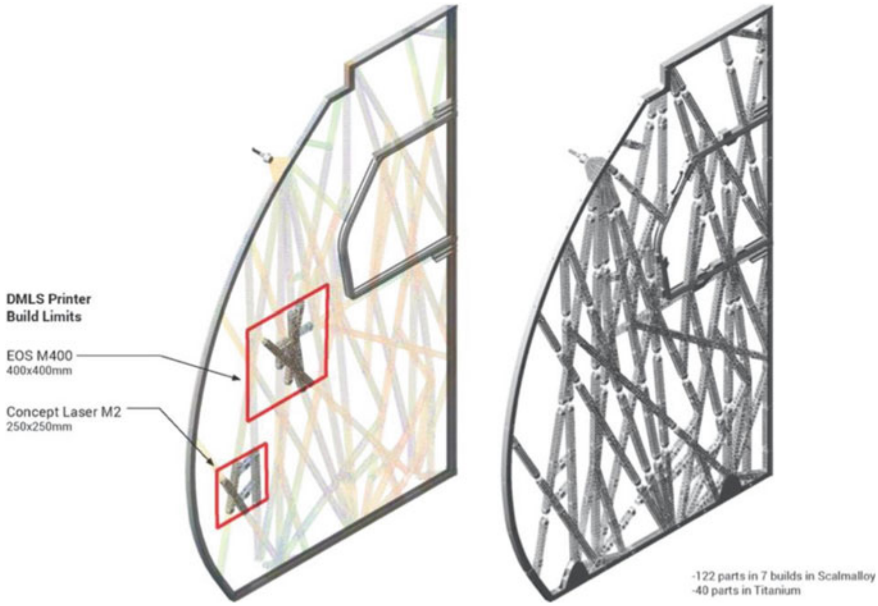

Fig. 15 Titanium connectors between the Scalmalloy parts (author's original)

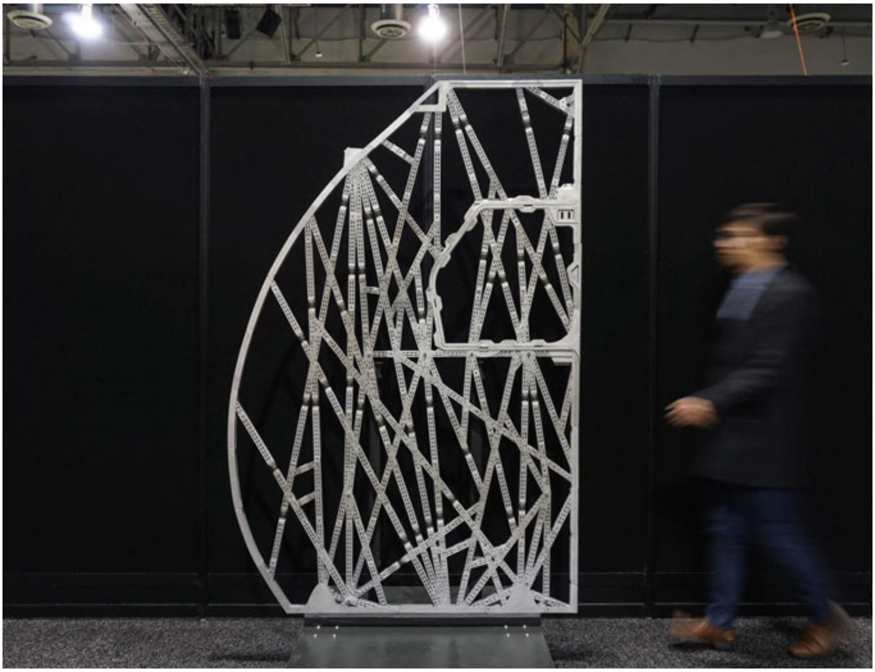

Fig. 16 Airbus Bionic Partition on display at Autodesk University 2015 (author's original)

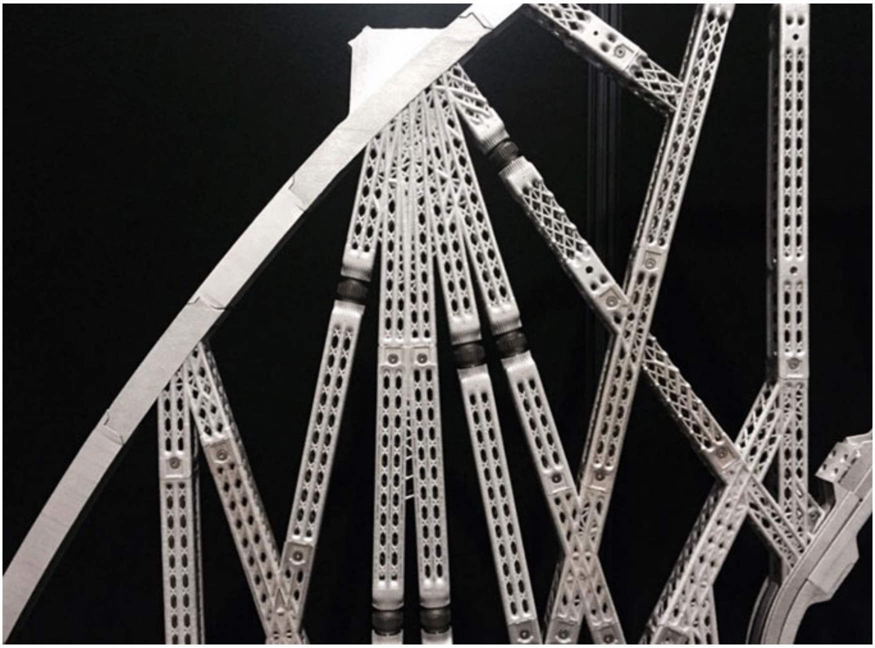

Fig. 17 Closer view of the Bionic Partition (author's original)

performed comparably to the original. Figure 18 illustrates the relative displacement of the existing and new partitions.

The Bionic Partition project was an important step in exploring the possibilities around applying Generative Design for aerospace: it was a relatively simple—when compared with the challenge of designing the airframe—and low-risk way of exploring the technique, while the longer-term opportunity is clearly to use such an approach for more fundamental and radical design work. This will hopefully become feasible as the technology matures.

6 Designing an Office Generatively: Project Discover and Autodesk's Toronto Office

Toronto is an important location for Autodesk Research, with a significant portion of its staff based there. When Autodesk was considering moving its Toronto office to the MaRS district of the city—the largest urban high-tech incubator in North America—there was an opportunity to use the office as a showcase for architectural-scale generative design. The technique had been tested with just two metrics in the Airbus Bionic Partition project, but could it scale effectively to help generate an

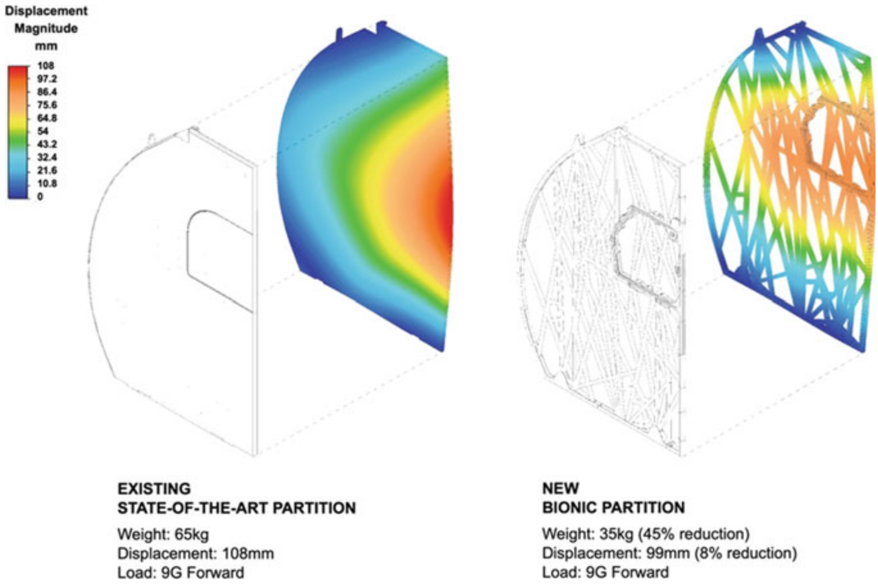

Fig. 18 Comparison of the old and new partitions (author's original)

architectural layout of an office space based on a larger number of performance goals?

Project Discover was designed to answer this very question (Nagy et al., 2017b). The first phase of the project helped establish what Autodesk's Toronto-based employees want from an office space: the employee base was surveyed to understand their requirements and preferences, and—of course—the corporate facilities and HR teams were involved to make sure business needs were considered, too. Based on this input, it was possible to craft a set of metrics that could be used to assess the quality of a particular design.

6.1 Evaluation Metrics

There were six metrics chosen to evaluate potential solutions for this design problem: adjacency, workstyle preference, interconnectivity, distraction, daylight and views to outside, as shown in Fig. 19.

6.1.1 Adjacency

The adjacency metric measured the distance for each employee to travel from their desk to a set of preferred neighbours and amenities. The main algorithm used for this

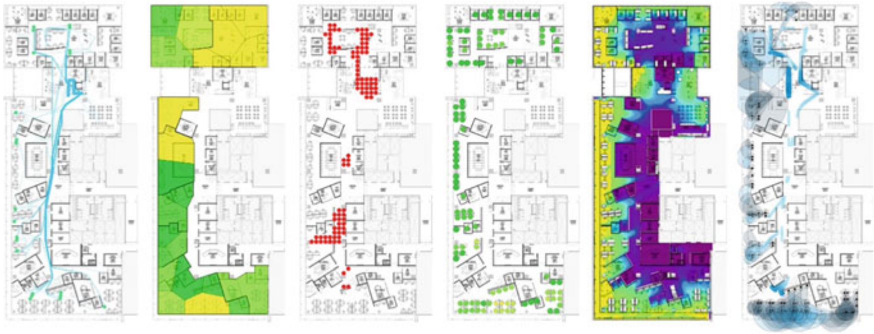

Fig. 19 Evaluation metrics (from left to right: adjacency, workstyle preference, interconnectivity, distraction, daylight, views to outside) (author's original)

was a "shortest path" analysis, to help understand the minimal path of travel from one point in the office to another. The score—between 0 and 10—was an indication of how little individuals need to travel to get to key points in the office (some of which are standard, others are specific to that individual). A score of 0 meant occupants had a high cost of travel, a score of 10 indicated the lowest cost.

6.1.2 Workstyle Preference

The workstyle preference metric measured the suitability of a neighbourhood to the assigned team's preferences. It determined how closely a team's preference and weighting of ambient conditions (light and activity) were met by their assigned neighbourhood. At the extremes, the score indicated whether none of the teams had their preferences met (0) or whether all the teams had them met (10).

6.1.3 Interconnectivity

The interconnectivity metric considered the amount of likely congestion in an office layout based on the paths people will take through the office. Congestion can be considered negative—which is certainly the case when prioritizing office designs that minimize the propagation of viruses through human contact—but in the case of this project, the team was looking to encourage serendipitous encounters and "water cooler" discussions. High interconnectivity scores are also likely to impact occupants looking for quiet work areas, something that will be discussed further for the distraction metric.

6.1.4 Distraction

The distraction metric measured the amount of negative visual and auditory activity from individual workspaces. It counted the number of colleagues who were in an employee's field of view when seated at their desk and considered desks that were close to zones with high auditory activity (as measured by interconnectivity). It scored designs poorly (0) that had all workstations with high visual/auditory distraction and scored them highly (10) if all workstations had no visual/auditory distraction.

6.1.5 Daylight

This was a measurement of the daylight levels in workspaces and amenity spaces. Industry-validated methods were used to calculate light levels via LEED v4 standards, with the score indicating the amount of occupied space that has adequate natural light at both 9 am and 3 pm. A score of 0 indicated 0% of the occupied floor area had adequate lighting while a score of 10 indicated 75% or more.

6.1.6 Views to Outside

This metric indicated whether people at their desks or walking through the office would have a view to the outside. An isovist calculation was performed from each of the sample points, with the overall score indicating how many of these points would have an unobstructed view of a window.

6.2 Design Generation

The next phase was to build a parametric model that could potentially generate thousands of different design variants, each of which could be assessed using the six metrics.

The inputs to this model would vary the way floorplans get divided into neighbourhoods—a Voronoi pattern was created from a set of variable neighbourhood centres and was then used for the division process—at which point the algorithm could place desks and amenities and then allocate teams to areas of the office.

While this model could be used to generate many random design options, it was unlikely this would result in finding the highest-performing designs: when a design problem has high dimensionality—and this one has six dimensions—it is (a) unfeasible to perform an exhaustive search by generating every possible design and (b) unlikely that a random search (or even a systematic chopping up of the input parameters to perform "optioneering") would find the most interesting solutions.

Multi-objective optimization can provide a more intelligent search of a solution space: an optimization engine makes use of a genetic algorithm to maintain a pool of high-performing designs, and—generation on generation—uses genetic operators such as selection, crossover and mutation to seek even better solutions based on this population. The inputs to the model are tweaked based on the parent solutions' and the child's metrics which are then evaluated to see whether they perform better or worse.

The specific algorithm used during Project Discover was NSGA-II, a genetic algorithm that has been used effectively in a number of different design-related activities such as printed circuit board layout for electronic engineering.

6.3 Design Exploration

The Generative Design process typically does not result in a single best design option: a set of results will be generated, many of which perform well against different goals. Therefore, a key piece of such a Generative Design system needs to be an environment allowing designers to explore the generated results and ideally gain an understanding of trade-offs between different performance metrics.

For the Airbus project—with two metrics—it was a straightforward process to scatter plot the results with one metric on the X axis and the other one on Y, helping us understand the inherent trade-off between weight and displacement (heavier designs typically displace less than lighter ones).

For Project Discover—with six metrics—things were more complicated: while it was possible to create scatter plots with four different metrics (in addition to X and Y, we can use size and colour to convey additional information), it was likely that over time this process would be applied to problems with even higher dimensionality. The future generative designer will need an environment that allows them to assign metrics to the axis of their choice, helping them gain a sense of any trade-offs and to look for interesting solutions.

Figure 20 shows the designs generated during Project Discover plotted based on their interconnectivity (Buzz) and adjacency preference metrics.

This exploration stage can be extremely valuable, in and of itself: it is at this point that the designer is likely to be presented with unexpected results. The generative system—if implemented properly—is not subject to the same biases as a human designer. We are formatted in such a way to typically favour rectilinear layouts, for instance, or at least to have angles that are consistent with an overall style. The generative process is not necessarily limited by these biases and so can often generate results that challenge the designer's natural inclinations.

For instance, Fig. 21 shows interesting results from Project Discover, some of which were unexpected:

1. Multiple types and sizes of amenity spaces surround each neighbourhood, leading to better scoring for productivity.

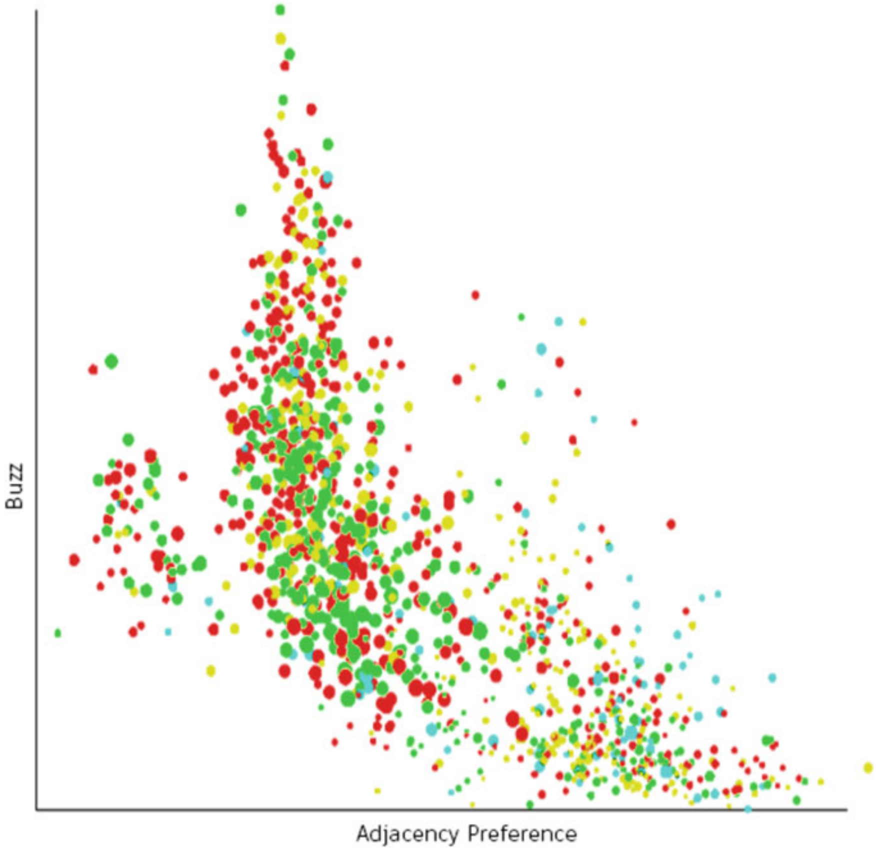

Fig. 20 Scatter plot of Project Discover designs (author's original)

2. Residual, irregularly shaped areas become semi-private informal social spaces that, while performance neutral, were unexpected, interesting design elements and well-received by the clients.
3. A diagonal line between neighbourhoods allows fitting more meeting rooms while giving each neighbourhood its own character.
4. Unusually shaped room used for open-ended activities.
5. Stepped walls create nooks as a threshold between public and private spaces.
6. Non-orthogonal, non-parallel boundaries obscure sources of distraction (desks in adjacent neighbourhoods and busy corridors) to improve productivity scores.
7. A back-alley connection between neighbourhoods, leading to a better score for adjacency.
8. A neighbourhood expanding out towards the window because the team prefers natural light.
9. A neighbourhood contracting towards the window because the team prefers less distraction from outside.

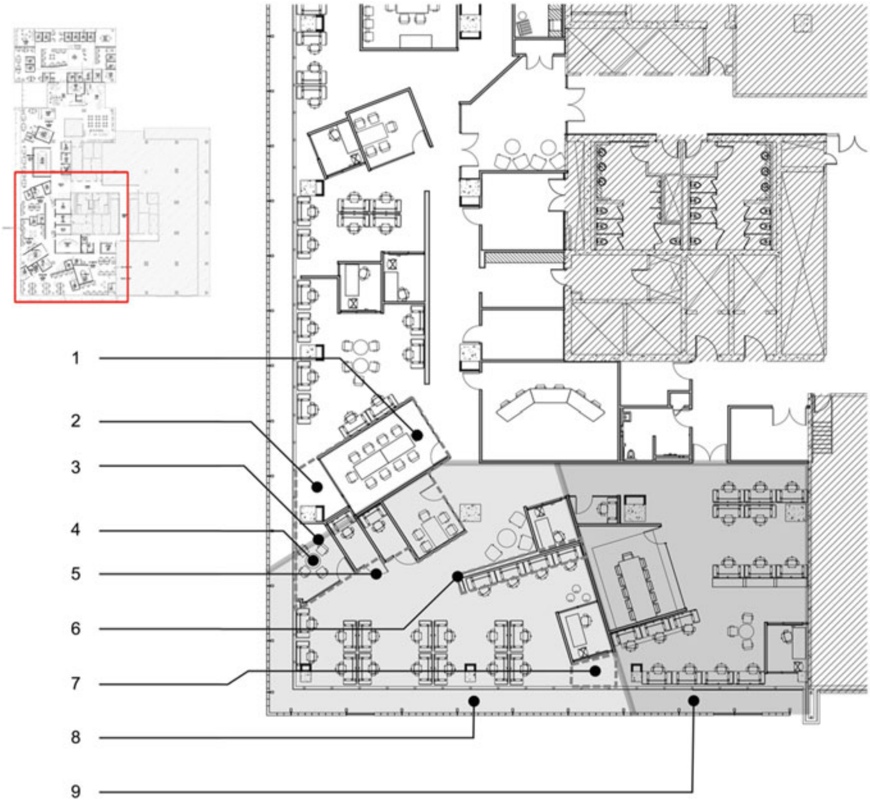

Fig. 21 Interesting outcomes in the design of the MaRS office (author's original)

6.4 Design Elaboration

Once a set of interesting designs has been identified, there is often a review process with project stakeholders. It is typical, at this stage, for a decision to be made on which of the design variants to elaborate further. It is worth noting that the metrics are an extremely valuable tool for this decision, as the selection process becomes much more data centric.

It is also worth noting that the resulting "design" is often far from being a complete blueprint that can immediately drive construction at the current stage of technological maturity: the value is in having important, high-level design decisions suggested by the generative process, while the detailed design work is likely to be performed manually, for now. This will certainly change as the technology matures—as this detailed work is often very time consuming and would also benefit from automation—but with early efforts such as Project Discover, this step was performed in a traditional way that would not impact the high-level evaluation metrics.

So while the generative process does not necessarily result directly in a completed design—today, at least—if successful, it should provide inspiration of interesting ways to attack the design problem, with data to support the inherent logic of the design.

7 Urban Scale: Applying GD for Residential Neighbourhood Layouts with Van Wijnen

Having demonstrated the opportunity for Generative Design to be used for architectural space planning through Project Discover, Autodesk Research was approached by the Netherlands-based development and construction company Van Wijnen to explore the potential of applying this methodology at the urban scale (Nagy et al., 2018).

Van Wijnen builds neighbourhoods of residential homes via an efficient, standardized process. They make heavy use of modern building techniques such as offsite fabrication and modular construction: it is this modularity and standardization that made it feasible to build a Generative Design workflow for the urban scale.

Seven metrics were identified to measure the quality of designs: project cost, profit, solar gain, backyard size, exterior views, programme and variety, as shown in Fig. 22.

The geometry system was driven by inputs indicating the location of streets intersecting the lot, with the various steps shown in Fig. 23.

The first step was to create a boundary-sensitive subdivision mesh that covers the layout's boundary. This will be the same for every design generated for this particular layout, of course, so could be generated just once.

In the second step, streets were placed based on the input parameters to the model, which were then used to subdivide the mesh into discrete lots containing parcels.

In the next two steps, houses and apartment buildings were placed into the allocated parcels.

Finally, the programme for the layout was allocated.

The whole process was driven by a small number of input parameters: the location of streets intersecting the layout. Everything else flowed from this.

Using this parametric model—which encapsulates both the geometry system and an implementation of the metrics that can be used to evaluate each design—the generative process can search the solution space for high-performing designs.

As discussed previously, an exploration step helps the designer to understand the trade-offs between different metrics and identify the most interesting designs to present to stakeholders, as shown in Fig. 24.

Once the various project stakeholders have assessed the selected designs—a process that is greatly facilitated by having data that supports the decision, in the form of the evaluation metrics—a final design can be selected for further refinement, as shown in Fig. 25.

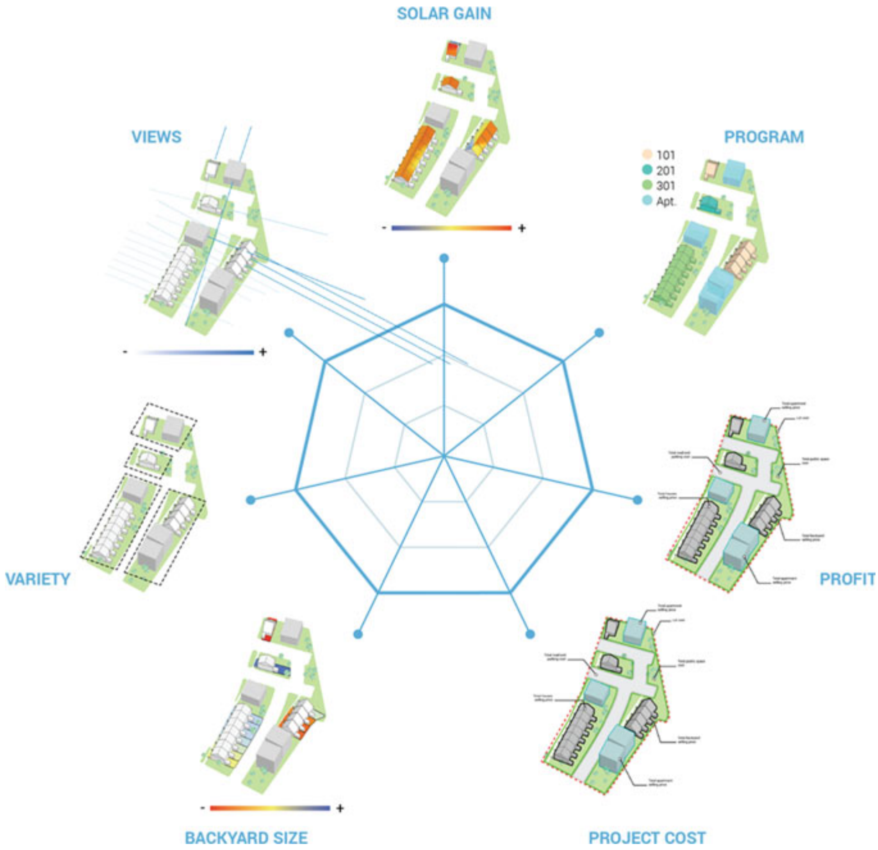

Fig. 22 Evaluation metrics for the project with Van Wijnen (author's original)

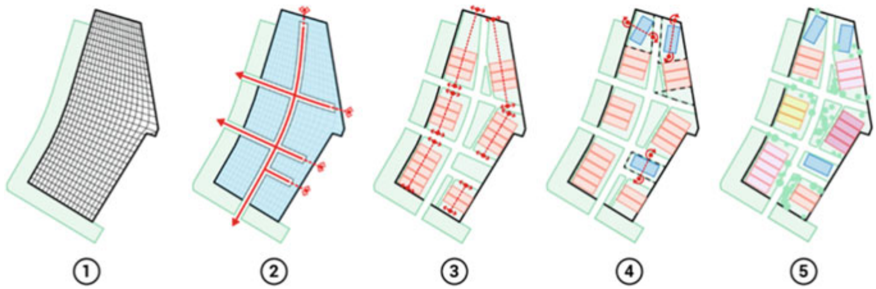

Fig. 23 Steps to define the geometry for a residential layout (author's original)

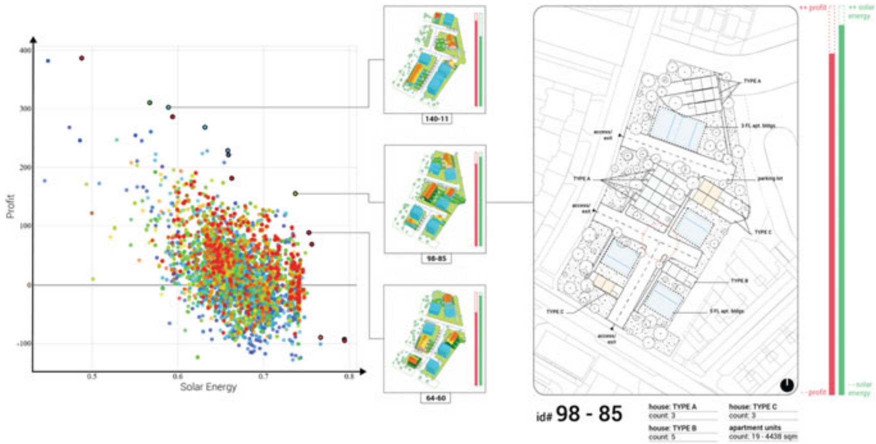

Fig. 24 Exploration of the generated designs and selection for stakeholder communication (author's original)

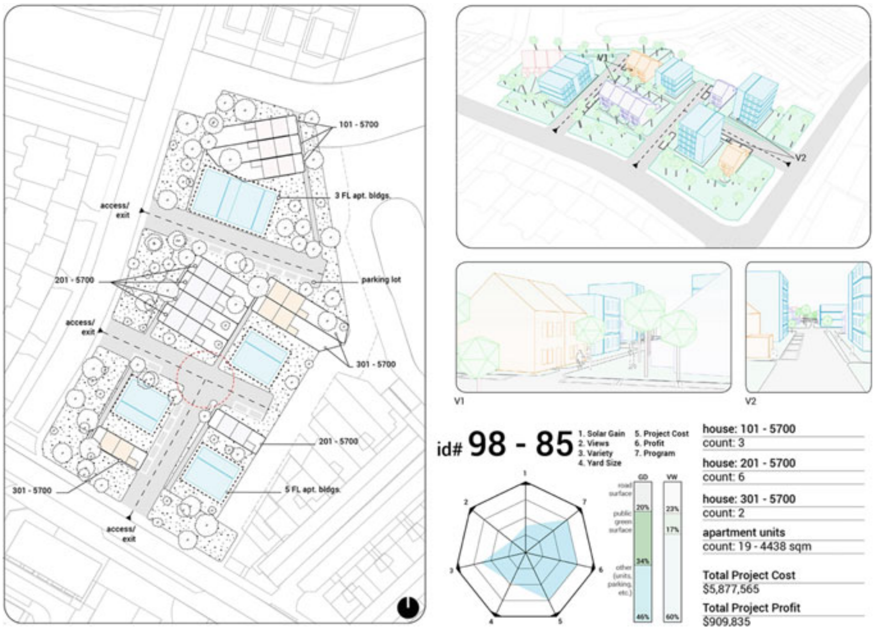

Fig. 25 Developed design (author's original)

This first application for Generative Design at the urban scale has opened the door for further experimentation and development in this space.

When asked about the potential for this technology, Jelmer Frank Wijnia, Generative Design Lead at Van Wijnen, said the following:

> In the end, Generative Urban Design will be a big timesaver for Van Wijnen - in seconds functional designs are generated - in a holistic way. It is really easy to see which project scores best on goals set by the user.
>
> Still, lots of functionality needs to be implemented; the more the better. Meeting the right criteria, setting the right goals for a project will take time.
>
> Therefore, at this moment Generative Urban Design feels more like a partner in crime than replacing the job of the designer.

8 The Future: Closing the Loop Between Digital Twins and Generative Design

It is interesting to consider an analogy for the two areas of research highlighted in this chapter: to think of them as being like the two hemispheres of the human brain.

On the one hand, we have the data-centric workflows we have explored via Project Dasher, where the real value is in collecting measurements and taking a highly analytical view of how buildings and infrastructure perform. We can think of this as being a left-brain function.

On the other hand, we have the more creative processes in Generative Design. While not strictly creative, it is sometimes hard to tell the difference between true creativity and something that looks a lot like it. This could be considered more of a right-brain activity.

Things become more interesting when considering opportunities to combine these two types of activity: there is significant potential for the historical data collected when building a Digital Twin to influence a Generative Design process.

For instance, the strain data captured for the MX3D bridge could help engineer the next version (should there be one) more optimally: as the first of its kind, it was always going to be the case that the bridge would be over-engineered until the characteristics of the material in the long-term could be fully understood. Real-world performance data can help future iterations of a design use less material and fewer resources.

Similarly, an office could be laid out based on collected data relating to its average occupancy and the typical behaviours of its occupants.

The data could, of course, inform the design activities performed in a more traditional manner, but the greater opportunity is to have the data drive a generative process, whether influencing it directly or via a surrogate model such as a neural network that gets queried as designs are generated and evaluated.

This could also reduce the complexity of the parametric model that currently needs to contain the full logic to define the geometry of many different design variations. Machine learning could be used to encode a “style” based on prior projects and allow this to be integrated into the generative process, whether in the creation of the geometry or the evaluation of designs relative to this style.

Projects combining the two disciplines are now starting to emerge, but the journey is just starting.

One early example relates to the use of Generative Design to create the layout for the exhibit hall at Autodesk University 2017 (Nagy & Villaggi, 2021): the design process took into account prior designs—in terms of the underlying logic used to create designs for the space—but there was no data representing the movement of people through an exhibition area. Autodesk Research was able to install cameras that monitored the movement of people through the AU 2017 space—once again using the anonymization technology from Project Ajna—that would allow post-event analyses to validate the quality of the selected design, and whether assumptions about the evaluation metrics were correct.

The longer-term opportunity offered by this data is to have the flow information more directly influence the next iteration of the Generative Design process. The loop is now closed, and over time—and ideally through multiple iterations—the assumptions will be validated and the model improved to reflect reality.

9 Conclusions

Automation is changing the way work is performed across many industries, as "software eats the world" (Andreessen, 2011). As technology advances—whether sensor hardware, cloud-based storage and compute, machine learning or genetic algorithms—there are significant opportunities to make sense of the built environment and to use these insights to improve its operation and to influence the next generation of design. Autodesk Research has been exploring these possibilities for the last decade or more, finding significant potential to apply technology to improve the way things are built and operated. Technologies developed during this time are becoming ready for mainstream adoption, with several vendors providing Digital Twin platforms and others delivering tools enabling Generative Design workflows. Autodesk Research believes that in the longer term, these two areas of technology will converge, closing the loop on the design process and enabling real-world performance to influence many processes that until now have been disconnected from this source of knowledge.

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Chapter 8
Artificial Intelligence and Data in Civil Engineering

Michael Rustell

Abstract Data and artificial intelligence are starting to have an impact on the civil engineering industry. This chapter will provide an overview of data science, artificial intelligence and machine learning and provide practical guidance on how to use these technologies to deliver complex engineering designs. Drawing from the author's experience as a consultant engineer and data scientist, the process of data science is explained in the context of civil engineering and a number of applications are described. Furthermore, a case study on Vessel Impact Analysis for the Thames Tideway Tunnel demonstrates how the design process can be augmented using data science to deliver a complex design using a substantial data model.

Keywords Artificial intelligence · Data science · Civil engineering · Machine learning · Deep learning

1 Introduction

1.1 Background

Civil engineering has evolved considerably during the past 10 years. The advent of high powered and affordable computing, large volumes of data and new algorithms that can capitalise on both has enabled artificial intelligence to start to have an impact on the profession. Most engineering companies are currently in the midst of some kind of digital transformation (Schönbeck et al., 2021) and a growing number of productivity tools that are being adopted are evermore dependent on high volumes of data and some kind of AI to make sense of it all in areas such as automation, risk mitigation, high efficiency, digitalization, and computer vision (Pan and Zhang, 2021a).

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_8

Whilst many of the productivity tools are useful irrespective of profession (such as Teams, Zoom and SharePoint) and scalable from the sole practitioner to the 100,000 employee multinational, there are an increasing number of engineering specific tools being adopted. For instance, existing tools such as CAD/BIM are evolving to include 'smart technologies' such as generative design (Sydora & Stroulia, 2020), automated ideation and optimisation capabilities (Hamidavi et al., 2020) and the incorporation of BIM, machine learning, and other new digital technologies (IOT, digital twin systems, block chain and cloud computing) construction sector is currently being investigated (Su et al., 2021).

There are huge benefits to these technologies, though as those currently leading digital transformation within companies will know—change comes slowly, expensively at first and the biggest hurdle is often getting people to try new working practices. Digital transformation has been accelerated as a response to the global pandemic where engineers are still delivering projects, but through distributed communication models facilitated by virtual meeting software. This would not have been possible 5 or so years ago and how well digital products are integrated into our work and life (Ebekozien & Aigbavboa, 2021).

This chapter will focus on how practicing engineers can harness the power of data and introduce the role of the 'Engineering Data Scientist' who is able to use data and AI to solve engineering challenges. This role has parallels with the 'centaur' concept that is presented in (Debney, 2020), though is more data-centric and focussed on the development of machine learning pipelines.

1.2 What Is Data Science?

Data science involves the systematic study of data structure, characteristics and data analysis. The use of increasingly rich data to depict complex scenarios enables the application of scientific understanding to infer knowledge from data which can then be used to develop actionable insight. Data science was coined 'the sexiest job of the twenty-first century' by Harvard Business Review (Davenport & Patil, 2012) due to the sheer volume of 'raw' data available today and the impact a good data scientist can have by translating this data into business efficiency and new products. Data science draws from several already well-established fields (Fig. 1), though its goals are different to each of them—data science strives to form data-driven beliefs that can be used to guide decision-making.

In general, data science enables us to use data to investigate the world in four distinct ways (Igual & Seguí, 2017).

1. Probing reality—often realised though A/B testing to optimise aspects such as the position/size/colour of a button on a Web page against explicit criteria to maximise the number of clicks.

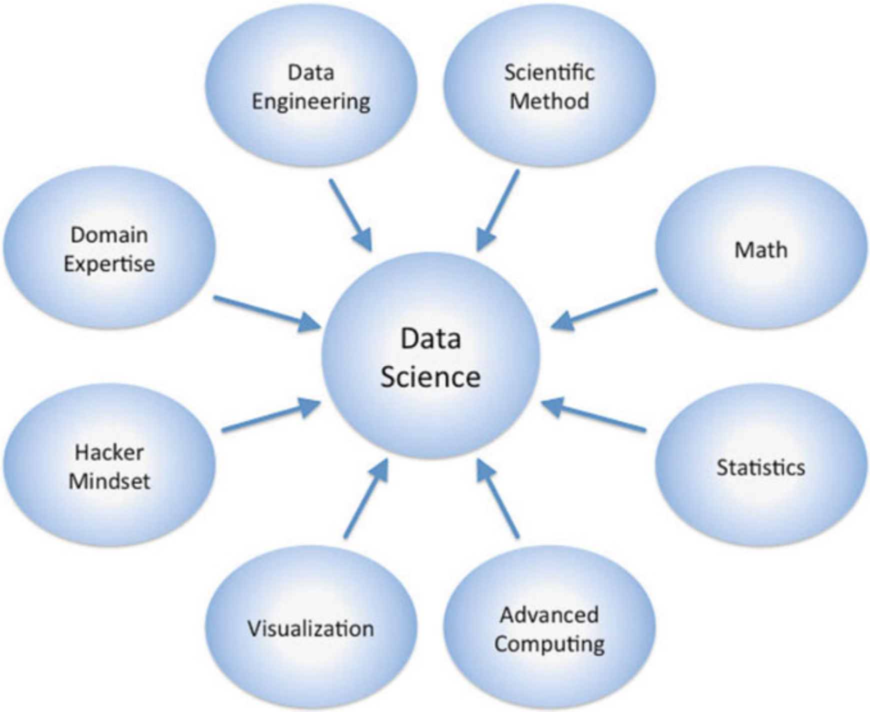


Fig. 1 Data science disciplines. By Calvin.Andrus (own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia commons (https://www.innoarchitech.com/blog/what-is-data-science-does-data-scientist-do)

2. Pattern discovery—Automatic analysis of digitised problems may uncover valuable patterns and natural groupings that can significantly simplify their solutions.
3. Predicting future events—Predictive analytics enable proactive rather than reactive decision-making in the face of future occurrences. For example, by evaluating data such as weather, past sales, traffic conditions and so on, predictive analytics may be used to improve the activities scheduled for retail shop employees over the next week.
4. Understanding people and the world—This is the goal that is now out of reach for the majority of business and individuals, but major corporations and government are pouring money into research in fields like natural language, computer vision and neuroscience. Data science requires a scientific knowledge of these domains, because in order to make the best choices, it is essential to understand the actual mechanisms that drive people's decisions and behaviour.

1.3 The Engineer as a Data Scientist

Most engineers are already doing elements of data science—using spreadsheets, automated calculation templates, dealing with geotechnical or topographical data, time series, etc. The difference between the engineer and data scientist is that the latter will explore the data sets using scientific principles to determine what information it holds and whether models can be developed to approximate relationships whereas the former will likely load the data into engineering software (such as CAD, BIM or an FEA package) which will then perform deterministic calculations to provide design insight.

Many of the early applications of AI were in facility layout problems, i.e. optimise the useable are of the building both for existing and new build facilities using heuristic (Armour & Buffa, 1963; Bazaraa, 1975; Kumara et al., 1987) or quadratic algorithms (Bazaraa, 1975), single objective optimisation algorithms (Goldberg, 1989) and later developing into multi-objective optimisation (Coello Coello, 2002). However, modern applications of AI and data-driven design are generally quite different from those from a decade or so ago—today is the era of data where very advanced machine learning and deep learning frameworks are open source, very high level (i.e. minimal coding is actually required for implementation), well documented, freely available, have large and active online communities and forums and most importantly have undergone extensive development and testing to remove (most of the…) bugs.

Engineers today can easily download comprehensive machine learning tools and apply them to their own data sets. Extensive documentation and examples are available online to provide guidance on not only training specific machine learning algorithms, but also how to structure machine learning projects linking multiple frameworks together, debug code and testing and analysis so that the user can determine the accuracy and suitability of the framework.

Where data science becomes more challenging is domain specific applications. To be successful in solving engineering problems, the data scientist must also be an engineer or to put it another way, the engineer must also be a data scientist. This is extremely challenging as engineers do not typically have the depth of mathematical knowledge (proofs, statistics and multivariable calculus) that one would learn on a physics or computer science course (which many data scientists emerge from), nor established programming skills. This is compounded by the fact that to solve real engineering problems, it usually takes several years working in the role and senior engineers are often less keen to learn entire new technologies and have higher change out rates so the cost to the company is higher. Most engineers who are successfully working as data scientists have invested significant time in their own training such as undertaking an MSc (in math, data or computer science) or a PhD in a technical area which involves more in-depth mathematics and programming. Training can be obtained through online formats such as Coursera, Udemy or DataCamp, which offer hundreds of accessible courses in applied AI and data science. Whilst this does require significant time investment by the engineer (hopefully with the company's

Table 1 Summary of differences between structured and unstructured data

Structured data	Unstructured data
Structured and easily displayed in tables in rows and columns	Cannot be structured into columns and rows as each observation may be unique
Typically dates, numbers and strings	Typically images, videos, emails, documents, satellite data, LiDAR data, drone surveys, audio
Can be interpreted by non-specialists	Needs specialist data skills to interpret and
Less storage required	Requires more storage
Easier to manage and integrate with other tools	Difficult to manage and integrate with other tools
Easier to interpret by machines—works well on many forms of machine learning even with small data volumes	Typically not easily interpreted by conventional machine learning—often requires deep learning and high volumes of data
Estimated to account for 20% of company data	Estimated to account for 80% of company data

support), it is a viable method to learn practical applications through an inexpensive and tailored curriculum.

It requires skill both as an engineer and data scientist to even identify where AI and data can be used effectively in an engineering context; it takes experience to understand which problems are worth solving algorithmically and requires even more experience to ascertain for which problems enough quality data can be procured to justify the development.

2 Data

2.1 Data Types

There are two main classes of data—structured and unstructured. Structured data are that which have patterns that make it easily searchable and standardised and are typically numerical or text-based and could be examined using business intelligence tools without the requirement to write code. Structured data are typically easily wrangled[1] into tables, which make human interpretation and checking of data easy and training machine learning algorithms relatively straight forward. The main differences between structured and unstructured data are summarised in Table 1. Prior to

[1] Data wrangling is the process of manipulating the data so that it complies with a format that is standardised for the machine learning algorithm that has been implemented and can involve simple tasks such as combining multiple data sets and ensuring that column headings are the same and that there are the same number of columns through to manipulations on the data itself such as turning continuous values into discrete ones or dimensionality reduction using techniques such as principal component analysis (PCA) to make the data set smaller and easier to deal with without losing important information.

the era of deep learning (from around 2015), it was estimated that 80% of a data scientists job was data wrangling (Gabernet & Limburn, 2017).

Unstructured data, on the other hand, are essentially all other types of data and include drone video, email, audio, site images, LiDAR, sensors, construction drawings, data from online databases, etc. sometimes originating from networks with complicated connections between its constituents (Dhar, 2013). To analyse this data, increasingly sophisticated and advanced analytical tools and algorithms are required along with the computing resources to run them (Sharma, 2021), which in comparison with earlier methods of data analysis, such as business intelligence or exploratory statistics, this is a significant evolution (Igual & Seguí, 2017). Unstructured data are the most common data type now, equating to around 80% of the global data produced each year (Sharma, 2021). Unstructured data can vary in areas such as length, pixel density, quality and picture size which can make dealing with them much more challenging as almost all conventional machine learning algorithms require structured data, i.e. that each observation has similar characteristics, though deep learning which can train using unstructured data, but this typically needs to be voluminous.

To analyse unstructured data, increasingly sophisticated and advanced analytical tools and algorithms are required along with the computing resources to run them (Sharma, 2021), which in comparison with earlier methods of data analysis, such as business intelligence or exploratory statistics, represents a significant evolution (Igual & Seguí, 2017) (Fig. 2).

As stated earlier, when using deep learning, data preparation is minimised and almost non-existent. However, most engineering applications at present are not based on huge volumes of data and are instead highly specialised and typically with modest data available. This being the case, you will likely need to clear the data, turning it into a 'tidy' structured data set that is conducive to model fitting. This is somewhat of an art form and can only be developed through practice, though there are many

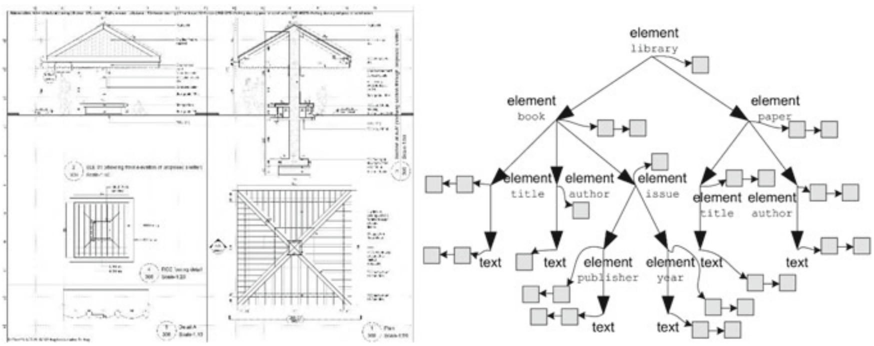


Fig. 2 CAD drawing (left) which is just a graphical representation of an underlying data structure (right). *Source* https://upload.wikimedia.org/wikipedia/commons/6/68/Construction_drawing_autocad.jpg; https://upload.wikimedia.org/wikipedia/en/0/07/Sedna-xml-document-clustered.png. Available through the creative commons licence

good tips in 'the tidyverse' (Wickham et al., 2019) as a philosophy (even if you do not use R it is still worth reading).

2.2 Getting Data

Obtaining data could be a challenge even if a person already owns this information. Most data that an engineering company already owns were not collected with machine learning in mind. The effort required to collate data can be exponentially greater than the highest estimate. Getting enough (similar and relevant) data are the largest challenge that engineering companies face. Data typically are fragmented, stored across multiple geographies, formats, languages, of variable quality from a range of very different projects and full of idiosyncrasy (and errors).

Where data are not tabular (rows and columns) but instead stored in forms and multiple databases and retrieval requires combining multiple processes then a data scientist may be able to develop a standardised pipeline that can automate this complex process.

2.2.1 Free Data

There are many sources of free data—maps are generally free, governments publish national and international data and many companies allow access to data. These can be very useful where they are open source and scrutinised by a developer community. In many cases though, free data does not have the level of validation and verification that is required in engineering projects nor is it specific enough for the engineering project. Aside from data that have been developed at the national level and have been made freely available (environment agency, local councils, governments, NASA, WHO, etc.), there is not much other relevant free data available. Three are some curated image sets that have been collected for machine learning challenges on sites like Kaggle (concrete/steel defects, seismic time series, etc.), though their main use is for engineers to learn data science.

2.2.2 Buying Available Data

Buying data are the tried and tested method that typically results in high quality, project specific and licenced data. There is the added fact that there will be a point of contact to discuss requirements and to query the delivered product. The type of data that can be readily procured is typically high-resolution geospatial data, stock images, bathymetric data, AIS data and time series of winds, waves or seismic activity. The data can be raw or may require some level of processing as part of the delivery and in many cases, the project cannot be accomplished without this data.

2.2.3 Creating Data Cheaply

An often-overlooked method of obtaining data is to create it yourself. An example of a problem where this is useful is for developing surrogate models—i.e. simple models that approximate other more complex models over a restricted domain (typically good for interpolation not extrapolation). Surrogate models can be trained using data derived from finite element analysis, particularly where there are nonlinearities, uncertainties and the design is sensitive to input assumptions. Surrogate models are discussed further in Sect. 4.2.

2.2.4 Acquiring Data Expensively

In many cases, the data that are required for the project does not currently exist and have to be captured. Examples of this include geotechnical site investigations, wave recordings on site, drone surveys, LiDAR, photographs, inspection reports, etc. There is usually a significant cost associated with these data sets, though in most cases, there is no alternative. Most projects require at least some project specific data to be captured and this is often facilitated through companies that specialise in this type of work and are able to advise on sampling strategies, data resolution, cost and help negotiate the contractual terms to ensure that risk is apportioned appropriately (Fig. 3).

Fig. 3 Survey drone with cameras and LiDAR. *Source* https://live.staticflickr.com/851/41994685850_73358db510_b.jpg. Available through the creative commons licence

3 Artificial Intelligence

3.1 Overview

Artificial intelligence is a general term that refers to a computer's ability to reason and make decisions. There are many types of artificial intelligence ranging from models that approximate simple relationships—such as linear regression through to large-scale complex models that mimic natural neural networks such as our brain. All current forms of AI are considered 'weak', i.e. they can solve problems that they are programmed for only—the 'strong' AI which can think for itself, as portrayed in sci-fi has not yet been developed, though this technology may not be around before 2100 (Neubauer, 2021).

Until less than 10 years ago, the majority of developments were in more general areas of machine learning such as algorithms, work flows, languages and environments though the major current developments in AI are largely in the domain of deep learning, where the volume of available data and computing power has facilitated a surge in algorithm development. Deep learning is a sub-domain of artificial neural networks, which is itself a sub-domain of machine learning, which is again a sub-domain of artificial intelligence as shown in Fig. 4.

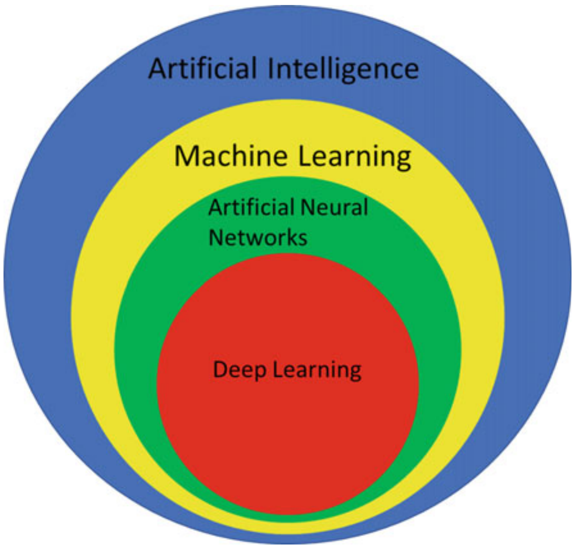


Fig. 4 Artificial intelligence hierarchy

3.2 *Machine Learning*

Machine learning generally aims to mimic the learning processes exhibited by humans to find patterns in data and use this to make predictions when shown new data.

Algorithms generally fall into the following four categories:

- Supervised—provided with inputs and corresponding outputs, the model learns their relationships so that it can make predictions of outputs when shown similar new inputs. Data for supervised learning are referred to as 'labelled data'. Supervised algorithms are trained using data in which there are a number of observations (rows), and for each observation, there are a number of predictors (variables as shown by Xn in Table 2) and one or more output values (shown by Y).
- Unsupervised—finding characteristics in data that differentiate one observation from another or grouping observations which exhibit similar characteristics. Data are referred to as 'unlabelled data' and the majority of data in existence are unlabelled.
- Reinforcement learning—such as for self-driving cars where the algorithm is updated in real-time using a live feed of data so that it can adapt to its environment and make decisions.
- Semi-supervised—the model is shown a small volume of labelled data (supervised learning) and a large volume of unlabelled data (unsupervised learning) so that predictions when shown unlabelled data are improved. This concept sits between supervised and unsupervised learning.

3.2.1 Classification and Regression

There are also two main applications of machine learning which can occur in all of the four categories previously listed:

- Regression—predicting continuous values such as wave heights, material densities or failure loads.
- Classification—determining the class of an observation such as whether a structural member will fail or not (rather than predicting the failure load) or qualitatively determining the structural health of a member from images (poor/moderate/good, etc.).

Table 2 Tabular data format for supervised learning

X_1	X_2	X_3	X_4	Y (output)
1	3	4	1	4
2	2	5	2	6
…				

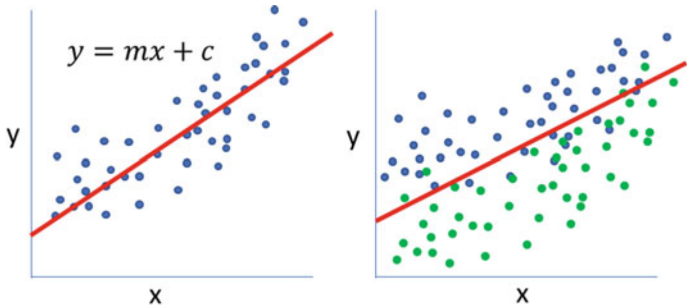


Fig. 5 Regression (left) and classification (right) of a two-dimensional data set

Figure 5 shows both regression and classification of a simple two-dimensional data set. In the case of regression, the line of best fit follows the trend of the data, though there is some error, i.e. points that do not lie directly on the line of best fit and the error is measured based on the average distance from the calculated value. In the case of classification, the line minimises the number of incorrect estimates of class and its accuracy is measured based on how many incorrect classes are estimated over the entire data set.

3.3 Important Machine Learning Algorithms

The following subsections describe important machine learning algorithms.

3.3.1 Linear Regression

Linear regression is a regression model which forms the conceptual basis for many of the more sophisticated algorithms including some deep learning algorithms. Many readers will know this as curve fitting in the form of $Y = MX + C$, where Y is the value that is being predicted, X is the data and M and C are coefficients that are found which minimise the average error in the predictions. This is easily accomplished in MS Excel though as the data becomes higher volume or includes additional dimensions programming languages are required.

Linear regression can be used to predict both scalar and vectors of Y, where in the latter, the data 'X' must be a matrix and 'C' a vector, i.e. $\{Y\} = \{M\}[X] + \{C\}$. Although the name uses the title 'linear', the fitted model may actually use higher order polynomials to find a better fit, though there is still a linear relationship between the inputs and outputs, i.e. $Y = C_0 + C_1X + C_2X^2 + C_3X^3 + \ldots$. This can again be used to predict both scalars and vectors of Y.

Linear regression is highly interpretable, i.e. easy to understand the decision basis it has used, though simplicity means that it cannot adapt to the nuances of the data in the same way a more sophisticated algorithm can, which can lead to a reduced level of prediction accuracy.

3.3.2 Logistic Regression

Logistic regression is actually a classification algorithm which uses an exponential formula to group the data into classes. The formula for the logistic regression model is shown below, which enables the probability of the class of an observation to be predicted based on a number of input variables X, i.e. $X = \{x_1, x_2, x_3, \ldots, x_n\}$, where each x variable is an attribute such as concrete age, original strength, maximum load and exposure. A series of coefficients (β) are found by the logistic regression model which are used to determine the class of the observation, such as (safe/unsafe). The exponent is used so that the predictions are between 1 and 0, with the observation being assigned to class that is most numerically similar.

$$p(x) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n)}}$$

3.3.3 K-Nearest Neighbours

K-nearest neighbours are a supervised learning method that can be used for both regression and classification. It calculates the output based on the outputs of the k-nearest observations (the user specifies k as an integer, an odd number usually up to 7). For regression, takes an average or root mean squared value of the results of the k-nearest training points as shown below:

$$y = \begin{cases} \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n} & \sqrt{x_1^2 + x_2^2 + x_3^2 + \ldots + x_n^2} \end{cases}$$

For classification, the result is the most common (mode) of the k-nearest observations in the training data. As the k-nearest neighbours algorithm needs to check the distance to all training points, it becomes exponentially slower as the training data set increases in volume so is only for reasonably small data sets.

3.3.4 Decision Trees

A decision tree is essentially a flowchart where each stage represents a rule that usually has two outcomes as shown in Fig. 6. In this model, once a terminal (oval) node is reached, this is the answer. Though more conducive to classification, decision trees can also be used for regression where the end nodes represent usually an average value from the training data observations that terminate at each of the terminal nodes.

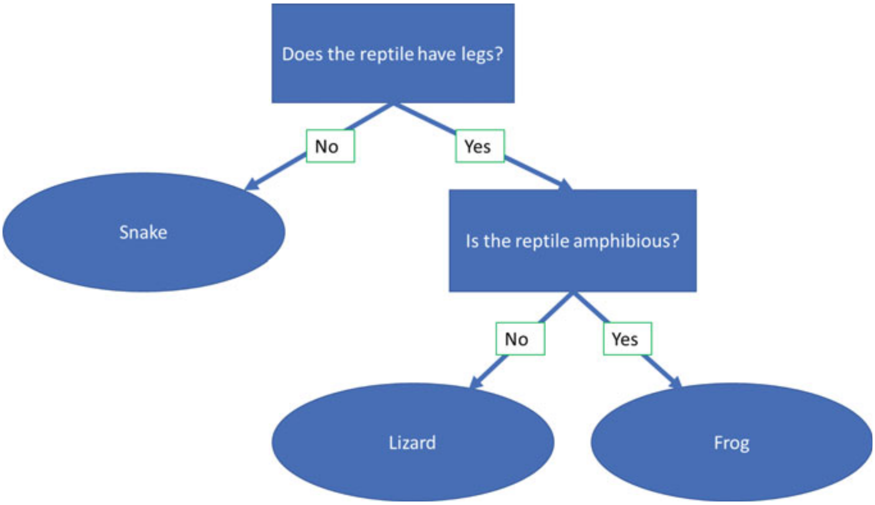


Fig. 6 Decision tree to classify reptiles

Decision trees are prone to overfitting (adapting too well to the training data and not able to generalise and predict on new data) though are highly interpretable (it is easy to understand the structure of the algorithm and how it makes decisions).

3.3.5 Random Forest

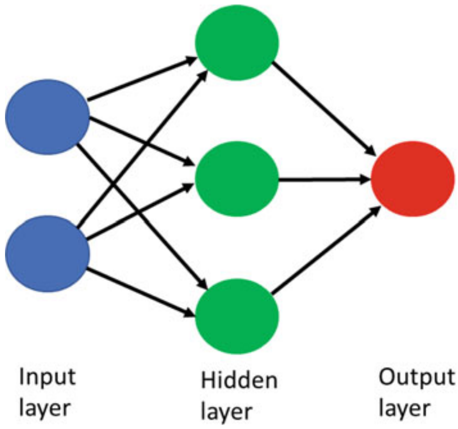
The random forest uses an ensemble of decision trees (i.e. many) where each tree is randomly pruned (restricted in some way) so that it tends to pick up some specific characteristic of the data. This overcomes the main issue of decision trees—overfitting and it is common for a random forest to include 500 trees or more. For regression, the output is the mean of the output estimates of each tree, and for classification, the output is the most common estimate.

3.3.6 Artificial Neural Network

The artificial neural network (ANN) works in a similar manner to how scientists believe the brain works. It uses layers of neurons where each neuron is linked to each neuron in the preceding and proceeding layers. A simple ANN has an input layer, a 'hidden' layer and an output layer as shown in Fig. 7 which depicts a simple 'feedforward' model, i.e. where all information flows from input to output without backward feedback.

ANNs require training in order to determine the optimal weights (coefficients) for each of the nodes in the hidden layer (or layers). These weights allow the model to produce output predictions similar to the training data. To find the weights (and tune

Fig. 7 Simple feedforward neural network



the network), calculus-based methods such as gradient descent are used, whereby minor changes are made to the weight of each node during iterative training cycles until the output error of the network is within acceptable limits.

Initial progress with ANNs was limited due to the size of model that was possible, though nowadays computers are very powerful and good data are freely available due to a global increase in research focus which has spurred recent developments in ANNs particularly in the area of deep learning.

3.3.7 Deep Learning

Deep learning is a sub-domain of machine learning which uses ‘deep’ neural networks, i.e. networks with more than around 10 layers. The additional layers enable specific patterns within the data to be learned—patterns that humans cannot see and patterns that cannot be picked up by other learning models. This is because the number of neurons in a medium deep learning model can surpass 10,000, whilst in a large model, this can surpass 1,000,000. Deep learning requires little to no data preparation, which was generally considered to be the most time-consuming part of using other machine learning algorithms (Fig. 8).

Deep learning, however, requires large volumes of data to train on and performance is correlated with the volume of available training data. Deep learning can learn from labelled data sets (supervised learning) for tasks such as image or sound classification and can also ingest unstructured data (unsupervised learning) to determine which features in different data sets differentiate them from each other, such as being able to find differences and similarities between different musical genres or types of image.

Even in the era of deep learning (where data processing is largely unnecessary), there is likely to still be some processing necessary and interfacing with the algorithm is still required. As it stands, deep learning is not an appropriate technology to derive

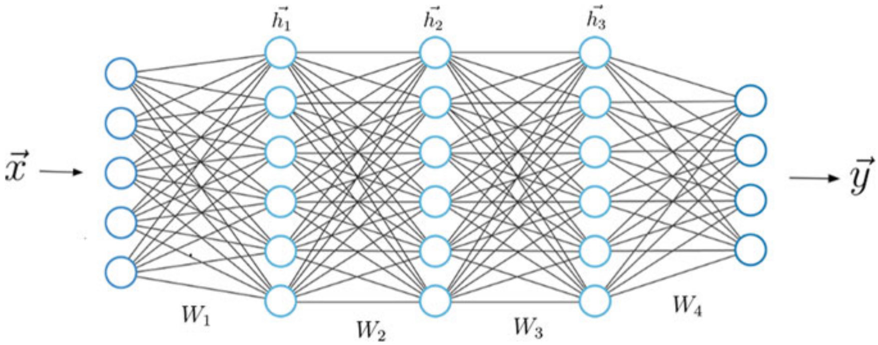


Fig. 8 Deep learning architecture. *Source* https://miro.medium.com/max/1866/0*AONVmd3v4wO_dWr6. Available under the creative commons licence

utility from most data that exists in engineering companies—most of the time there just is not enough relevant data.

Though there are potential uses such as learning design from BIM or DWGs of the previous projects and current projects using computer vision (Lu et al., 2020), deep learning requires many thousands of examples, and companies just do not have thousands of similar projects—how many similar use multi-storey buildings does a company work on per year? Perhaps with the advent of the national digital twin, deep learning will become an essential technology when there is the volume of real-time data to facilitate its use.

3.3.8 Generative Adversarial Networks

Generative adversarial networks are a recent development within deep learning where two networks compete to develop novel solutions to a problem. The first network—the 'generator' develops a data distribution that is similar to the original data distribution and the second network—the 'discriminator' evaluates whether it is being shown a real or simulated data distribution, when the discriminator is fooled, this acts as training data for the generator. The discriminator is trained on subsets of the real-data distribution.

GANs are considered to be the most exciting development in deep learning in the past decade as they are able to develop original artwork in a variety of forms including audio, visual, photo and other kinds of images at a level that can pass for real as shown in Fig. 9. They are also able to transmute one style of art onto another, for instance reproducing the Mona Lisa in the style of van Gogh or applying the jazz music style to classical music. GANs may have future application in generative design within civil engineering though at present there are a limited number of GAN use cases in civil engineering (Pan and Zhang, 2021b).

Fig. 9 Images created using GANs. Oil paint style landscape (left) and young woman's face (right). *Source* https://commons.wikimedia.org/wiki/File:An_example_of_an_AI-generated_Landscape_Painting.jpg and https://commons.wikimedia.org/wiki/File:GAN_deepfake_white_girl.jpg. Available through the creative commons licence

4 Applications of Data Science in Civil Engineering

The civil engineering sector is overcoming the challenges, it has faced in the past, increasing production and overall efficiency due to AI/data science-powered algorithms. Data science has carved out a place for itself in the civil engineering industry by making project development more efficient and cost-effective. The civil construction industry has a net value of more than $10 trillion each year, and data science has played an important role in this area as well. The following list conveys some of the current applications of data science in civil engineering:

- Urban planning, water distribution and sewage system forecasting (Palmitessa et al., 2021; Troutman et al., 2017).
- Risk assessment and mitigation of floods, earthquakes, cyclones and other natural disasters (Luo et al., 2021; Noymanee & Theeramunkong, 2019; Tiwari et al., 2021; Xiong et al., 2021)
- Health monitoring of building's foundation (Mishra, 2021; Ruggieri et al., 2021).
- Smart motorways and highway network planning (Pennetti et al., 2020; Singh et al., 2021).
- Geotechnical engineering simulation and modelling of soil (Jong et al., 2021; Shi & Wang, 2021; Wu et al., 2021).
- Construction planning and management (Amer & Golparvar-Fard, 2021; Amer et al., 2021).

A variety of causes are contributing to the rapid and dynamic transformation of the globe. Data science has taken over all disciplines of engineering, with a particular emphasis on civil engineering. We must be prepared for the next major challenge, which is the automation of the civil engineering sector (Quraishi & Dhapekar, 2021).

4.1 Predictive Maintenance

To enhance the quality of their building operations, construction companies are using deep learning such as drone imagery and LiDAR data for both maintenance surveys and to compare as built drawings with the as built structure. Engineers are also using machine learning to predict MEP maintenance costs (Cheng et al., 2020). A state-of-the-art overview on the topic is provided in Dalzochio et al., (2020).

4.2 Surrogate Modelling

Another practical application would be to train a model to predict how changes in inputs are likely to effect changes in output parameters. In engineering, this is often the purpose of a finite element analysis, though in complex models, particularly when dealing with nonlinearities (and the large number of uncertainties associated in comparison with linear analyses). In this type of analysis, where there are potentially a large number of runs that may be required to fully bound the problem, a multivariate statistical model such as a Latin Hypercube Monte Carlo simulation can be used to generate a number of sample sets from the distributions that represent the inputs. This can then feed into the finite element model and the key results (response variables) can be extracted. Now, a surrogate model is trained to approximate the outputs based on the inputs. The surrogate model is essentially a 'black box' which is trained to learn the relationships between inputs and outputs without needing to learn anything about the actual model. Once the surrogate model is developed with acceptably low error, it can be used in place of the computationally intensive real model to run in a fraction of the time. Critical to the success of the surrogate model is the sampling strategy from the real model as sufficient combinations of inputs must be achieved. The number of runs required is exponentially proportional to the number of inputs and this can easily reach 1000 model runs required, which can far exceed the available computing time, though for complex nonlinear models which may involve fatigue assessment, a surrogate model may facilitate a design optimisation.

The surrogate model itself can be any type of machine learning regression model and its selection is where the skill of the data scientist comes in. Surrogate models have been used in numerous civil engineering applications including seismic engineering of ground tanks (Abbiati et al., 2021), aerodynamic structural optimisation (Ding & Kareem, 2018), alloy beam-column connections (Mohammadi Nia & Moradi, 2021) and the design of caisson foundations (Zhang et al., 2020).

4.3 Design Automation and Parametric Design

Parametric design is essentially automating the design process. This can be as simple as an Excel spreadsheet for a beam design—where the user may only need to change a few parameters in order to check whether the design passes the code check, or it could be a sophisticated computer program that develops a design from a topological surface that is user designed using a simple point and click interface. One of the goals of parametric design is to formulate the design problem as an optimisation problem, typically with more than one objective (such as minimising weight whilst maximising stiffness). Once this problem has been formulated in terms of inputs and outputs, the model is created that maps the inputs to the outputs (such as a finite element model). In sophisticated analyses, it is typical to use a script or programme to automatically modify the input parameters, run the model, extract the objective functions, evaluate them and then modify the input parameters to improve the objective functions. This is usually done a number of times until there are minimal improvements happening or a predetermined number of iterations has been reached. This is optimisation and is a very useful tool. Parametric design and optimisation tools are becoming commonplace in CAD software such as Autodesk Fusion 360, which allows complex models to be developed, parameterised and optimised rather quickly.

4.4 Code-Based Checking

Whilst this is technically possible, AI which is trained to identify code contraventions in design either explicitly—by specifying where the contravention is and what type of contravention it is or implicitly where it realises that the design it is presented is more similar to the training instances that were identified as ‘fail’ rather than ‘pass’, though is unaware exactly the reasons for the contravention. The explicit version is likely to be more useful as it requires less data and also teaches the AI to classify the fault, so that in the future, it is able to say why something is incorrect, though this would place more emphasis on the design codes being built into the algorithm somewhere.

5 Applied Data Science

5.1 Specifying the Problem

Specifying the problem is the process of describing what aspect of the engineering problem must be solved using data science. This requires the engineer to think like a data scientist and dig deep to understand what the problem actually is. The data science problem specification is actually closer to a hypothesis that you will try to prove; something along the lines of: 'Is it possible to train a machine learning algorithm to optimise pipe configurations'. The specification also requires contemplation of what data are necessary—that which are already owned (such as existing pipe network configurations, pipe diameters and unit costs) and that which must be procured, potentially at a cost.

As the engineer thinks through the problem, the data requirements and the wider context of the work, they start to get a feel for the types of solution that may be appropriate—is it regression, classification, reinforcement? What frameworks are they competent in? Have similar problems already been solved? Although you are specifying the problem, part of this is developing a solution approach to help you determine whether this is a problem that is worth solving, or if a solution is even possible.

Engineers are good at problem solving; problems involving data and machine learning as part of the solution are not taught in current curricula, and therefore, most civil engineers are disadvantaged when it comes to

- Being able to represent the problem as decision variables and objective functions
- Developing an algorithm that depicts the solution step by stem
- Formulating the problem as an optimisation task
- Selecting the most appropriate off the shelf algorithm(s) if appropriate
- Integrating the engineering aspects into the framework
- Getting good data
- Assessing the data quality
- Developing the data pipeline
- And most importantly—Validation and verification.

These are tough skills to learn and require mastery of engineering fundamentals as well as enough data science ability to hold it all together. Mastery of the engineering fundamentals really is critical though as in many cases, the engineer will be developing bespoke programmes using fundamental domain knowledge and must be able to validate and verify the solution methodology and outcome. It is common for engineers to take extracurricular courses in data science to obtain these skills.

5.2 Developing the Solution Architecture

Developing the solution architecture is thinking through the problem enough to know what types of solution may work and their time/cost implications. Is it a small, specific problem (development of an engineering tool), large and general (something that can potentially be used on other similar problems), or is it something else entirely?

Data scientists focus on developing the value and information from data and use a wide range of processes to achieve this. This includes

- Preliminary analysis of the data
- Fitting simple models

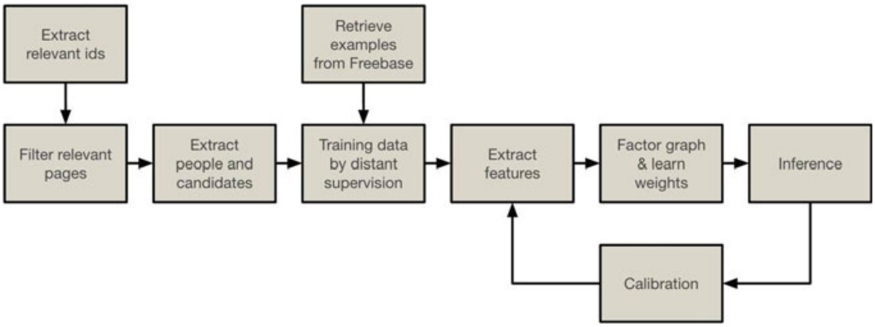


Fig. 10 Data pipeline example showing process from extraction through to inference. *Source* https://upload.wikimedia.org/wikipedia/commons/7/78/Pipeline_research_project_Wikipedia_Knowledge_Graph_with_DeepDive.jpeg. Available through the creative commons licence

- Graphical data exploration
- Training machine learning algorithms
- Developing data pipelines (a pipeline is an automated process from raw data, through processing, machine learning and graphing/reporting)
- Describing what the algorithms are doing to peers and leadership
- Deploying models for use by other within the company or profession.

Developing the architecture may be as simple as ‘we will train several regression models using identical K-fold hold out sets of data and assess them against a final test set to determine which is best. After that, we will select the best model and refine it by tuning the hyperparameters’. Acceptance will be achieved with 95% accuracy on the test set, or it could be a more developed document that solves a much more complex problem, requiring cloud run time for large deep learning models or multiple process as shown in Fig. 10. The scale of the solution will be dictated by the complexity of the problem and that computing and data availability.

One of the greatest risks when innovating is getting something wrong, and not knowing it is wrong. This risk is exacerbated where complex model architectures are developed without commensurate validation and verification, particularly when a simple architecture may be just as good. To quote the ‘Zen of Python’ (Zarzycki, 2018):

> Simple is better than complex.
>
> Complex is better than complicated.

There is always a desire to be cutting edge, particularly in young engineers and it takes experience to determine the minimal amount of complexity necessary to solve the problem. The decision between simple and complex models is usually the trade-off between interpretability and accuracy. Where models become more complex, they are more difficult to explain to other people (particularly if they are not ‘data scientists’ themselves) and to validate and verify. This is OK if the solution needs to be complex (and for all but the most rudimentary problems it usually does), but time is required to build the solution piece by piece and develop testing routines and documentation (this is mostly for the benefit of the programmer). This is both time consuming and expensive, but necessary.

5.3 Training the Models

This stage is essentially where you fit ML models to the data and assess their efficacy. Training predictive algorithms are the process of finding the input parameters that minimise the error in the predictions. In traditional machine learning, the best algorithm may only produce 90% accuracy, though with deep learning (provided there is sufficient data), it is generally quite easy to achieve 99% or higher accuracy (this is because deep learning requires huge volumes of data and complex multi-layer networks which are able to learn the nuances of the data).

During the model training stage, a number of models may be developed, based on the available data, the experience of the practitioner and the type of problem being solved. Part of the training process is tuning the hyperparameters which are algorithm specific parameters which specify key components of the algorithm, such as the number of trees or number of features for splitting in a random forest. Tuning them is the process of optimising the performance of the algorithm and is often more experimental than theoretical.

5.3.1 Training, Validation and Test Data Sets

When developing machine learning models, it is wise to split the available data into three groups:

1. Training—This data are used to train the model and are reused during the training process and can be used for multiple models that are being developed
2. Validation—Once the model is performing well on the training data set, it is used to predict the validation data set which it will not have seen before and therefore will not be biased by it at all. The validation data set should not be used more than once as this can introduce bias into the model. Validation data are often used when comparing multiple models or tuning their hyperparameters.
3. Test—A final data set is used on the final model, i.e. the best performing and optimised one to determine its accuracy.

There are a number of methods that are commonly used to optimise data, one of the most popular is K-fold cross-validation which is a resampling method where the data are partitioned into k subsets (commonly 10) and then the model is trained k times, each time using $k-1$ of the subsets together and validating using the left-over subset. This is done for all combinations, so there is k training and validation cycles. The validation accuracy is then usually the average of the validation accuracies across the k training/validation splits.

5.3.2 Bias and Variance

The predictive accuracy of the model is usually discussed in terms of bias and variance. Bias is how accurate the model is at predicting the training data—if the model is 85% accurate, then its bias is 15%. Variance is the difference between the predictive accuracy on the training data vs the test data—if the model has an accuracy of 82% on the test data, then its variance is $15\% - 18\% = 3\%$. Where a model scores well on the training set, but poorly on the validation set, i.e. has high variance and does not generalise, this is known as 'overfitting'.

5.4 Using Other Peoples Models

Though developing a solution from scratch is a great learning experience, it is time consuming and inefficient if that problem has already been solved. In some cases, the exact problem has already been solved. If it is a mathematical problem or a code routine, then sometimes, it is possible to directly implement this within the solution, though if it is a machine learning problem then data preparation, retraining, testing and deployment will be required. The fact that many codes are open source means that there is some chance that the code has been reviewed already, though this should not be relied on and due diligence is required before implementation. Well written code repositories should come with tests that include expected outcomes for verification purposes.

5.5 Visualisation

> The simple graph has brought more information to the data analyst's mind than any other device.—John Tukey

Visualisation is critical to both conveying the results as well as exploring the data. Good data scientists typically create graphs frequently and during all stages of the analysis, from data extraction through modelling and to plotting of results. It is through visualisation that the analyst becomes acquainted with the patterns of the data and the relationships between the variables and starts to develop an understanding of the quality of the data and the most suitable approaches to modelling.

Plotting data have been refined into an art form, most accurately captured in 'the grammar of graphics' (Wickham, 2016), which describes the process of building graphics using layers and enables high-quality, highly detailed and even interactive plots (if using the interactive Plotly package (Sievert, 2020)).

During plotting, the analyst will aim to explore the how each variable relates to each other variable and there are a number of useful methods of doing so. The scatter plot is probably the most interpretable for comparing one variable against another

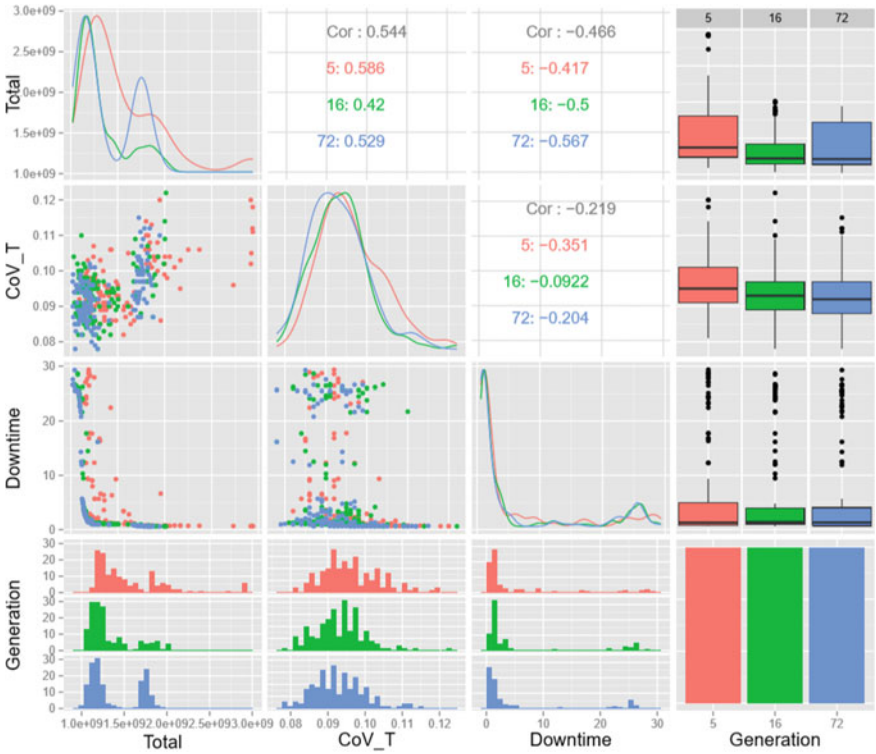


Fig. 11 Compound graphic of the Pareto fronts of generations 5 (red), 16 (green) and 72 (blue) of the runs of a genetic algorithm to show the improvement in successive populations. Including density plots, correlation matrices, boxplots, scatter graphs, histograms and a barplot for each combination of the three objectives. *Source* Rustell (2016)

(2-dimensional) and can easily be extended to higher dimensions through pair-wise plots. An example of this is shown in Fig. 11, which compares three-generations of data developed using a genetic algorithm of a three-dimensional data set to show both the interaction of the variables as well as how the algorithm is improving the population of results through the generations.

5.6 Validation

Validation is one of the two most important aspects of machine learning for engineers (the other is verification, see below). Validation is the process of developing the correct conceptual approach to solve the problem. Much of validation should be undertaken without any actual development.

Whilst developing a validation strategy, it is not uncommon to realise that machine learning is either not necessary or the 'best' algorithm is something simpler than you hoped for. Consider this a small victory, if you arrive at this conclusion.

5.7 Verification

Verification is the process of checking that what comes out of your model is correct. In both Python and R, there are packages developed for verification purposes and to help you develop tests to ensure your code works as it should such as 'testthat' (Wickham, 2011). These tests should be run frequently to ensure that all processes are working as expected and this is especially true when you have been developing as there are sometimes unexpected conflicts caused with changes.

6 Practical Guidance

Though there is realisation in the industry that data and AI are part of the solution, developing viable products that solve engineering problems is challenging. Part of this is that any new product requires inputs—time, money, etc., and also requires the necessary skills in order to understand the problems and deliver the solution. Whilst data scientists can develop tools that solve complex problems, most applications do not amount to a step change—rather an incremental one where there is some time saving or added accuracy gained. It is true that there are some things that cannot be done any other way—though to develop miraculous applications, be prepared to put in the time up front—mostly in getting enough good data.

There are many things that can go wrong, too many to list in fact, though some of the most common ones are

- Not getting enough data
- Not getting quality data
- Not knowing you have bad data
- Lack of experience in specifying data requirements
- Lack of machine learning ability or experience
- Lack of programming skills
- Lack of familiarity with machine learning frameworks
- Not being able to frame the engineering problem as a machine learning/data science problem
- Assuming you will be able to solve the problem using machine learning/data science
- Not having other engineers who understand the technology enough to challenge your decisions and validate your work
- Not developing sufficient documentation.

Getting good and quality data are the most important item—data science skill can be hired or developed, but if the data are bad then even the best model is still going to produce unreliable results.

6.1 Developing Data Skills

Developing data skills take time, and in most cases, the skills are quite far outside of those encountered during engineering education and working as an engineer. Sadly, there is no magic bullet and time investment is required. Fortunately, there are many high-quality courses available from some of the world's most respected practitioners and universities in places such as Coursera and Udemy. It is possible to get real-data skills in a relatively short time frame (months), and ideally, some of this occurs during work time with employers recognising the value of the skill set. Companies that invest in their people usually do better in the long run, though not all companies have the luxury of playing the long game when managers are more concerned with more pressing issues such as winning work and retaining staff.

6.2 When not to Do Data Science

Although the author advocates for data science in civil engineering, sometimes the best data science is no data science—or at least no machine learning. Data science, machine learning and artificial intelligence are hot topics and everyone wants to do it. Remember that these are just tools, and they are the best tools for some jobs, but not the best tools for all jobs. Throwing machine learning at a problem is likely to make the problem worse, not better if its limitations, applications and methods are not fully understood.

The worst kind of mistake is the one that goes undiscovered. Unfortunately, when doing data science, where you may be using many packages or libraries and data sources and multiple programming languages, there are many opportunities for errors to creep in. This is why debugging and verification are a critical component of the process.

In many cases, the addition of machine learning is not necessary and can create false confidence as engineers deal with technologies that are not fully understood. Machine learning should be used sparingly and in ways that are testable and verifiable. After all, people's lives may ultimately rely on the assumptions that are made when developing such a model.

6.3 Biggest Value Projects

In the grand scheme of things, a civil engineering company is just another large company, facing the same challenges as another company in another field. Some of the biggest opportunities for data science in a company are generic to most companies—these include staff engagement and retention, bidding and winning work, standardisation of solutions and documents, harnessing individuality, improving delivery of products, optimising workflows, reducing errors, etc.

In order to get traction in a company and raise interest in digital technologies, a high-profile flagship project can be useful. Whilst these projects are typically more hype than substance, they can work well for both internal and external marketing and for getting colleagues and employees excited about the possibilities. A well-executed and simple but effective AI project can inspire others whilst also giving executives something to shout about. The key here is to solve a known problem on a limited domain with a tangible output that can be measured and compared to the previous way.

There are countless large 'generic' problems that have been solved and for which there are open-source code available—often in the form of descriptive notebooks in popular languages such as R and Python. Many of these models can feasibly be applied to the medium to large engineering company with comparatively little effort, and in most cases, metrics to determine the accuracy and error in the models are included in the pre-developed pipelines. The benefit of this approach is that the groundwork has been done for you, though it is rarely a drag and drop implementation—there is always a lot of work to do, particularly in getting and preparing data, though these readily available models can save months of development time.

6.4 When to Ask for Outside Help

The reality is that only the largest engineering companies are likely to have significant and dedicated fulltime data scientists available as members of staff and even then, this is likely to be a small centralised team who do not necessarily have a civil engineering background. A single data scientist if implemented properly can have a significant impact on a company, though for larger projects, it may still be necessary to call for outside help.

When dealing with external data science consultants, it is critical that the engineering problem is fully understood by all parties and that sufficient data are captured to enable a solution to be developed. Whilst data augmentation can be used to boost the training data, this is not a substitute for getting enough data. The initial discussions should focus on the data capture strategy to determine whether it is possible to capture enough data for a price that makes sense. If some data, even if it is not the 'real' data can be shown, then this can enable the data scientists to start to think about algorithms and frameworks, which can inform how much data may need to be captured.

7 Case Study—Accidental Vessel Impact for Thames Tideway Tunnel

Thames Tideway Tunnel is an under-construction 25 km tunnel running under the River Thames through central London connecting the 34 most polluting sewer outflows and diverting nearly all of the 39 million tonnes of sewage previously discharged into the river to Beckton Sewage Treatment Works. The author was part of the consortium designing and constructing the central tunnel section, which included foreshore structures on the river embankment at eight sites: Falconbrook pumping station, Cremorne Wharf, Chelsea Embankment, Kirtling Street (main tunnel site), Heathwall pumping station, Albert Embankment, Victoria Embankment and Blackfriars Bridge as shown in Fig. 12.

Situated in an active shipping channel, accidental impact from a passing vessel represents a critical design case for the foreshore structures that protect the tunnel shafts (Fig. 13). As a vessel approaches a structure, there is a small probability that it will become aberrant due to three identified failure modes—human error, steering/helmsman failure or propeller failure, each with their own probability of occurrence. Though the probability of any vessel becoming aberrant and impacting

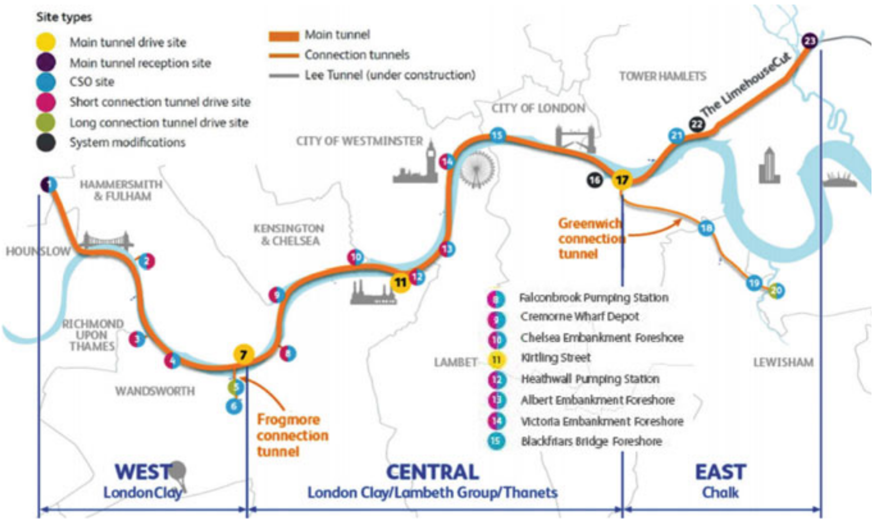


Fig. 12 Diagram of the main tunnel sections indicating the eight foreshore sites in the central section. *Source* https://commons.wikimedia.org/wiki/File:Thames_Tideway_Tunnel_proposed_route_and_sites.jpg. Available through the creative commons licence

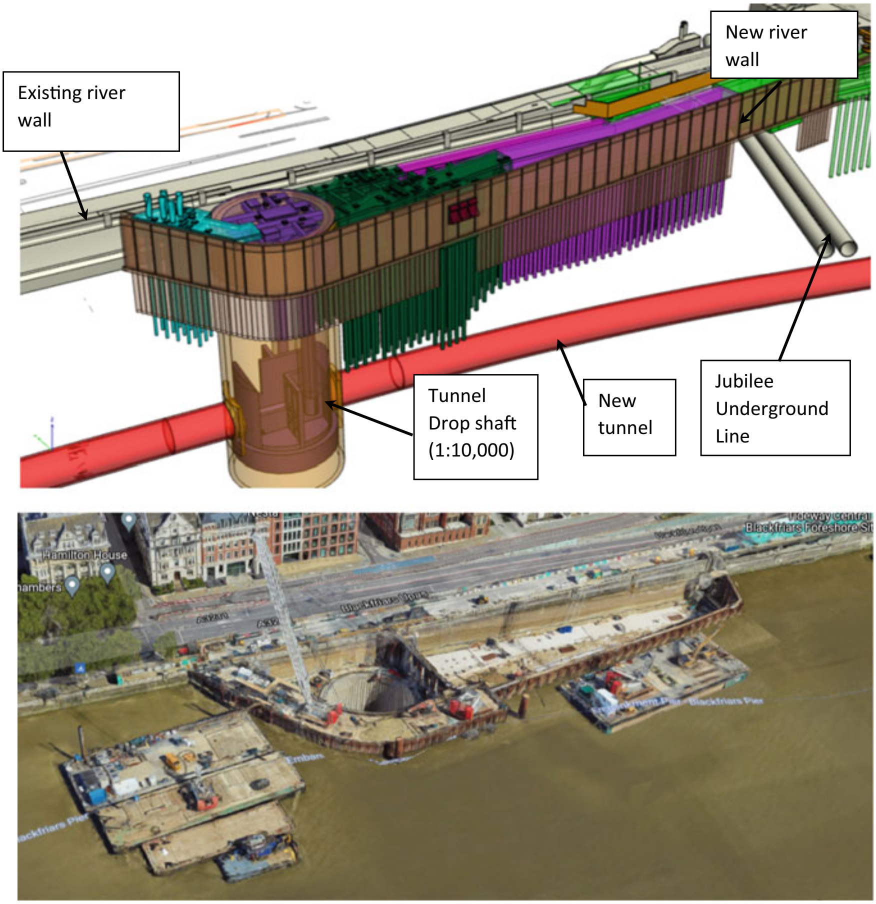


Fig. 13 3D model of Blackfriars foreshore structure, tunnel drop shaft and existing river wall (top). Google Map image of Blackfriars Bridge Foreshore in construction (bottom). *Source* Google Maps

a foreshore structure is small, when considered over the 3 million vessel passages predicted to pass the structures during the 120-year design life, the probability of impact increases substantially due to the cumulative risk of the individual events.

The implementation of data science methods on this project had the following impacts on the project:

- AIS data captured hundreds of thousands of vessel movements by hundreds of vessels across the eight sites;
- Characteristic vessels were easily developed using statistical methods which sped up computing time;
- The entire population of vessels was analysed at discrete time steps;
- Significant time saving on finding vessel data such as draught and beam length from online databases for hundreds of vessels;

- The integration of all the impact events across all vessel types at each site for both upstream and downstream travel;
- Visual plotting of results and vessel paths as part of verification;
- Ruling out of some of the very large aggregate barges as they had a much higher than 10,000-year return period for impact;
- Significant reduction from the deterministic design impact forces at most sites due to probabilistic approach.
- Significant cost saving in materials and construction time due to member design using reduced loads.

7.1 Project Aim

The aim of the accidental vessel impact study was to develop a data-driven, fully probabilistic approach to vessel impact in order to provide a rigorous basis from which 1:1000-year and 1:10,000-year return period design forces and guidance for their application could be derived. For this, site data on the specific vessels that pass each site with information such as their displacement, travelling speed, distance from the river centreline (i.e. how close the embankments they travel), draught, beam and length would be required; bathymetric surveys and the coordinates of the outer walls of the structure as well as the importance of the specific sections of wall (and whether they would be designed for 1:1000-year or 1:10,000 year return period forces) were also necessary (Fig. 14). With this information, a fully probabilistic data model could be developed which could simulate vessels passing each structure in both directions of travel and determine both the likelihood of impact as well as the impact force associated with the impact and the area and height of the impact as determined by BS EN 1991-1-7:2006 for each specific structural zone in each structure. With this information, the 1:1000-year and 1:10,000-year design forces could be calculated by multiplying the probability of impact of a single vessel passage by the number of passages expected over the 120-year design life and then ordering the forces by magnitude and calculating the cumulative probability.

7.2 Data

For the study, automatic identification system (AIS)[2] data were recorded between the 1st July 2014 and the 31st August 2014 at three locations per site—100 m upstream, at the site and 100 m downstream. This resulted in between 3000 and 30,000 observations at each of the three locations at each site, totalling around 350,000 observations. As the data were only captured for 2 months during the summer (where there are the

[2] Automatic identification system (AIS) is a technology that is required for all vessels over 500t DWT, though is included in many smaller than this, particularly in busy waterways. AIS allows the vessel data such as speed, location and heading to be recorded.

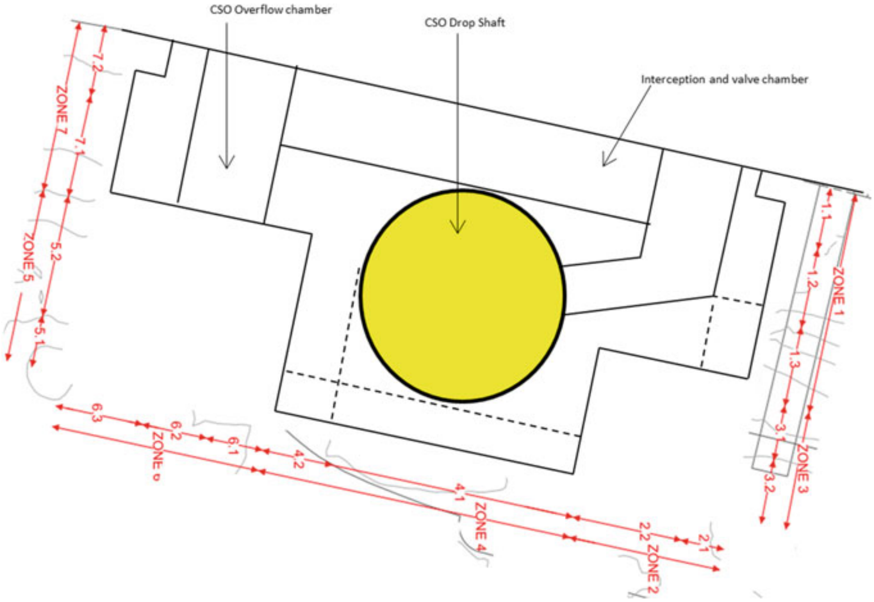


Fig. 14 Zoning at Victoria Embankment

most journeys), the multiplication factors shown in Table 3 were used for seasonal vessels. This factor is not applied to tug trains or cargo vessels. Characteristic speeds were derived as the average of the highest one third of recorded speeds for each vessel

Table 3 Monthly multiplier to estimate vessel transit volumes for months without AIS records

Month	Multiplier to apply to summer volume to account for seasonal variation in vessel volumes (%)
Jan	40
Feb	40
Mar	50
Apr	60
May	60
Jun	100
Jul	100
Aug	100
Sep	100
Oct	60
Nov	50
Dec	40

to reduce the influence of sampling error and to capture a realistic design speed for each vessel.

AIS typically does not record vessel draught, beam and length. To obtain these, a Web-scraping script was written using the rvest package (Wickham, 2021) to pull vessel parameters such as laden and unladen mass, draught, length and beam as well as the image of the vessel from an online vessel database, using the vessel names from the AIS data as the key. Using the image, each vessel was classified as 'inland' or 'sea-going' based on engineering judgement (only large aggregate carriers were classed as 'sea-going' based on their stiffened hull) so that the correct Eurocode equation system is applied (sea-going vessels are much stiffer and typically deliver a higher impact force). Both methods are fundamentally derived from the kinetic energy equation:

$$E = \frac{1}{2} m v^2$$

Vessels were also determined as either laden and unladen (which affects the displacement and draught) depending on the direction of travel and the AIS data indicated higher velocities depending on the direction of travel, which when corrected for current speed, indicated that higher velocities were correlated with unladen vessels. Table 4 provides a sample of some of the characteristic vessel classes that were identified from the AIS data.

7.3 Vessel Aberrancy

Once a vessel becomes aberrant (due to human error, steering/helmsman failure or propeller failure, each with their own probability of occurrence), it is most likely to maintain its heading, though it could veer off course. An earlier study indicated that aberrance angles between −35° and +35° are possible and the probabilities can be determined using a normal distribution (0° having the highest probabilities and −35° and +35° reducing to zero) as shown in Fig. 15.

The total probability of a vessel impact at any time is calculated as the sum of the probability of impact of the three individual failure modes with as they pass the structure as shown in the equation below which is integrated with respect to time t and impact angle θ:

$$P(i) = \int_{0}^{t} \int_{-\theta}^{+\theta} \left(p_f(h) + p_f(s) + p_f(p)^* \right) p_{nf} \cdot t_s \cdot d\theta \cdot dt$$

where

Table 4 Sample characteristic vessels used in the fully probabilistic impact analysis, derived from AIS data and Web-scraping

Vessel	Direction	V (m/s)	Displacement (Tonne)	Daily movements	Length (m)	Propeller failure possible?	Sea-going?	Draught (m)
Aggregate carrier	Upstream	5	2000	0.71	55.5	TRUE	TRUE	4
	Downstream	7.6	600					2.75
Large tug	Downstream	5.04	568	0.48	120	TRUE	FALSE	2.5
	Upstream	4.68	1568					3.5
Medium tug	Downstream	5.1	500	2.20	60	TRUE	FALSE	2.5
	Upstream	5.2	500					2.5
Medium passenger 300 t	Downstream	6	300	6.58	50	TRUE	FALSE	2
	Upstream	6	300					2
Large passenger 900 t	Downstream	4.7	900	2.74	60	TRUE	FALSE	2.5
	Upstream	6	900					2.5
Tug + Barges 1500 t	Downstream	4	1545	6.00	100	TRUE	FALSE	2.5
	Upstream	5.5	545					2
Construction barge 1500 t	Downstream	4	2363	3.20	80	TRUE	FALSE	2.5
	Upstream	5.5	863					2
Construction barge 1000 t	Downstream	4	1545	2.00	100	TRUE	FALSE	2.5
	Upstream	5.5	545					2
Waste tug + 2 barges 1765 t	Downstream	4	1765	0.50	100	TRUE	FALSE	2
	Upstream	5.5	669					2.5
Waste tug + 3 barges 2180 t	Downstream	4	2180	1.00	145	TRUE	FALSE	2
	Upstream	5.5	680					2.5
Thames clipper	Downstream	8.2	80	48.28	39	TRUE	FALSE	1.3

(continued)

Table 4 (continued)

Vessel	Direction	V (m/s)	Displacement (Tonne)	Daily movements	Length (m)	Propeller failure possible?	Sea-going?	Draught (m)
	Upstream	8.2	80					1.3

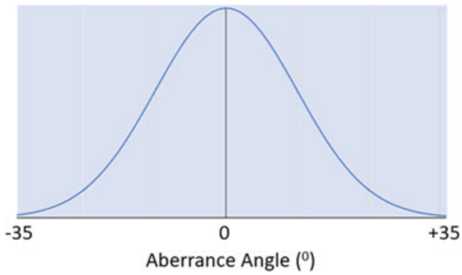


Fig. 15 Probability density function of aberrance angle

Fig. 16 Screenshots at 40 s intervals of potential aberrance angles that would lead to impact with the structure. The green line represents the vessel travel path

$p_f(h)$, $p_f(s)$, $p_f(p)$ are failure probabilities for helmsman, steering and propeller failure.
p_{nf} is the probability of correction.
t_s (s) is the time step.

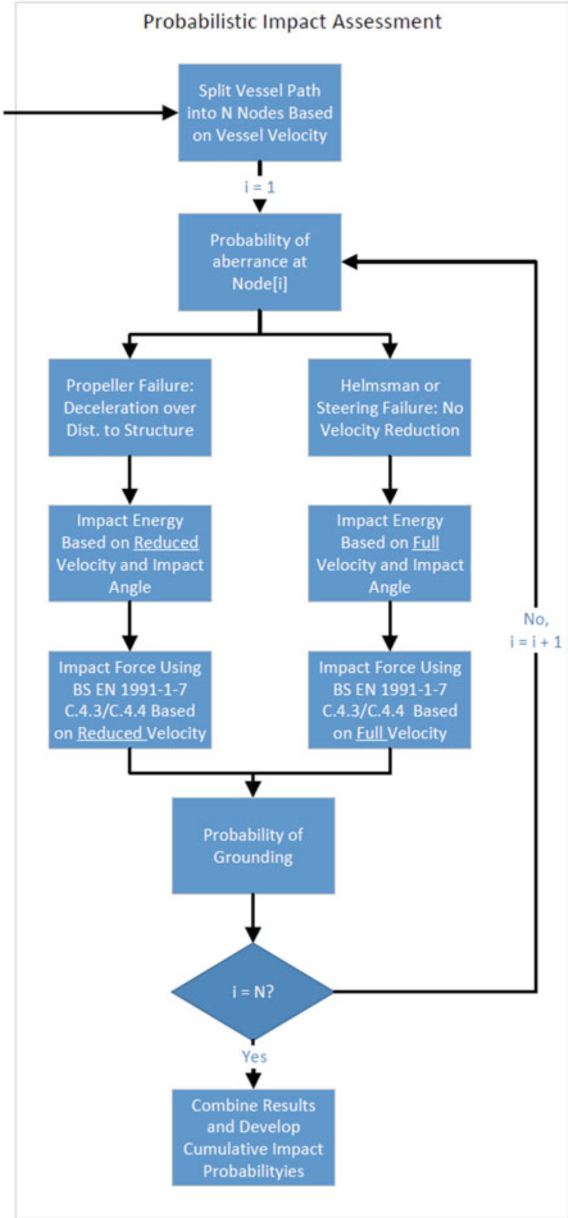
To illustrate this, Fig. 16 shows a vessel approaching and passing Blackfriars Bridge at 40 s-time intervals, indicating the change in the probability of impact at each time step as indicated by the area of the shaded area in the PDF in each step. As the vessel approaches the structure and passes it, the probability of impact is a function of both the range of aberrance angles that would result in impact and the distance to impact (for propeller failure, the vessel is assumed to slow to current speed over a distance of 8 * LOA (length overall)).

7.4 Model Overview

No model existed for this type of analysis, therefore it was necessary to first develop the conceptual framework before writing the computer code in the statistical language R. Figure 17 provides an overview of the framework, indicating the key stages which are undertaken for a single vessel passing the structure.

The fully probabilistic impact assessment allows a reduction in impact velocity when propeller failure is the failure mechanism as the vessel slows down. This is in

Fig. 17 Probabilistic impact assessment algorithm based on a reduced impact velocity and interpolate between



accordance with BS EN 1991-1-7:2006 + A1:2014 clauses C4.3 (5) (inland vessels) and C.4.4 (2) (sea-going vessels) and the employers requirements which allow a reduction in impact force based on post-aberrancy reduction in velocity in the case of engine (propeller) failure. A corresponding modification in impact probability is also calculated based on the increased time to correct course. From this, the cumulative probability of all impact events throughout the entire range of characteristic vessels and discrete impact events at each node of the analysis can be used to calculate the 1:10,000 and 1:1000-year events statistically over the entire vessel population.

The model also includes a grounding analysis based on laden and unladed states and has been performed at each site which has included an additional 0.75 m subtracted from the foreshore levels to account for reliability of bathymetric data and additional depth for the vessel energy to be dissipated through the river bed prior to impact. The tide height is based on a sinusoidal function between MLW and MHW which is then combined with the vessel draught to determine whether the vessel will ground prior to impact. Tug and barges are assumed to travel at high tide only; therefore, no grounding analysis was included on these vessels.

7.5 Modelling Assumptions

The following assumptions were made for the analysis:

1. Large vessels and tugs travel down the centre of the river—this is based on analysis of the AIS data.
2. The characteristic vessel speed is taken as the average of the highest third of all recorded speeds for that vessel
3. The analysis is performed at discrete locations based on the vessel speed and time step which is typically 5 s (1 s has been used for the clipper passing BLABF in the upstream direction as the exposure window is short).
4. For the propeller failure mode, the vessel is assumed to slow down to ambient current speed over a distance of 8 × LOA in a still river. With current action taken into consideration, the stopping distance increases. The probability of correction for this failure mode is calculated taking this extension of time into account.
5. Allowance has been made for bridges which are considered to be permanent structures, whereas in river assets such as piers and jetty have been considered as temporary structures and have not been considered.
6. Hydrodynamic mass coefficients of 1.1 and 1.4 have been used for frontal and lateral loads, respectively, when using the Inland Waterway equations, as per EC 1-7:2006 (C.4.3(2)) and are already included in the loads stated.
7. No dynamic factors have been added to the loads. Eurocode 1-7:2006 (C.4.3) suggests 1.3 and 1.7 for frontal and lateral impacts, respectively, where no specific site data are available. These dynamic factors should be applied to the

Table 5 Discrete impact events for each structural zone

Structure	Zone	Energy (MJ)	Angle (°)	Type	Hydrodynamic coefficient	Probability
Blackfriars	1	3.4	24	Inland	1.1	3×10^{-7}
Blackfriars	4	2.1	3	Inland	1.1	2.4×10^{-6}
Victoria	1	1.9	56	Sea-going	1.4	5.6×10^{-8}
Victoria	1	2.1	45	Inland	1.4	3.2×10^{-8}
…						

design forces for each site in lieu of a full dynamic interaction model being set up and analysed for each site.

8. The impact forces are based on 'hard impact', i.e. all displacement is assumed to occur in the incumbent vessel with the structure remaining static during impact.

7.6 Applied Data Science

Using the model, each of the characteristic vessels were simulated passing each structure at its characteristic speed, for both upstream and downstream travel. The probability of impact to each structure zone in each time step was captured. This provided data in the form in Table 5, which also includes the impact angle which is necessary for determining whether the impact is frontal or lateral, which affects the hydrodynamic coefficients.

Once all vessel types had been run, all results were grouped by structure and zone using tidyverse workflows (Wickham et al., 2019). This included both upstream and downstream travel. The individual probabilities were then multiplied by the estimated number of journeys for the vessel type at year 120 of the design life and the hydrodynamic coefficient (1.1 for frontal impact and 1.4 for lateral impact as per BS EN 1991-7) as shown in Table 5.

The data were then split by structure and then by zone and the forces were then calculated using the applicable BS EN 1991-7 equation (for inland or sea-going vessels) using the respective hydrodynamic coefficient to calculate the impact force. The impact events were ordered by magnitude of force.

So that the probability of impact at a single structure was not underestimated (as would be if considering each zone to be independent of the others), the probabilities were normalised by the overall probability of any zone being impacted in each structure which essentially scaled up the individual probabilities in each zone.

The cumulative probability of impact was then calculated as shown in Table 6, which shows a representative single zone of one of the foreshore structures. Each structure had one cumulative impact table created per zone so that the design forces could be estimated for the 1:1000 and 1:10,000 year return period design events. This results in a cumulative impact probability curve from which the 1:1000-year and 1:10,000-year design forces were easily obtained (Fig. 18) for the purpose of

Table 6 Impact force and cumulative probability

Force (MN)	Probability	Cumulative probability	RP (Yr)
1	0.00003	0.00003	33,333
1.5	0.00004	0.00007	14,286
2	0.00003	0.0001	10,000
2.3	0.000035	0.000135	7408
2.5	0.00005	0.000185	5406
2.8	0.00009	0.000275	3637
3	0.00008	0.000355	2817
3.1	0.00055	0.000905	1105
3.2	0.00009	0.000995	1005
3.3	0.000035	0.00103	971

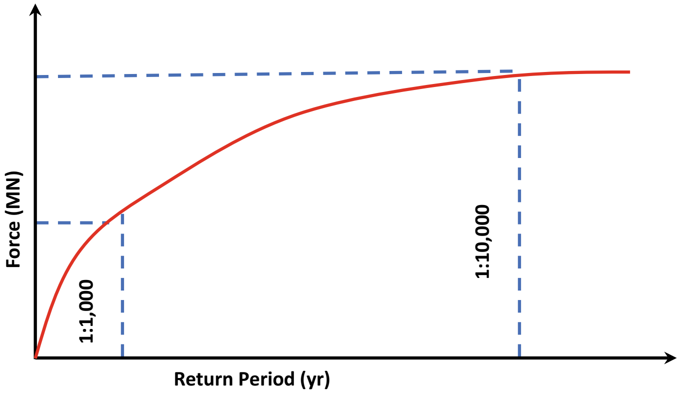


Fig. 18 Cumulative impact force return period over the entire population of vessels

detailed design of the individual zones in each structure, some of which were required for 1:1000 year RP events and other for 1:10,000 year RP events.

8 Conclusions

This chapter has focussed on providing an overview to the method of data science in the civil engineering discipline, drawing from the experience of the author. There are currently many niche applications of AI and machine learning in practically all sectors. In time, it may be common for young engineers to implement AI frameworks to solve various engineering problems as the technology becomes more firmly rooted in the engineering office. However, wider sector culture change represents a significant short-term challenge as does developing data skills and the technologies and frameworks that will be necessary and finally, learning to trust in these new methods which may appear to pull answers from thin air in some cases.

The implementation of data science techniques ultimately comes down to engineers developing entirely new skillsets which are currently taught on computer science courses. This can be achieved though completion of online courses, though presently, none of the applications are focussed on civil engineering problems—engineers will need to figure out how to apply these new technologies on projects.

Ultimately, there are many potential applications for AI in the profession and it is likely that in the coming decades, AI will become more ingrained in engineering working practice, helping us to deliver better, safer and more efficient designs.

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Chapter 9
Potential Application of Blockchain Technology to Transform the Construction Industry

Navodana Rodrigo, S. Perera, Sepani Senaratne, and Xiao-Hua (Sean) Jin

Abstract Blockchain was introduced as a digital currency management technology, which has disrupted various industries within the last decade. It contains a decentralised distributed ledger that is updated, shared and managed through a peer-to-peer network, hashing algorithm, public-key cryptography and consensus mechanism. The salient features of blockchain, decentralisation, anonymity, security, immutability amongst others, influence various industries to adopt blockchain. This chapter explores the potential application of blockchain in the construction industry. The construction industry is often critiqued due to its disaggregated structure, sequential nature of works, lengthy supply chains and involvement of multiple stakeholders. Blockchain technology due to its salient features has the potential to resolve these issues by automating manual processes, providing a platform that tracks and monitors transactions and creating a secure and reliable infrastructure that increases trust and transparency. As an emerging disruptive technology, blockchain has the ability to transform the construction industry through improvements in various aspects related to construction supply chains, property transactions, payments, certification and quality assurance amongst others. RxEAL and LandBlocks are a few of the blockchain-based prototype systems introduced in construction. Blockchain contributes to sustainable construction whilst assisting to achieve the United Nations sustainable development goals. Blockchain is already disrupting many other sectors of the economy and is not far from disrupting the construction industry, for which, the stakeholders should be prepared to boldly embrace and exploit this emerging technology well in advance.

Keywords Blockchain · Construction industry · Features of blockchain · Blockchain architecture · Applications

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_9

1 Introduction

Blockchain is an emerging technology that disrupts and evolves information technology with a wide range of applications in various industries (Erol et al., 2020; Risius & Spohrer, 2017). Blockchain comprises a decentralised distributed ledger, which could be shared between all participants (nodes) and the transactions could be easily traced with the assistance of the blockchain network (Wouda & Opdenakker, 2019). The immutable nature of information stored on a blockchain allows maintaining consistency of records, auditable information trails, efficient tracking exchanges of value, improved security and trust (Bag et al., 2020; George et al., 2019). Compared to a traditional information system, a blockchain application stands out due to its salient features such as decentralisation, anonymity, security, immutability amongst others (Rodrigo et al., 2020) as well as blockchain's unique verification and validation process on recording transactions (Gaur, 2020).

Blockchain as a technology evolved from the first introduction of cryptocurrency, bitcoin in 2008 by the group, Satoshi Nakamoto (Nomura Research Institute, 2016). Blockchain was first used in cryptocurrencies then came to be known as Blockchain 1.0 that securely validates and stores information of transactions (Dimitri, 2017). Subsequently, blockchain applications that started to be implemented into economic and financial applications related to stocks, bonds, smart contracts amongst others were termed Blockchain 2.0. The evolution of blockchain applications in other economic sectors such as health, science, art, culture and so forth is called Blockchain 3.0 (Swan, 2015). The numerous benefits of blockchain have resulted in industries exploring its potential applicability. The construction industry has been historically reported as the second least digitalised industry (Agarwal et al., 2016) traditionally lagging behind other sectors. A recent study conducted by Perera et al. (2021a) identified that 57% of the builders and 48% of the designers in NSW are in the state of a basic level of digital maturity, whilst 38% builders and 45% designers are at the advanced level of digitalisation. With the onset of the fourth industrial revolution, the industry is under significant pressure to modernise and deliver greater economy and efficiency (Alaloul et al., 2020). Blockchain technology provides the basic infrastructure necessary for the advancement of procurement processes in construction (Perera et al., 2021b), thus paving the pathway for greater digitalisation of the construction industry. This chapter explores the potential application of blockchain technology to transform the construction industry.

The chapter focusses on elaborating the fundamentals of blockchain technology and exploring blockchain applications in general and specifically related to the construction industry. Section 2 highlights the key elements of blockchain technology; peer-to-peer network, hashing algorithm, public-key cryptography, consensus mechanism and the overall blockchain architecture. The salient features of blockchain are discussed in Sect. 3. There are three main types of blockchain; public, private and consortium, which are explored in Sect. 4. Section 5 reviews the most popular blockchain platforms, which are used in developing various blockchain applications. Subsequently in Sect. 6, the blockchain applications related to Blockchain

1.0 (cryptocurrencies), Blockchain 2.0 (financial applications) and Blockchain 3.0 (applications in other industries) are discussed in detail identifying the currently available use cases in the market. Section 7 analyses the potential applicability of blockchain technology in the construction industry, whilst Sect. 8 explores the blockchain applications in sustainability identifying the ongoing and potential use cases. Section 9 summarises the key points discussed in the chapter.

2 Fundamentals of Blockchain Technology

Blockchain enables digital transactions of assets in a decentralised network without the intervention of any intermediaries (Monrat et al., 2019). A decentralised, distributed and shared database or ledger are provided in blockchain, where data are allowed to be inserted only without updating or deleting existing data preventing tampering and revision (Xu et al., 2019). Blockchain technology consists of several fundamental concepts such as peer-to-peer network, hashing algorithm, public-key cryptography, consensus mechanism and blockchain architecture that enable the transactions to be recorded on the blockchain.

2.1 Peer-to-Peer Network

Satoshi Nakamoto introduced the first peer-to-peer electronic cash system named bitcoin, which enabled direct online payments without the involvement of a third party (Nakamoto, 2008). In a peer-to-peer network, no client is superior to the other and all share the burden equally to provide network services (Kaushik et al., 2017). The data shared with one client of the peer-to-peer network is received by all other members within the network without any alterations to the data (Selmanovic, 2015). Blockchain technology uses this peer-to-peer network to carry out transactions and store data in a decentralised distributed ledger. The distributed database runs on multiple nodes across a peer-to-peer network, with each node verifying the security and integrity of the data included in blocks (Angrish et al., 2018).

2.2 Hashing Algorithm

A blockchain encompasses a chain of blocks where each block contains data associated with an asset such as persons, property amongst others, an immutable hash of the prior block, the unique hash of the current block, the timestamp and a nonce, which is a random number that aids in generating a valid hash for subsequent blocks (Angrish et al., 2018; Kishigami et al., 2015). The first block created in a blockchain is known as the genesis block, which has no previous block and its hash is entirely

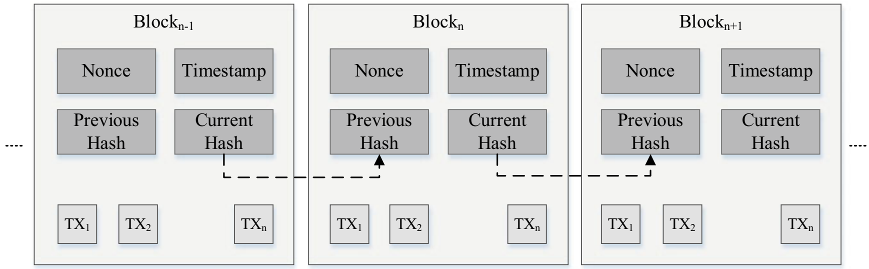

Fig. 1 Data stored within blocks in a blockchain (author's original)

zeroes (Bach et al., 2018). Figure 1 illustrates data stored within each block in a blockchain.

The important feature of a hash value is that it is extremely difficult to derive the original input value (Selmanovic, 2015). According to Kaushik et al. (2017), a good hashing algorithm ensures a good level of security due to its following features;

(1) A fixed output length (E.g. 256),
(2) The smallest change in the input must produce a notable difference in the output,
(3) The same input must produce the same output,
(4) The output value could not be reversed to find the input value, and
(5) The hash value calculation should be fast.

2.3 Public-Key Cryptography

Public-key cryptography is used in blockchain to improve the security of transactions. Public-key cryptography encrypts data packages to ensure it is impossible to crack (Li et al., 2018b). Every user has 2 keys; (1) private key, which is kept in confidentiality and used to sign transactions and (2) public key, which is shared with others and used to validate the authenticity of data (Kaushik et al., 2017; Zheng et al., 2017). The public key is used to verify the signature and check whether the transactions or data have been tampered with (Neudecker & Hartenstein, 2019). According to Swan (2015), a back calculation to derive the private key from the public key is either impossible or prohibitively expensive. Public-key infrastructure is widely used for the distribution and management of digital certificates (Crosby et al., 2015). Public-key cryptography is of paramount importance to maintain the confidentiality of data in construction projects and various applications used related to documentation management, payment and certification amongst others.

2.4 Consensus Mechanism

The responsibility for the verification of data on a decentralised blockchain system could be undertaken by any arbitrary or assigned node/s on the network (Angrish et al., 2018). This process that assists network participants to act as verifiers for transactions in exchange for rewards is identified as mining. The bitcoin blockchain uses a mining algorithm called the proof of work (PoW) consensus algorithm to verify the transactions. Similar to PoW, there are various consensus algorithms such as proof of stake (PoS), delegated proof of stake (DPos), practical Byzantine Fault Tolerance (PBFT), Ripple, proof of authority amongst others, which are used by various blockchain platforms (Bach et al., 2018; Perera et al., 2020; Zheng et al., 2017). Few of the most popular consensus mechanisms have been discussed in detail.

Proof of Work (PoW)—PoW consensus algorithm requires the nodes of the network to calculate a hash value of the block header. The block header consists of the nonce, which is changed frequently by the miners to calculate the hash values (Zheng et al., 2017). When a node reaches the targeted value, the block is broadcasted to other nodes and all other nodes must mutually confirm the correctness of the hash value (Mingxiao et al., 2017). Once the block is validated, the new block is appended to the blockchain. The mining process carried out in platforms such as bitcoin involves many computer-based calculations that require a massive amount of computation power, which result in waste of resources (Monrat et al., 2019).

Proof of Stake (PoS)—PoS uses the coin age concept to validate transactions. The holders with more coins and who are involved in the mining process for longer periods have more rights in the network (Monrat et al., 2019). The formula that is used in PoS is *proofhash < coin age x target* (Mingxiao et al., 2017). Proof hash is the hash value of the weight factor, the unspent output value and the fuzzy sum of the current time. Coin age of a coin is its value multiplied by the time since it was created. Target is the required amount of coins specified by the network along with the difficulty adjustment (Bach et al., 2018). According to Zheng et al. (2017), in comparison with PoW, PoS saves more energy and is more effective. Due to its advantages, some blockchain platforms that used PoW in the initial stage, transforms to adopting PoS. For instance, Ethereum is planning to move from Ethash, a PoW consensus mechanism (Wood, 2014) to Casper, a consensus mechanism that adopts qualities of PoS (Zamfir, 2015).

Delegated Proof of Stake (DPoS)—DPoS employs a voting mechanism for transaction validation and blockchain consensus on behalf of the voters (Xiao et al., 2020). The users of the network vote to select a group of delegates who are responsible to create new blocks (Ferdous et al., 2020). It makes use of the shareholders' votes to reach a consensus fairly and democratically (Zhang & Lee, 2020). In comparison with PoW and PoS, DPoS consensus mechanism is less costly with reduced wastage of energy and provides higher efficiency due to enhanced speed of transactions (Sayeed & Marco-Gisbert, 2019).

Practical Byzantine Fault Tolerance (PBFT)—PBFT uses an improved Byzantine Fault Tolerance consensus protocol with low algorithm complexity and high practicality in distributed systems (Castro & Liskov, 1999). This consensus mechanism consists of five phases; request, pre-prepare, prepare, commit and reply (Zhang & Lee, 2020). PBFT was introduced as a solution to tolerate Byzantine faults that could work efficiently in the presence of malicious Byzantine replicas (Monrat et al., 2019). According to He et al. (2018), PBFT can only be used in a private or permissioned blockchain due to the limitations related to scalability.

Ripple Protocol Consensus Algorithm (RPCA)—RPCA is a low latency consensus algorithm, which maintains robustness for Byzantine failures (Schwartz et al., 2018). According to Zhang and Lee (2020), the consensus mechanism in Ripple is performed by validating nodes, where each node owns a list of trusted nodes called unique node list (UNL). This enables each node to declare the nodes it trusts, instead of a global assumption on which nodes, the protocol tolerates (Cachin & Vukolic, 2017).

The selection of a suitable consensus mechanism for applications related to the construction industry is of paramount importance. PoW provides a higher level of security in validating transactions due to its mining mechanism. However, PoW has limitations resulting from its scalability issues and massive use of computation power for mining, which creates sustainability issues as the construction industry is currently adopting sustainability approaches to achieve the United Nations' sustainable development goals. The other consensus mechanisms such as PoS, DPoS and PBFT amongst others do not result in these issues. Blockchain applications in construction could be developed using a blockchain platform that uses a consensus mechanism with improved efficiency and sustainability.

2.5 Blockchain Architecture

Blockchain architecture contains various layers and various researchers have introduced different classifications. Lu (2018) identified six layers, which are data layer, network layer, consensus layer, contract layer, service layer and application layer. According to Dinh et al. (2017), there are four abstraction layers, namely consensus layer, data model layer, execution layer and application layer. Rodrigo et al. (2020) identified four layers, which are network layer, consensus layer, contract layer and application layer. Perera et al. (2020) mentioned the blockchain abstract layers as network layer, consensus layer, data model layer, execution layer and application layer. Summarising the blockchain layers identified by various researchers, layers of blockchain architecture were developed as demonstrated in Fig. 2.

The lowest layer is the network layer, which refers to the peer-to-peer network that is responsible for inter-node communications (Perera et al., 2020). The arrangement of nodes and access to data within the network layer is limited depending on the type of the blockchain; public (permissionless), private (permissioned) and consortium (Rodrigo et al., 2020). The consensus layer contains protocols that result in appending

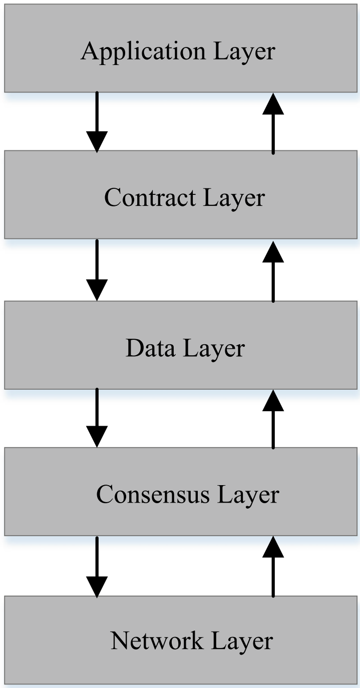

Fig. 2 Layers of blockchain architecture (author's original). Adopted from Dinh et al. (2017); Lu (2018); Perera et al. (2020); Rodrigo et al. (2020)

blocks to the blockchain (Dinh et al., 2017). There are various consensus mechanisms used by various blockchain platforms as discussed in this section previously under consensus mechanisms. The data layer manages the structure of blockchain contents with the assistance of timestamp, Merkle tree, hashing algorithm and public-key cryptography (Mosakheil, 2018). The contract layer consists of smart contracts and incentive mechanisms (Lu, 2018) along with the details of the runtime environment that supports blockchain operations (Dinh et al., 2017). The application layer contains various blockchain applications related to cryptocurrencies, FinTechs and all other applications related to different industries such as construction, health, art and so forth.

3 Salient Features of Blockchain

Blockchain is a disruptive technology that is embraced by various industries such as health, science, banking, agriculture, art and so forth, to develop enterprise solutions due to its salient features (Hasan & Salah, 2018). These features have been identified in various studies, and a summary is presented in Table 1.

Table 1 Salient features of blockchain

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Anonymity	Blockchain users can choose to remain anonymous, but provide proof of their identity (Wang et al. 2019a) through public-key cryptography	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓	

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Auditability	All transactions that occurred within the blockchain network are recorded on a distributed ledger and validated through a digital timestamp, which provides the possibility to audit and trace the previous records (Monrat et al., 2019)	✓			✓	✓			✓	✓	✓			✓		

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Data integrity	Data security provided by the blockchain enables data integrity, which refers to the correctness and completeness of data (Manglekar & Dinesha, 2018)	✓			✓	✓		✓	✓			✓		✓		✓

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Decentralisation	In a decentralised peer-to-peer network, many-to-one traffic flows and single point of failure could be eliminated. All nodes within the network have equal power, rights and obligations (Lu, 2018)	✓			✓		✓	✓	✓	✓	✓	✓	✓	✓		✓

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Disintermediation	Unlike a centralised system, a transaction in a blockchain peer-to-peer network could be conducted between any two peers without the authentication of a third party (Monrat et al., 2019), which enables disintermediation (removal of third party intervention)	✓				✓			✓	✓	✓	✓			✓	✓

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Immutability	In a public blockchain, it is nearly impossible to modify the transactions stored in a distributed ledger, which is shared amongst all nodes (Monrat et al., 2019). Data stored in blockchain systems are considered as immutable	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Security	The public-key cryptography used in blockchain enhances security against a single point of failure and malicious attacks (Casino et al., 2019)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Transparency	The distributed ledger can be seen and accessed by any user within the network, making all transactions and operations transparent (Manglekar & Dinesha, 2018)	✓		✓	✓		✓	✓	✓	✓	✓	✓			✓	✓

(continued)

Table 1 (continued)

Feature	Description	References														
		Casino et al. (2019)	Dorri et al. (2016)	Funk et al. (2018)	Gorkhali et al. (2020)	Li et al. (2018a)	Lu (2018)	Knirsch et al. (2019)	Monrat et al. (2019)	Perera et al. (2020)	Rodrigo et al. (2018)	Schmidt and Wagner (2019)	Sousa et al. (2020)	Wang et al. (2019b)	Wang et al. (2019a)	Yadav and Singh (2020)
Trust	The transparency, security and immutable nature of data stored in blockchain build trust amongst users (Wang et al. 2019a)	✓		✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓

The construction industry is often critiqued due to its inefficiency and low productivity. The disaggregated structure of the construction industry, sequential nature of works, lengthy supply chains and involvement of several stakeholders is a few of the root causes for its problems (Ashworth & Perera, 2015; Shojaei, 2019). Blockchain technology due to its salient features has the potential to resolve these issues by automating manual processes, providing a secure and reliable infrastructure with increased trust and transparency (Mathews et al., 2017; Perera et al., 2020). Blockchain could introduce an error-free process for contract administrators to build and monitor construction contracts with improved trust and integrity (Koutsogiannis & Berntsen, 2019). Traditionally, construction companies built trust by establishing long-term relationships with their supply chain stakeholders. With blockchain, companies need not inherently trust their stakeholders since trust is pre-built into blockchain systems (Wang et al., 2019a). According to the fundamental concepts of blockchain and its salient features, a blockchain taxonomy has been identified and discussed in the following section.

4 Blockchain Taxonomy: Public, Private and Consortium

Blockchain can be classified into three different networks according to management and permission limitations as public, private and consortium (Andoni et al., 2019; Lu, 2018).

Public blockchain is also known as permissionless blockchain (Kolekar et al., 2018). Any organisation or individual can apply to join a public blockchain and access the ledger (Hamida et al., 2017). In a public blockchain, it is extremely difficult to change an existing block as all subsequent blocks include the hash of the previous block, which needs to be changed within a limited time and it is visible to the entire network (Li et al., 2018a). Lu (2018) stated that in the future, it could be difficult to maintain these blockchains as it has no restrictions on scalability. A few of the most popular public blockchains are Bitcoin, Ethereum, Litecoin, amongst others (Haferkorn & Diaz, 2014). The key advantages of public blockchains are lower infrastructure costs, network being self-sustained and reduced management overheads (Casino et al., 2019).

Private blockchain is also known as permissioned blockchain (Kolekar et al., 2018). In a private blockchain, users need to be granted access to join the network (Hamida et al., 2017). Data privacy in a private blockchain is higher due to access rights (Li et al., 2018a). Private blockchain networks could avoid expensive PoW mechanisms and adopt more suitable consensus mechanisms (Casino et al., 2019). Artificial incentives are not necessarily required to guarantee the operation of the system as validator nodes are known and trusted to behave honestly (Andoni et al., 2019). There is more tendency to use private blockchains for applications in database management, auditing and other performance demanding solutions (Zheng et al., 2018). Multichain is a popular open platform for developing and deploying private blockchains (Greenspan, 2015).

Consortium blockchain is also known as a federated blockchain. A consortium blockchain is a hybrid combination of public and private blockchains (Zheng et al., 2018). Similar to a private blockchain, a consortium blockchain has better scalability and privacy protection level. It allows the selection of leader nodes to verify transactions enabling a partially decentralised design (Casino et al., 2019). Consortium blockchains have been mostly used in the banking sector. Hyperledger Fabric is an open platform that could be used to develop and deploy consortium blockchains (Hyperledger Fabric, 2020).

The construction industry consists of lengthy supply chains involving several stakeholders and has complex processes resulting in various issues. Blockchain is a potential technology to overhaul and address such issues. Depending on the requirements of the application, a suitable blockchain could be selected. Yang et al. (2020) presented two case studies that have used Hyperledger Fabric, a permissioned blockchain and Ethereum, a public and permissionless blockchain as procurement and supply chain solutions to address issues of fragmentation in the construction industry. One size does not fit all is true with blockchain applications as well. Therefore, many variations of blockchain technology moving from true open in one end of the spectrum to fully in-house and private on the other end of the blockchain solutions have been proposed. Further, hybrid approaches that are in the middle of the spectrum exploring numerous salient features of blockchain are increasingly coming to the fore as plausible solutions. These platforms are explored in detail in the next section.

5 Blockchain Platforms

There are various blockchain platforms developed by various organisations, groups and developers. Few of the most popular blockchain platforms are discussed in this section.

Corda is an open-source blockchain peer-to-peer network that has been designed for business purposes. It allows building interoperable blockchain networks that transact in strict privacy where its smart contract technology allows businesses to transact directly, with value. The language used by Corda is 'Kotlin', an improved version of Java. Corda validation process of transactions is carried out on a need-to-know basis signifying that only the parties involved in the transaction will know about the transaction details (Corda, 2020). In Corda, you can reveal transactions to few parties if required, making it a permissioned blockchain platform. Though the transactions will be revealed to the involved parties only, the verification and validation process are carried out through a notary pool. The notary pool does not update the record, however, it will check whether it is a valid transaction or not. The signature of the notary pool is proof that a user has not double spent. In Corda, states do not simply represent digital cash whilst it can represent anything, for example, bonds, bids, invoices and so forth. Corda was used by Siam Cement Group to manage procurement and payment in supply chains, which assisted in streamlining the processes by 50% (Banchongduang, 2018).

EOSIO is a blockchain platform that can be used for both public and private use cases as EOSIO is customisable to address a wide range of business needs (EOSIO, 2019). C++ is the programming language that is used to develop smart contracts in EOSIO, thus, as a result, developers that are familiar with this language and development patterns can encounter a seamless user experience. EOSIO is developed by Block.one and they have raised more than 4 billion USD for the initial coin offering (ICO) of EOSIO in 2017 as the largest ICO in history. According to EOSIO (2020), it can handle millions of transactions per second, with a block time of 0.5 s, eliminated user fees and the possibility to deploy decentralised applications quickly and easily. EOSIO has enabled higher throughput and higher scalability due to the usage of DPoS. Through DPoS, the EOSIO blockchain network need not wait until all the nodes have completed the process of validating the transaction, for it to be recorded as final. Compared to other consensus algorithms, DPoS consumes less energy to validate transactions.

Ethereum is known as the pioneer for blockchain-based smart contracts which has enabled developers to build decentralised applications (DApps) (CoinMarketCap, 2020). Ethereum blockchain platform enables digital money transactions using the cryptocurrency, Ether (ETH). The Ethereum platform consists of a turing-complete (computationally universal) language, which is functionally different from bitcoin (Wang, 2017). In Ethereum, only the final balance is maintained and it is known as the account/balance model. Ethereum's smart contracts are written based on different computer languages such as Solidity (similar to C and Java), Serpent (similar to Python), LLL (a low-level Lisp-like language) and Mutan (Go-based). In 2016, a hacker found a loophole in the code written for the smart contract, DAO, which was run on the Ethereum platform and stole 3.6 million of ETH equivalent to 70 million USD at that time (Falkon, 2017). Scalability in the Ethereum platform is very low, therefore, Merkle trees have been introduced to improve security and scalability along with optimising transaction hashing (Buterin, 2015). Currently, the Ethereum blockchain network is trying to adopt the sharding data partitioning concept, without compromising decentralisation and security of the network (Chauhan et al., 2018). RxEAL is an Ethereum-based platform that was developed to improve transactions in rental markets (Schwertner, 2018).

Hyperledger Fabric is an open-source permissioned blockchain platform developed to address enterprise and business needs. Due to its highly modular and configurable architecture, Hyperledger Fabric has enabled innovation, versatility and optimisation in various industry use cases (Wang et al., 2019b). It uses the programming languages, Java, Go and Node.js, as a result, the developers may not require additional training to learn a new language if they already have the skill set needed to develop smart contracts. Hyperledger Fabric, version 2.3, was released in 2020 (Hyperledger Fabric, 2020). Hyperledger Fabric provides the flexibility to use the consensus mechanism, crash fault tolerance (CLT), for deploying single enterprise operations as it improves performance and throughput whilst for multi-party decentralised use cases, the traditional Byzantine fault tolerance (BFT) consensus protocol could be used (Nawari & Ravindran, 2019). Hyperledger Fabric being a permissioned network provides higher security, privacy and confidentiality. The prototype system, LandBlocks, was developed using Hyperledger Fabric for land registry applications and property transactions (Nanayakkara, 2020).

MultiChain is an open-source platform where users can establish and deploy a private blockchain within an organisation or between organisations (Ali, 2018). It offers a rich set of features including extensive configurable architecture, rapid deployment, fine-grained permission management, native unlimited assets, data streams and so forth (MultiChain, 2021). MultiChain provides maximal compatibility with the bitcoin ecosystem, and mining is carried out with the help of the consensus mechanism, PoW (GitHub, 2021). As a result, it requires a higher computational power, impacting environmental sustainability massively. MultiChain is used by many organisations for various business purposes either using the platform as a product or involving in building blockchain applications on the MultiChain platform.

NEM is a blockchain-based peer-to-peer cryptocurrency and development platform whilst XEM is the cryptocurrency that is used for transactions. NEM is written in Java with a version of C++ (NEM, 2020). Proof of importance is a novel consensus mechanism that is used in NEM, which considers network theory to assign a rating of each account's importance in the network (NEM, 2018). Proof of importance considers three key factors; (1) vested stake; (2) transaction partners; and (3) number and size of transactions within 30 days to allocate rewards, and as a result, active participants are rewarded at the expense of inactive ones (NEM, 2020). Proof of importance is considered better compared to PoW and PoS consensus mechanisms. NEM provides blockchain platforms in both forms; public and private as both solutions are API compatible with higher flexibility and future-proofing. NEM has been designed with improved scale and speed, resulting in its public blockchain to demonstrate a greater throughput and scalability. Compared to Ethereum, which can handle nearly 15 transactions per second, NEM can scale to hundreds of transactions per second whilst the catapult release is expected to independently handle thousands of transactions per second (NEM, 2017).

Since blockchain technology was introduced in 2008, it has evolved disrupting various industries. The subsequent section discusses the evolution of blockchain.

6 Blockchain Applications: Blockchain 1.0, Blockchain 2.0 and Blockchain 3.0

Blockchain technology has disrupted various industries and three generations of blockchain have been identified; Blockchain 1.0 for cryptocurrencies, Blockchain 2.0 for smart contracts and financial applications and Blockchain 3.0 for applications in industries other than finance as introduced in Sect. 1 (Perera et al., 2020; Swan, 2015).

Blockchain started evolving as a technology around 2009 soon after Satoshi Nakamoto introduced bitcoin, a peer-to-peer electronic cash system in 2008 (Nakamoto, 2008). The deployment of cryptocurrencies including currency, transfer, remittance and digital payment systems is recognised as Blockchain 1.0 (Swan, 2015). **Blockchain 1.0** is focussed on applications using public-key cryptography for peer-to-peer monetary transactions within a decentralised platform (Kiu et al., 2020). Currently, there are more than 8000 cryptocurrencies with a total market capitalisation of more than 1.1 trillion USD where Bitcoin, Ethereum, Tether, XRP, Litecoin are a few of the popular cryptocurrencies that have a higher market capitalisation globally (CoinMarketCap, 2021).

Blockchain 2.0 is the next generation of blockchain technology, which introduced smart contracts in 2015 with the release of Ethereum, which discussed applications related to financial markets (Gronbaek, 2016). Smart contracts enable to digitise and automate the execution of business workflows where execution is enforced by the consensus mechanism (Christidis & Devetsikiotis, 2016; Hamida et al., 2017). Blockchain 2.0 covers economic, market and financial applications and can be extended to areas such as equity, debt, insurance, title, smart property amongst others (Li, 2018; Shojaei, 2019).

Blockchain 3.0 expanded beyond finance and markets related to smart asset transactions and incorporated DApps (Kiu et al., 2020) entering the markets related to government, health, science, culture and the arts contributing to a decentralised and cooperative society (Li, 2018; Swan, 2015). In Blockchain 3.0, the salient features obtained by trustless (since no trust is required between transacting participants) decentralised blockchain such as immutability, transparency, disintermediation and so forth are used in other systems that are built on top of blockchain infrastructure (Di Francesco Maesa & Mori, 2020). The potential blockchain applications to transform the construction industry in general and specifically related to sustainability are discussed in the following sections.

7 Blockchain Applications for the Construction Industry

Blockchain as an emerging technology has disrupted various industries. Similarly, it has the potential to transform the construction industry in various aspects.

7.1 Supply Chain Management and Logistics Management

The decentralised and fragmented nature of the construction supply chains could be resolved using blockchain for advanced material traceability (Shojaei, 2019). In the supply chain, product traceability connects all the processes involved in generating and distributing goods commencing from raw materials to completed products and handing them over to consumers in the end. Integration of blockchain with the Internet of things (IoT) and RFID tags could improve construction efficiency and enable real-time monitoring. Karale and Ranaware (2019) suggest using a cloud-based tracking system integrated with blockchain to monitor products and their components along the supply chain. Origin chain is a blockchain-based traceability system that provides transparent tamper-proof data within an automated regulatory-compliance checking platform.

7.2 Property Transactions Management

The property sector currently faces various issues related to payment, technology transfer, sales amongst others (Wang et al., 2017). Introducing a blockchain-based land registry could perform title transfer without the involvement of intermediaries such as lawyers and third party organisations, connecting buyers and sellers directly. In many countries, the full potential of blockchain technology has not been implemented due to possibilities of legal implications and society's apathy to change. However, it does not mean that full implementation of blockchain eliminating many intermediaries cannot be implemented; it will happen gradually. The automated process in blockchain saves significant time and cost and increases accuracy in record keeping (Karale & Ranaware, 2019). Sweden's land registry is piloting a blockchain-based system for real estate sale transactions and mortgage deeds, where the buyers and sellers are directly connected with the land registry and bank details (Nguyen et al., 2019). Centre for Smart Modern Construction developed a prototype system for decentralising land registry applications and property transactions in New South Wales (NSW), Australia, using Hyperledger Fabric, an enterprise blockchain platform (Nanayakkara, 2020). This system removes the involvement of intermediaries such as solicitors and third party organisations whilst directly connecting buyers and sellers through the NSW land registry and Reserve Bank of Australia.

7.3 Documentation Management and Integration with Building Information Modelling

Construction projects involve an enormous number of documents with several revisions where players mistakenly interpret the previous information, which had already been superseded by the revised document (Kiu et al., 2020). Aconex and Autodesk Buzzsaw are a few of the central data platforms that assist to organise electronic files, however, centralisation is a limitation that causes mistrust amongst stakeholders. Blockchain allows stakeholders to interoperate and validate the information in a decentralised environment through a consensus mechanism before storing it in the blockchain (Wang e al., 2017). Integration of blockchain with building information modelling (BIM) could resolve some of the intriguing issues in the construction industry and improve multi-stakeholder aggregation, data ownership, traceable recordkeeping amongst others (Hijazi et al., 2019). BIMCHAIN integrates BIM and blockchain allowing a construction project to be mapped and tracked at every stage establishing ownership of models and tracking improvements and changes during the design stage and resolves the interoperability issues (Kifokeris & Koch, 2019).

7.4 Payment and Certification

Delayed and missed payments are a serious issue in construction resulting in cash flow issues, businesses going into administration, rise of disputes and so forth (Wang et al., 2017). The use of smart contracts along with cryptocurrencies has the potential to guarantee timely payments, protect parties from insolvency and reduce the ambiguity of contractual transaction date (Cardeira, 2016; Qian & Papadonikolaki, 2019). Blockchain connects all project stakeholders allowing each actor to track progress and automate payments for completed work packages (Kifokeris & Koch, 2019). Smart contract-enabled blockchain applications provide greater trust with automation and effective operation to mitigate payment issues in the procurement process (Nanayakkara et al. 2019b; Perera et al., 2021b).

7.5 Contract Management

Smart contracts could be developed to satisfy contractual conditions related to payment, confidentiality, enforcement amongst others, which avoid malicious and accidental errors minimising the need for trusted intermediaries (Li et al., 2018a). A smart contract is unambiguous and predictable, making it more trustworthy for parties (Hunhevicz & Hall, 2020). It could improve the efficiency of the contract administration process minimising the time spent on contract registration, monitoring and uploading due to its automated and tamper-proof system (Wang et al., 2017). With regards to the legal aspects of construction projects, it has the potential to save time through management of variations, requests for information and discrepancies in information (Li & Kassem, 2019). Smart contracts will not be able to completely replace traditional construction contracts, due to the difficulty of converting all conditions into smart contracts, limitations in blockchain platforms, limitations in construction stakeholders and financial institutions to adopt blockchain and so forth. However, smart contracts act as an intelligent contract enforcement system to ensure actors comply with legally binding documents (Kiu et al., 2020).

7.6 Facilities Management

The facilities manager's role commences after the building is handed over to the client. Even if the BIM Model is handed over, the history of data cannot be traced, which is one of the major issues faced by a facilities manager. Integration of blockchain and BIM or building maintenance system (BMS) could resolve this issue as all details of the building could be traced to the source (Mathews et al., 2017). It enables digital twinning of built assets providing detailed information throughout the lifecycle of the assets from inception to decommissioning (Li et al., 2018a). Smart contracts could be developed to automate maintenance work orders and upon verification of completeness, payments are to be released to the contractor (Shojaei, 2019).

7.7 Quality Assurance and Compliance

Quality assurance and compliance are major concerns in construction projects. In 2017, Grenfell Tower in West London caught a building-wide fire killing 71 people, which had resulted due to its cladding not meeting the safety standards, regulations and compliance (Symonds & Ellison, 2018). A similar cladding used in the Lacrosse building in Melbourne caught fire in 2014 evacuating 400 occupants (Shergold & Weir, 2018). The under-designed structural elements, construction and material deficiencies resulted in cracks in the Opal Tower in Sydney in 2018 (Carter et al., 2019). Blockchain technology could be used as a regulatory tool to monitor whether standards and quality assurance related to compliance are met (Li & Kassem, 2019; Nanayakkara et al., 2019a). Product and provenance-related information could be stored on material and product passports, which could be used for quality assurance in construction projects (Wang et al., 2017) and at a later stage for a circular economy (Kinnaird & Geipel, 2017).

8 Blockchain Applications for Sustainable Construction

The material transparency discussed in blockchain-based applications related to supply chains contributes to sustainability aspects especially related to whole life cycle cost, carbon emission estimates and raw material verification (Shojaei, 2019). Potential and partially developed applications for enhancing sustainability in construction are discussed in this section.

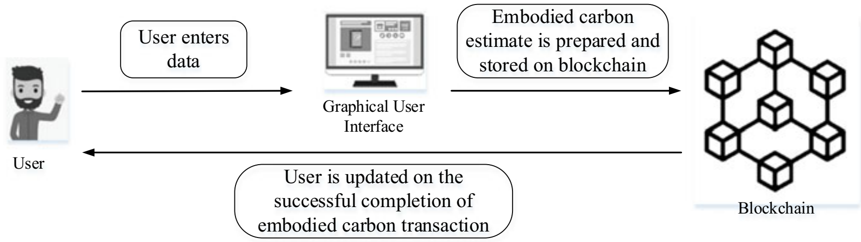

Fig. 3 Process of the blockchain-based prototype system that estimates embodied carbon (author's original)

8.1 Embodied Carbon Management

The embodied carbon estimates prepared using various carbon estimating databases and tools tend to be inaccurate due to various reasons such as differences in system boundaries, lack of standardisation, lack of transparency and so forth (Rodrigo et al., 2019). A blockchain-based embodied carbon estimating system that integrates the value chain concept could be used to accurately estimate embodied carbon in construction supply chains. Figure 3 demonstrates how the data flow within the blockchain-based prototype system that estimates embodied carbon. When the user enters supply chain-based embodied carbon data into the graphical user interface (GUI), the transactions are validated through the consensus mechanism used within the blockchain platform and the data are recorded and stored in the blockchain. Finally, the user is updated on the successful completion of the transaction. The identified issues in carbon estimating, could be resolved through the blockchain-based prototype system that consists of salient features, security, immutability, transparency, trust and so forth (Rodrigo et al., 2020).

8.2 Energy Trading and Energy Management

Burger et al. (2016) opined that blockchain has the potential to improve the current energy practises and processes through innovative approaches related to peer-to-peer energy trading and decentralised generation. Distributed ledger technology and smart contracts allow the generating unit to directly trade with the consumer via autonomous trading (Andoni et al., 2019). Energy consumption and production can be tracked using blockchain, which provides a basis for better supply and demand control (Shojaei, 2019). TransActive Grid, a US-based start-up enables renewable energy trading using blockchain and smart contracts (Rutkin, 2016). Its pilot project comprising five homes in Brooklyn successfully produced their energy through solar power, and excess energy was sold to their neighbours without involving a utility company. Exergy is another pilot project comprising of a distributed ledger technology implementing a peer-to-peer energy platform similar to the case study in Brooklyn (Exergy, 2018).

8.3 Water Trading and Water Management

Water is a scarce resource, however, its demand increases continuously. Blockchain technology could be used to solve the distribution issues and monitor the water management system efficiently and effectively (Sriyono & Aziz, 2020). A peer-to-peer water trading platform that facilitates wastewater exchange and rainwater harvesting has been suggested to develop a prosumer market. Water trading allows water users to buy and sell water access entitlements or rights to respond to the supply and demand (Nguyen et al., 2019). WaterChain is a blockchain-based platform that connects leading water innovators and funders to improve the quality of water globally (WaterChain, 2018).

8.4 Waste Trading and Waste Management

Construction waste management involves various steps such as segregation, transportation, recycling and disposal, where authorities are unable to track all of these steps due to the volume and variety of processes (Joshi, 2020). Introducing a blockchain-based decentralised waste management system could allow tracing the process from its generation to disposal. An IoT-based solution integrated with blockchain could be used to track the waste production and management process along with penalties or rewards systems (Karale & Ranaware, 2019). Chidepatil et al. (2020) suggested a blockchain system that integrates with artificial intelligence for plastic waste segregation and recycling process. Ratnasabapathy et al. (2019) introduced a blockchain-based platform for construction and demolition waste data management and trading of waste materials.

8.5 Health and Safety Management

Health and safety are a major concern in construction sites, which contribute to social sustainability. Kifokeris and Koch (2019) opined that blockchain has the potential to be used for on-site health and safety incident registration. Blockchain could provide an immutable record of incidents, which could be traced and monitored (Hunhevicz & Hall, 2020). Parties need not be concerned about losing data related to the incident as data stored on the blockchain are immutable and could be easily accessed. The management could easily obtain up-to-date information of all incidents and could use it for auditing purposes in the later stages.

9 Conclusions

The construction industry is often critiqued due to its inefficiency and low productivity. The fragmented nature of the construction industry, lengthy supply chains and involvement of several stakeholders is a few of the root causes that have created problems in the industry. Blockchain is an emerging technology that disrupts and evolves information technology with potential for a wide range of applications in various industries. The construction industry being historically reported as the second least digitalised industry and to fill the knowledge void, this chapter explores the potential application of blockchain technology to transform the construction industry.

This chapter explores the applicability of blockchain in the construction industry by evaluating various aspects of blockchain. The fundamentals of blockchain technology, peer-to-peer network, hashing algorithm, public-key cryptography and blockchain architecture are consistent despite its application in construction or any other industry. However, the consensus mechanism plays a vital role in selecting a suitable blockchain platform to develop an application related to the construction industry. The salient features of blockchain such as trust, transparency, security amongst others emphasised the importance and applicability of blockchain for transforming the construction industry. The exploitation of blockchain taxonomy revealed that one blockchain network does not fit all applications, therefore, a hybrid approach that lays in the spectrum between public and private blockchains could be contemplated. Considering these aspects, a suitable blockchain platform could be selected to develop blockchain applications in the construction industry. There are various potential and start-up blockchain applications related to the construction industry especially in the areas of supply chain management, property management, documentation management, payment, BIM and so forth. The construction industry intends to achieve United Nations' sustainable development goals, for which blockchain has the potential to assist by using it in sustainability-related applications in construction, for example, embodied carbon management, energy management, water management, waste management amongst others.

Blockchain technology has the potential to transform the construction industry to improve its inefficiencies whilst providing solutions to the prevailing issues. The high cost of software, hardware and IT specialists, construction industry's lack of maturity in digitalisation, resistance to change, resource limitations could act as barriers to implement blockchain. Despite blockchain being introduced only more than a decade ago, it has disrupted many industries. Thus, blockchain is not far from disrupting the construction industry, for which the stakeholders should be prepared to boldly embrace and exploit this emerging technology well in advance.

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Chapter 10
Parametric Design—A Drive Towards a Sustainable Future

Alex Edmonds, Theo Mourtis, and Mark Boyle

Abstract Traditionally, design involves the development of ideas within a static environment. Identifying the optimal solution can be a time-consuming and highly iterative process, with numerous variables which could be altered and investigated. Due to time constraints, the full breadth of combinations is rarely assessed, and the final solution is usually identified using experience and design judgement. The result is often a reproduction of tried and tested designs without exploration of innovative and new ideas, with potentially beneficial options remaining untested. Parametric design allows a more dynamic approach. Using parametric software, key project parameters can be identified and rapidly altered to allow different solutions to be tested with relatively little effort. Combined with optimisation algorithms, the design outcomes of each option can be understood and evaluated. In its basic form, parametric design can bring about considerable design efficiency on projects across the built environment. At a deeper level, however, questions can be asked on materiality, minimisation of waste and optimisation of the construction process itself. The key for unlocking and driving sustainable design across the built environment may therefore lie in the ability to understand the variability of design and drive positive outcomes through the use of parametric tools. This chapter will overview the basic principles of parametric design and present a selection of case studies into the practical application of the technology to achieve positive project outcomes. Addressing key lessons learnt, the opportunities to drive the future of design to achieve sustainable outcomes will be outlined.

Keywords Parametric design · Parametric modelling · Genetic algorithm · Topology optimisation

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_10

1 Introduction

Traditional design methodologies involve the development of geometric options and technical elemental design within a static environment. Whilst, in any given project, there are numerous variables which can be investigated; a full assessment of the potential benefits of differing combinations can be a time-consuming iterative process. Due to time, budget and resource constraints, the full breadth of solutions is rarely assessed, and the final solution is often identified using experience and design judgement. Whilst this tried and tested way of working delivers satisfactory options, potential optimal solutions may remain untested, leaving new and potentially innovative and more sustainable designs unconsidered. With the need to challenge building design to deliver better environmentally sustainable outcomes, historic methods of design will not allow rapid testing of new ideas. These historic methods, with individual elements, be they structural elements, façade components or MEP systems, being designed manually for the geometry which is under consideration, do not allow the full optimisation of key parameters (materials, geometric layout, embodied carbon, etc.), to enable designers to identify the best outcome for future buildings.

Parametric modelling and design allow a more dynamic approach to design to rapidly assess multiple options and push the selected design towards a chosen optimal outcome. Through the identification of variable parameters across the project, parametric software can be used to rapidly alter key variables to allow different solutions to be tested with relatively little effort and in a compressed timeframe. Each combination can easily be reviewed the impact on other parameters, and the key benefits and drawbacks of multiple options can be collaboratively discussed with design partners to identify the optimal solution.

1.1 Parametric Modelling Versus Parametric Design

Whilst linked, it should be noted that parametric modelling and design are two separate aspects of computational design. Computational design—the use of computational strategies to aid the design process—has been gaining more traction in the last decade. Used as a tool to extend and enhance traditional design skills, the use of computers and more accessible visual programming languages has unlocked opportunities to further optimise and automate the design process across the majority of disciplines in the built environment.

The use of parametric modelling has allowed designers to unlock the optimised possibilities that are available through geometric parametric manipulation. Whilst traditional modelling involves defining static geometry—drawing 3D elements in space, interconnected to form a building massing, parametric modelling involves the definition of variable parameters to the elements. This allows rapid manipulation of the 3D geometry of the massing through varying the parameters assigned to the building components.

The next evolution of parametric modelling is parametric design, where the design outcome of the geometric options is automatically altered to suit the new arrangement. Parametric design is about automating the work (Debney, 2020). For static geometry, an engineer will need to design each column. However, if the column height is a variable parameter in a model, designing each iteration of the column height would be a lengthy exercise. Parametric design automates this process, applying algorithms to the model which identify the most appropriate size for the column given its height, allowing an automatically reactive model which self-updates based on the geometric manipulation. This generative design activity allows not only the spatial impacts to be understood, but also a host of other data which can be used to assess options, including material sizes, carbon quantities and net floor areas. The two differing techniques are discussed in this chapter, with outline case studies discussing the use of both.

1.2 The Future of Parameterisation

In the drive towards an environmentally sustainable future, this ability to assess the variability of key design parameters may be key to unlocking viable building designs which can deliver on both economic and sustainable design principles. Indeed, the most prolific use to date for parametric modelling has been to understand, model and construct complex buildings around the world. This has resulted in some truly fantastic architecture; however, the next generation of parametric designs should aim to push the boundaries of sustainable design, using the tools on offer to optimise our environmental impact of the next generation of building typologies.

2 Parametric Design Software

There are numerous different software packages which can be used for parametric modelling, each one with different user interfaces and mechanisms for parameterising the design. The commonly used packages can be used across a range of applications, including product and mechanical component design through a building geometry. With a range of plugin's and differing user interfaces, selecting the best package to use will depend on the intended use and experience in CAD software. Some of the more commonly used packages include those listed below:

- Rhino 3D with Grasshopper 3D plugin[1]

[1] https://www.grasshopper3d.com.

- Autodesk Dynamo[2]
- Solidworks[3]
- Catia[4]
- Creo Parametric[5]
- FreeCAD[6]
- Siemens NX[7]
- Autodesk Inventor.[8]

Whilst a number of packages require previous experience in CAD, there are some which are more tailored towards beginners in the field of parametric design. For most packages, there are numerus free online tutorials available, covering introductions to the basics of use, through an advanced application.

For the purposes of the following examples and case studies, we have used Rhino 3D and Grasshopper, due to the prevalence in the architectural and engineering fields. Rhino 3D with the Grasshopper Plugin, uses a visual programming language to input the design geometry and alter the parametric values assigned to this geometry. A range of computational plugins are available to allow optimisation algorithms to be run within Grasshopper and visualised in Rhino.

3 Basic Principles of Parametric Modelling and Design

Parametric design is widespread in historical designs around us. Perhaps, the most well-known example is the work which was done by Antonio Gaudi during the design of the Sagrada Familia. His use of hanging weights and chains to find the most optimal form for the building, and the ability to vary the lengths of the chains and see the resultant form changes is an early form on physical parametric modelling Fig. 1.

The idea of using hanging chains to derive the idealised form of a catenary arch was first proposed by Robert Hooke in 1675, when he postulated that:

Ut pendet continuum flexile, sic stabit contiguum rigidum inversum

As hangs a flexible cable so, inverted, stand the touching pieces of an arch

The use of this theory to define a catenary arch led to the design and construction of many of our landmark architectural buildings, including St Paul's Cathedral in London, designed by Christopher Wren, who consulted with Hooke in the design of the dome at St Pauls to reduce the thickness of the dome itself.

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[2] https://www.autodesk.com/products/dynamo-studio/overview.

[3] https://www.solidworks.com.

[4] https://www.3ds.com/products-services/catia/.

[5] https://www.ptc.com/en/products/creo/parametric.

[6] https://www.freecadweb.org.

[7] https://www.plm.automation.siemens.com/global/fr/products/nx/.

[8] https://www.autodesk.com/products/inventor/.

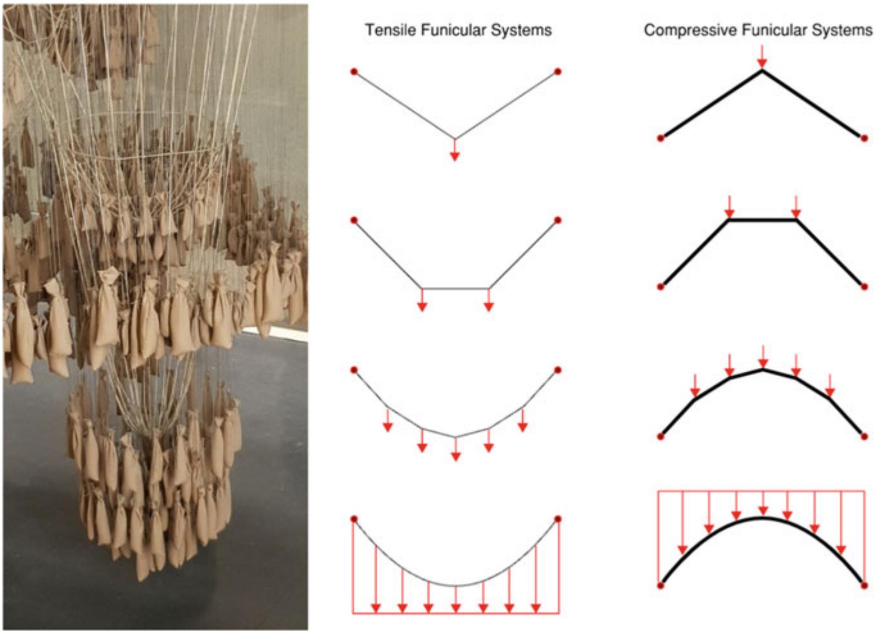


Fig. 1 Gaudi's physical parametric model and examples of funicular shapes in 2D

This theory, of hanging chains to find forms, allowed numerous architects and engineers to play with the two key parameters in the physical model—the length of the chain and the width of the supports, to develop stable designs for many historic buildings (Fig. 2).

Whilst we now use computational software to undertake parametric modelling, the principles are still the same as in Hooke and Gaudi's day. The fundamental principle of parametric modelling is the ability to varying key design parameters to investigate the impact on the holistic design. In a standard design project, the design team will step through a decision tree, making choices on key elements of the design as they progress. The further along the tree the team travels, the more difficult it is to backstep and try different options to see if there is value in change. To back up the tree too far would be costly and time-consuming, and with the typical programme pressures on design teams, this is not often done. This means that potentially value adding options are taken off the table early on during the design process (Fig. 3).

In essence, parametric design involves a dynamic decision tree, where you can flick between differing values of variables throughout the project rather than locking in a decision earlier on. This maintains flexibility during the design process and the ability to rapidly step back up the decision tree to test different options (Fig. 4).

Fig. 2 Examples of gothic, form found architecture (author original)

3.1 The Basic Process

The basic process starts with the development of a parametric model and then extends to the inclusion of the required design algorithms to allow generative design outcomes. It is key at this stage to understand what the intended outcome of any parametric study is to be, which allows the model to be set up with the correct interdependencies between design features, known as parameters.

The process therefore begins with the identification of key parameters (or design features) and constraints within the design. Typical constraints could be:

- The site boundary.
- Planning constraints—building height or massing.
- Material availability.
- Below ground constraints, including buried services or assets.
- Foundation constraints, including capacity or adjacency to waterways or other assets.

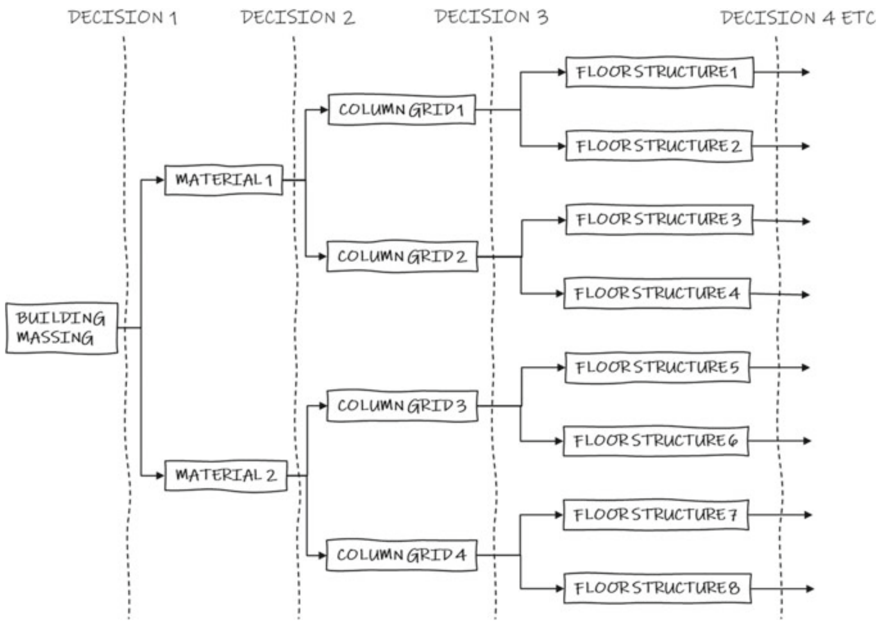


Fig. 3 Static decision tree (author original)

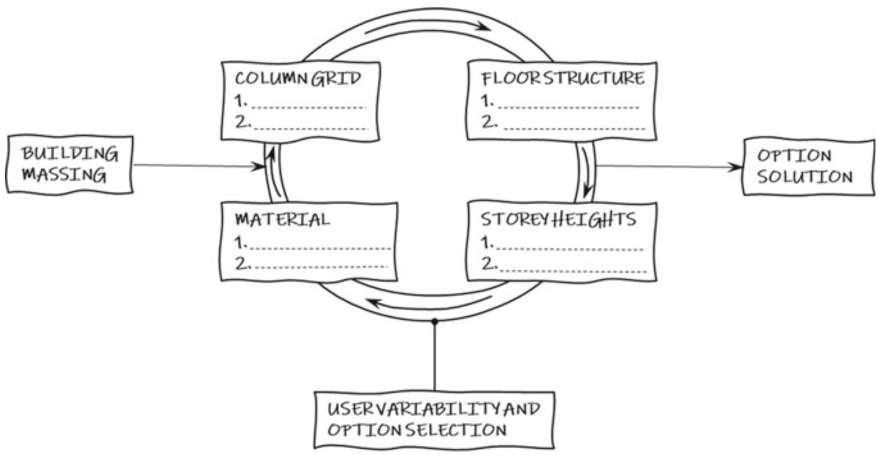


Fig. 4 Dynamic decision tree (author original)

- Structural span lengths or depth constraints.

Once the constraints are defined and the building has boundaries for optimisation within, the key design parameters can then be identified. These could include:

- Material types and quantities.

- Structural column grid.
- Floor-to-floor heights.
- Service distribution zones.
- Loading requirements.

This list of parameters can be used to start developing the base parameters which will be used as the outline for the creation of model (Fig. 5).

At this point, it is worth considering the value of varying different parameters and whether constraints should be added to the parameter variation. For instance, if the structural grid is likely going to need to support a unitised façade system on a multiple of 1.5 m centres, then the parameterisation of the structural grid can be linked to this value. The more parameters which are added to the list, the more

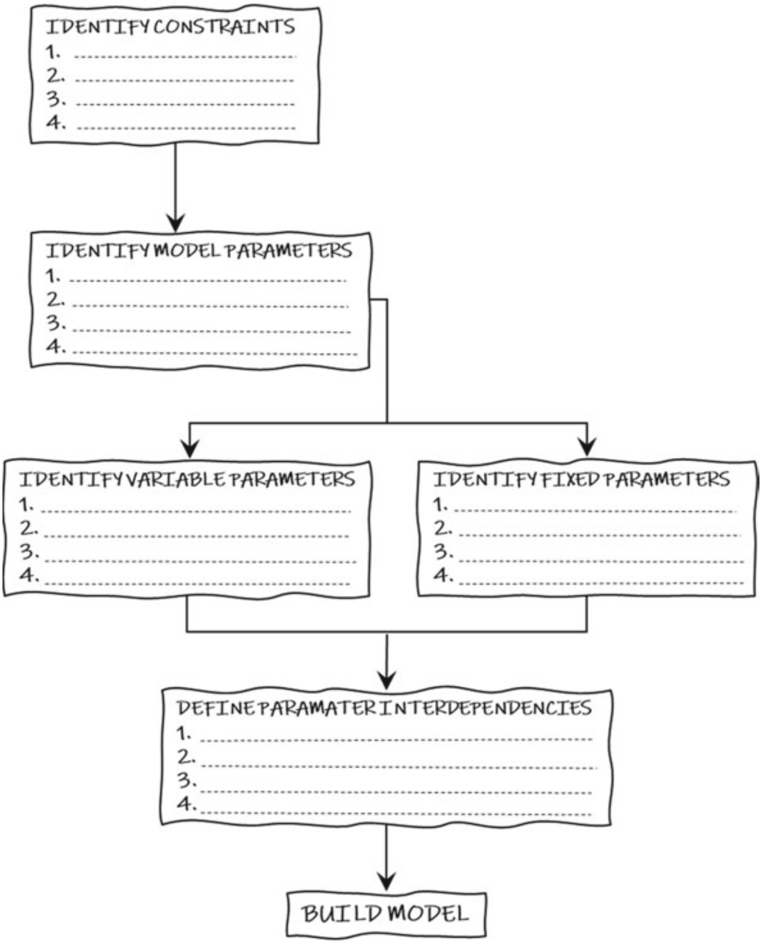


Fig. 5 Model development outline (authors original)

complex the model will become, and this may result in a more positive outcomes as more options which will be produced for investigation. Conversely, the more complex the model becomes, the more potentially for error in the model and analysis, and the more difficult it may become to set up and manage the model. In some instances, therefore, there is little value in varying certain parameters—for instance if there is a client requirement for a certain floor-to-floor height, or certain materials are likely to command a premium in a certain geographic location. One common flaw of parametric modelling is to overcomplicate the parameters. Experience of both parametric modelling and design can help to identify key parameters which drive better outcomes and root out inconsequential parameters. This simplifies the modelling, the analysis run time and overall design process.

Once the list of parameters is identified, it is possible to start identifying the interdependencies and the limits of each of the variables and identifying the required calculations which will need to be embedded in the model to allow the implications of key decisions to be overviewed.

Once the key parameters, constraints and interdependencies are identified, it is possible to begin developing the parametric model to evaluate the outcomes of the various options.

With the model now set up, it is possible to begin to add in the feedback loops, and algorithms needed to develop the parametric design aspect of the project. These algorithms will allow iterative design solutions to both update the elemental design due to geometric changes and optimise the design to drive efficiencies and idealised solutions.

4 Parametric Modelling

The key tools in the parametric modelling process include the definition of the parameters, their variability, the interdependencies between them and any constraints associated with the design in question. It is perhaps prudent to define a 'parameter' and make a distinction between it and a constraint. The dictionary definition of parameter is a 'measurable factor forming one of a set that defines a system or sets the conditions of a systems operation'. But, it is perhaps best to consider a parameter as a variable design feature which both contributes to and constrains the design. Constraints, which are themselves another type of design feature, are different in that they are fixed design feature. It is also important to recognise parameters, and constraints can sometimes be interchanged. For example, a door width can be a parameter for a room layout if it can go on any position on any wall or be any width. Whereas, a door can be a design constraint if it is fixed in position and width, say it is an existing doorway into an already constructed room.

Definition of the parameters themselves needs to be accompanied with the limits of their variability. For instance, in their most basic form, this can be simply a numerical range which is applied to the parameter.

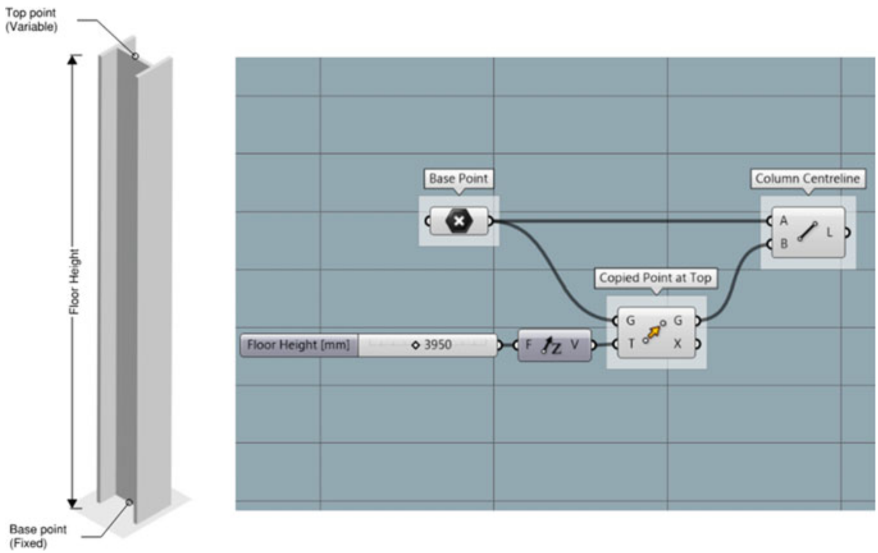


Fig. 6 Parameterised column—overview and Grasshopper 3D (author original)

By way of simple example, let us assume, we want to allow the variability of the floor-to-floor height of a single floor plate. Figure 6 indicatively defines a column height, varying the height whilst keeping the base in a fixed location.

Once a key parameter can be identified and defined, it is then possible to link a number of elements to this parameter. Building on the previous example, this will then allow a whole floor of column lengths to be varied, in essence varying the floor-to-floor height across the project (Fig. 7).

Building on this example, adding in an additional variable—the number of floors in the building—can then allow us to play with how many levels we can achieve within the given height. By adding in another variable parameter and linking this to the column heights, it is possible to play with the two variables, or parameters, in order to investigate various options (Fig. 8).

Whilst a simple example, this basic model could be useful to understand the implications of adding an additional floor, for instance will saving ~100 mm in the servicing zone at each floor allow an additional storey? This value-added discussion is relatively simply answered using even a basic parametric model.

It is also possible to add in a number of 'intelligent' algorithms to the system which can allow some implications of varying the parameters to be seen. The most obvious one would be the structural column size:

- As the storey height increases, so too does the effective length of the column.
- As the number of storeys increases, so will the load applied to the column.

Both of these aspects will affect the design of the column and cause it to increase or decrease in size and tonnage. Using a linked algorithm to calculate the size of the

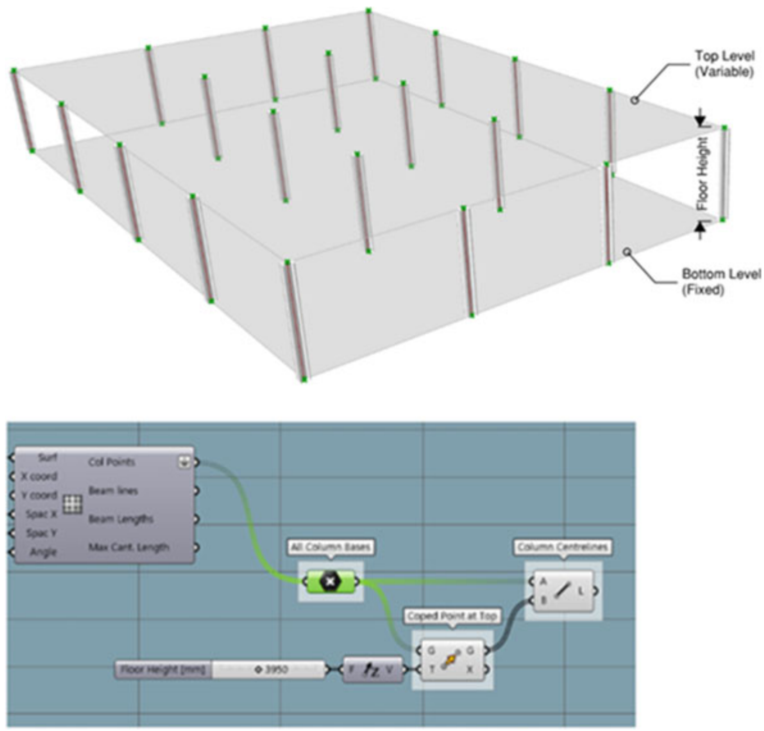


Fig. 7 Linking of elements to the parameter—overview and Grasshopper 3D (author original)

columns in the above model, it is therefore possible to extract the tonnage output and implications of varying the inter-storey height and the number of storey in the building. Whilst this is a simple example, there are further opportunities to optimise the output, covered in more detail in the following section.

The above outline gives a flavour of the parametric design process and basic tools; however, this is the tip of the iceberg in terms of capabilities of the various available software packages. Some further examples and recommended exercises for Grasshopper in particular can be found on the below resources:

- Grasshopper 3D Tutorials[9]
- McNeel Wiki Tutorials[10]
- Parametric House[11]
- Black Spectacles.[12]

[9] https://www.grasshopper3d.com/page/tutorials-1.

[10] https://wiki.mcneel.com/labs/explicithistory/examples.

[11] https://parametrichouse.com/rhino-grasshopper/.

[12] https://blackspectacles.com/topics/grasshopper-rhino-tutorials-training.

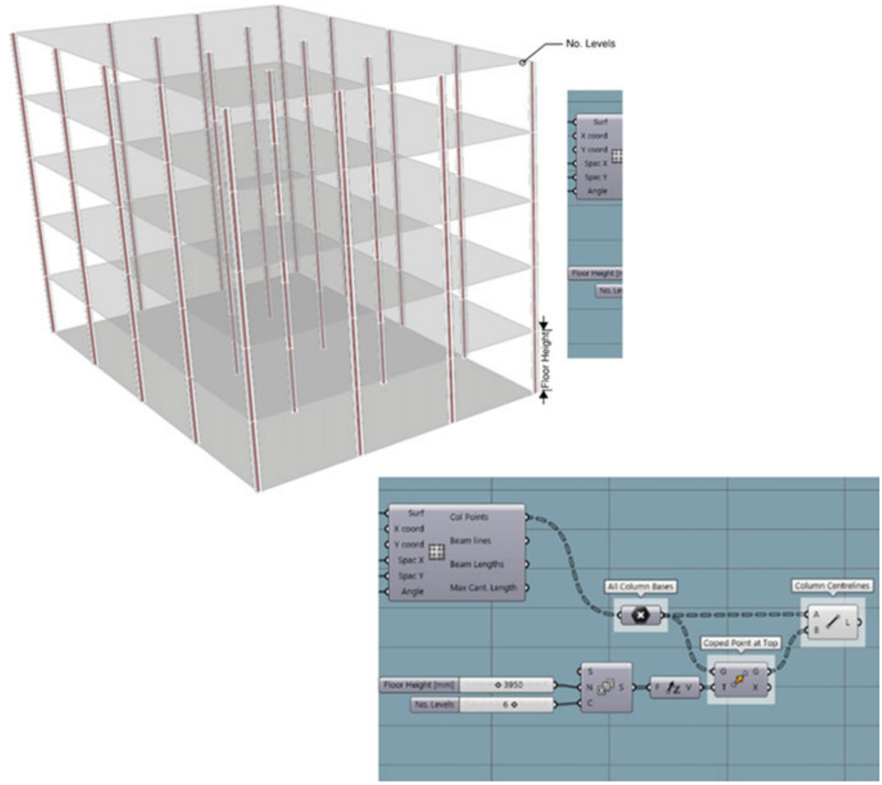


Fig. 8 Adding the additional variable—overview and grasshopper 3D (author original)

A number of other, paid and more in depth training resources for the varying different parametric software packages can be found on platforms such as Pluralsight.[13] These resources allow upskilling of organisations and individuals for a relatively modest cost and would be a recommended place to start when embarking on the journey into parametric modelling and design.

5 Parametric Design

The next evolution of parametric modelling is parametric design, where the use of built in or bespoke algorithms to generate a design outcome from the parametric model. This technique can be used to further develop the geometric options described in Section 0 to identify efficiencies in the overall design. This could include the most efficient use of materials, the most optimal spatial layout and least amount of

[13] https://www.pluralsight.com.

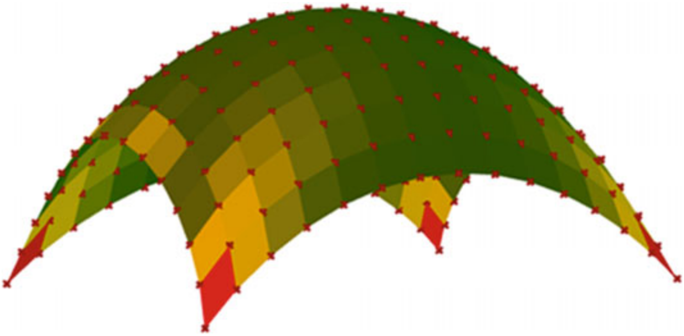


Fig. 9 Form finding of rectangular area with uniform loads (author original)

embodied carbon or any manner of targets which can be linked to the parameters in question.

There are various options for undertaking optimisation design, using a variety of plugins to the available software. These can be used individually to target specific design drivers, or can be linked together to evolve a design in conjunction with other design consultants.

5.1 Form Finding

Form finding is the method of finding an efficient 3-dimensional form for a complex surface, or series of elements. Used frequently in the structural design of organic shapes, the technique uses bespoke algorithms to identify the geometric form which provides the most efficient structural result to a defined set of rules. Often this method is used to define grid shells and other natural gravity systems, where the elements of the system are in pure axial load rather than under bending. This technique has been well documented and was used by Gaudi to define the structure of the Sagrada Familia as described in Section 3. This technique aims to identify a certain geometry, bespoke to the particular constraints that removes all bending actions in the elements. This geometry is known as a funicular form and is often the target of the majority of form finding designs (Fig. 9).

5.2 Manual Optimisation

There are various ways of undertaking manual optimisation within Grasshopper, using manually input algorithms and constructing feedback loops to re-analyse the

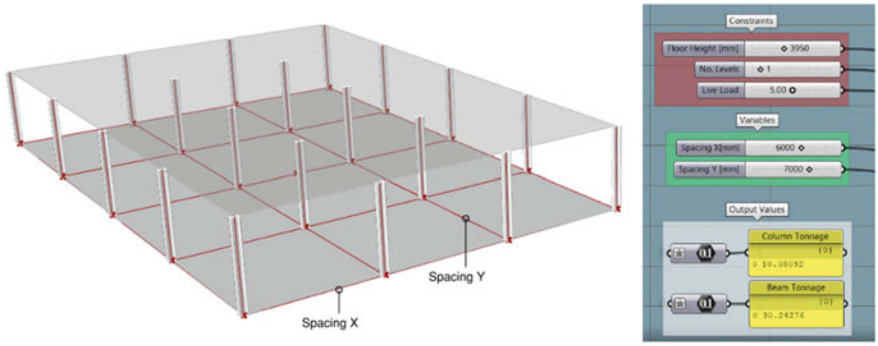


Fig. 10 Manual optimisation (author original)

output until a set of target results are achieved. Through this technique, the implications of geometric alterations can be understood and allow informed decision-making. For instance, increasing the column grid will either increase the floor plate steel tonnages or will increase the depth of the beams. These two options can be assessed to select the most appropriate for the particular project (Fig. 10).

5.3 Genetic Algorithm Optimisation

An extension of manual optimisation is the use of genetic algorithms within the optimisation scripting to automatically find the most optimal solution. Based on the theory of natural selection, where stronger traits are identified and passed down through generations, similarly, genetic algorithms identify and promote the 'strongest' and most optimal solutions to a given problem. Using genetic algorithms allows designers to define a series of target outcomes and then let the script run through, altering the parameters accordingly to identify how closely the target can be achieved.

By way of an example, if designing a flat slab, what is the most optimal column layout to reduce the thickness and reinforcement content in the slab? Using an algorithm to vary the locations of the columns, and recalculating the slab design at each iteration, will allow the optimal location to be identified. This concept is covered in more detail in one of the case studies outlined in Section 6.

5.4 Generative Design

Generative design uses analytical formulae to identify the most optimal solution to a given problem. Commonly used with a genetic algorithm process (defined later), this method undertakes numerous iterations of solutions to the problem and assesses each

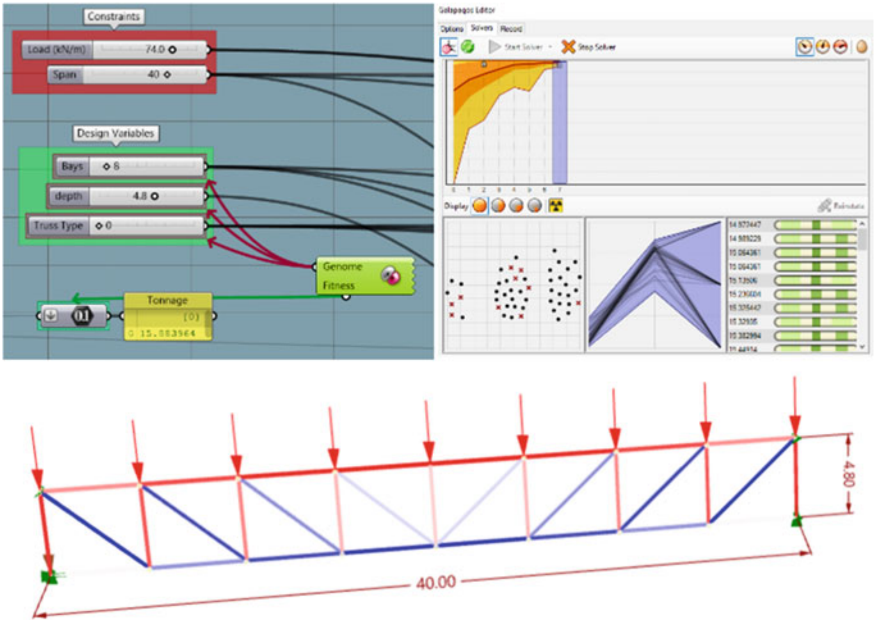


Fig. 11 Generative design of a simple truss (author original)

one against a set target to identify the most optimal solution. By way of example, when optimising the form of a truss, a target can be set to minimise the amount of material in each element, using a ratio of axial force/length. This crude design approach ignores buckling, but allows a good approximation to understand the design. Allowing a number of variables to be altered (depth, geometry, etc.) can allow an algorithm to rapidly assess numerous different arrangements to identify the option which best fits the target (Fig. 11).

5.5 *Topology Optimisation*

Topology optimisation uses mathematical analysis to optimise the material content within a bound area. In structural engineering, this can be thought of as the process of either removing lazy or underutilised material, or growing or adding material to highly stressed areas. However, it is not limited to structural engineering and can be used to plan water flow systems, traffic networks and city plans.

In the case of structural engineering, using a set of input loads and boundary conditions to this area, the optimal material layout can be derived to understand what the most efficient layout would be. Simplistically, material which is not engaged in transferring forces is removed from the 2D surface or 3D volume. In Grasshopper, the millipede plugin can be used to optimise a 2D surface when a set of boundary

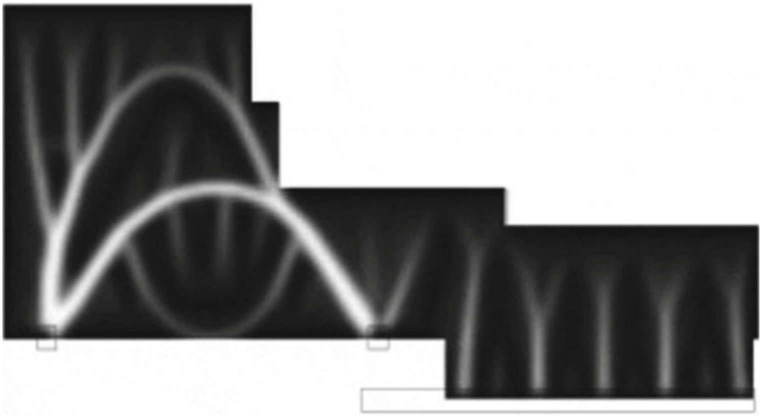


Fig. 12 Topology optimisation in millipede (author original)

conditions are defined. SOLIDWORKS simulation allows topology optimisation of a 3D volume in a similar manner (Fig. 12).

6 Case Studies

The following case studies outline in more detail where some of the previously outlined parametric design techniques have been used on real-world projects. Applied to both complex geometric challenges and more standard designs, each case study provides, and overview of the method followed and the key outcomes from using parametric design. Whilst the first three case studies outline an individual technique, the final study brings a number of different techniques together to find the optimal design solution as part of a wider design collaboration.

6.1 Case Study 1: Form Finding

Our first case study concerns a theatre roof structure, which was originally envisaged as an iconic open-span roof to provide a unique identity to not only the theatre, but the wider development as a whole.

The original concept featured a flat long-span roof, supported on perimeter columns and creating a column-free space through the majority of the building. The architectural intent involved exposed beams to the underside of the roof that follow a radial arrangement and span from the internal walls to the columns on the outer perimeter. The complex shape of the internal hall and perimeter edge in plan combined with the long spans resulted in a visually and materially heavy and costly structural solution.

An alternative approach for the roof geometry looked to use the clear height above the building massing to give curvature to the long-span structure. This option would reduce the bending moments and increase axial forces in the steel roof elements, developing a funicular geometry and resulting in a more efficient structural system. It would also add to interior and exterior building aesthetic.

Defining the funicular form is not always straightforward, especially in the 3D environment. As noted earlier, Antonio Gaudi used the concept of the hanging chains for this reason. A chain is a structural element that can only work in tension. Therefore, supporting it from the roof and hanging loads from it, Gaudi was able to find a structural layout, where everything worked in tension. Inverting that shape gave the Sagrada Familia concept design, where everything worked in pure compression—perfect for the masonry construction of the time.

Nowadays, parametric design techniques in form finding have allow us to do similar experiments in the digital world, with many more capabilities.

- A planar surface is defined, using the inner/outer edges of the system, depending on the project constraints.
- This surface is converted into a mesh, with a selected element density. This density is usually defined by the target size of the cladding panels.
- An analytical model is created where all mesh edges are converted into springs, and all mesh nodes are given a mass (or load vector). Certain nodes are used as supports, by restraining their movement in all directions.
- A physics engine runs iterations, allowing the system to deform as the loads are applied, until it converges to a certain deformed geometry.

The main parameters defining the exact shape of the final geometry, other than the surface shape and support conditions, are the spring stiffness and nodal loads used in the analytical model. Different values for these result in different curvatures, which in theory, are all funicular systems. However, when real structural elements replace the analytical springs, there is an optimum curvature that minimises the overall energy of the system. Therefore, a fine tuning is required to determine the optimum values for these variables, before arriving on the final geometry.

Another aspect to consider is planarity and repetitiveness. Optimising the structure is not the only driver for reduced costs and material quantities. Especially for free-form roof structures, the planarity of panels is essential for rectangular glass, whilst repetitiveness of both cladding and structural elements is key, due to the large quantities involved in both trades. To account for this, additional constraints can be used in the analytical model, to tweak the funicular geometry to suit standard sections and a practical cladding grid, exchanging partially bending action for practicality.

In the case of the theatre, applying this method presented a viable alternative roof option for consideration. Using the inner concrete wall supports and a perimeter stiff beam (fabricated box section, working in biaxial bending), the roof plane was allowed to deform to create a funicular shape. The result was a more complex shape with deeper curvature at long spans and almost flat members in the shorter ones, as a direct response to the unique shape of the roof in plan. This not only resulted in a lighter and more sustainable structural system, but also contributed in the architectural vision of an enhanced user experience, with a varying clear height around the theatre terrace.

6.2 Case Study 2: Slab Optimisation

An example residential development is a multi-storey tower as part of a wider residential development. The tower structure is a post-tensioned flat slab system, with blade columns and a central RC core for lateral stability. To suit the residential layout, the structural layout has been coordinated to hide all blade columns inside the partition walls.

Generally considered 'as efficient as it can be' given the coordination constraints, this structural system is commonly used across residential projects, with engineers placing columns to the best of their abilities to optimise the flat slab behaviour, usually based on experience and past projects. However, to drive efficiencies in the flat slab design, it was proposed to challenge the position of some columns which appeared to have flexibility in terms of location along internal partition walls. The study targeted columns within the tower layout which could move along the partition lines between units, without affecting the architecture.

Based on an initial inspection, how is it possible to identify the most optimal location for positioning these columns? It is possible to easily check the impact on the structural slab design if a certain column is shifted by a meter and maybe do a similar exercise a few more times. However, if each column has a range of movement of 10–5000 mm (plus and minus) and that we have nine columns, this leads to thousands of possible combinations. Even if symmetry is applied to limit the number of columns to four, this is still in the magnitude of thousands, which practically means it is impossible to exhaust all options, and ensure the most efficient solution has been selected.

This is where computational power through parametric design provides a solution. A parametric model is set up, in which the slab is modelled as a mesh that has two support types:

1. Fixed supports—shown in red and representing all the columns or core walls that are not able to move.
2. Free supports—shown in blue and given the ability to move along the partition walls, within a certain range per column. These are grouped to ensure symmetry and reduce the size of the problem (Fig. 13).

The design variables here are just four sliders that indicate the position of the free columns under the slab. The mesh is dynamic, and it is adapted in every column move to ensure that the support point is also a mesh node. This geometry is then assigned attributes (loads, cross sections, boundary conditions, etc.), and real-time analysis is performed each time a variable is altered.

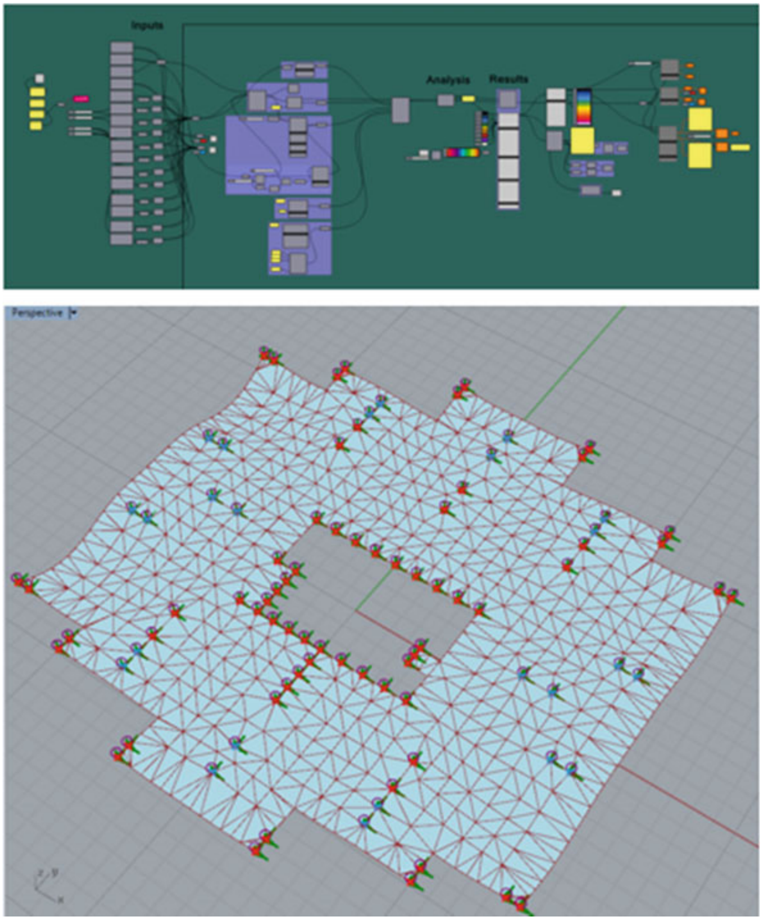
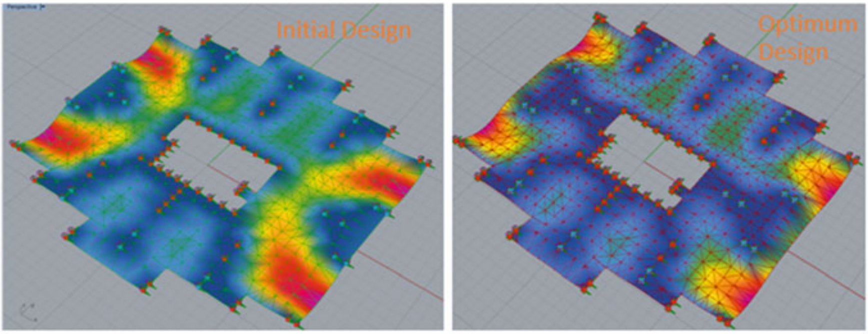


Fig. 13 Parametric model

The exploration of the design space to find the optimum arrangement is accelerated by the use of genetic algorithms. In any optimisation problem, three important aspects need to be defined, namely the input variables, the constraints and the objective function. The first two have already been defined as described; however, the third one is not that straightforward. A flat slab can be optimised for reducing deflections, maximum bending moment and the sum of bending moments or the strain energy. All of them are desirable targets, but each one of them gives different results. As part of the process therefore, it is necessary to rapidly analyse each generated option and compare it against a set of target criteria. The post-processing of the options allows the objective function to be defined and 'zero'd' in on.

With a targeted outcome of reduction in the strain energy in the slab as the criteria, a new location was proposed for the columns, accompanied with a range of movement that resulted in similar results, allowing for any changes by other parties due



Slab Optimisation	max deflection D	max Moment maxM	Net Moment netM	Strain Energy U	REDUCTIONS D	maxM	netM	U	Parameters [m] mainY	mainX	secY	secX
Original	14.2	51	26373	37.6	-	-	-	-	0	0	0	0
minimise D	13	70	26565	37.4	-0.08	0.37	0.01	-0.01	-0.7	-2	1.113	0.97
minimise Mmax	14.8	38.2	23902	29.1	0.04	-0.25	-0.09	-0.23	-0.046	1.29	1.83	1.74
minimise netM	15.8	41	22822	28.3	0.11	-0.20	-0.13	-0.25	-0.143	3	0.664	1.98
minimise U	14.5	52.7	23020	27.5	0.02	0.03	-0.13	-0.27	-0.05	3	0.65	1.544
Proposed:	14.4	42	23268	27.8	0.01	-0.18	-0.12	-0.26	0	2	1	1.5
								Range:	-0.5 to 0	2 to 3	0.6 to 1.5	1.4 to 2

Fig. 14 Optimisation results for the flat slab study

to unforeseen constraints. The end result provided around 7% less reinforcement material, without creating any implications to architecture or buildability, since there is still the same number of columns positioned inside the partition walls. Whilst not a significant saving, the reduction in the reinforcement content, for no impact on the spatial layouts or use of the space, represents an easy win to reduce the embodied carbon and costs of the projects. Given the huge number of similar residential building built around the world, such an approach, if you used industry wide, can play a large part in driving sustainable outcomes on projects (Fig. 14).

6.3 Case Study 3: Generative Design

Can a building structure grow itself, similar to natural microstructures? Maybe not entirely yet, but the latest technological advancements have brought us new methods of investigating efficient structures that allow us to explore a whole new design space. These methods usually sit under the term of generative design—an iterative process that involves an algorithm generating solutions to a well-defined problem and ranking them based on predefined objectives to achieve the target efficiency.

An example of using such techniques is the concept design of the Circular Quay tower in Sydney. This tower had a very irregular shape in plan with a ‘bird’s mouth’ feature in the front façade, splitting the tower envelope in two. The purpose of this bird’s mouth was to clearly frame the views out to the Harbour Bridge and Opera house on the two sides of harbour, and provide smaller facades that face these prominent city features to lessen the impact on key city views. After some initial studies on structural systems, an external mega-bracing system was selected over a core with outriggers option, for both structural and architectural reasons.

A desire for a distinct building identity pushed the team to explore alternative and more efficient bracing layouts that would be unique to the tower shape and constraints.

The first step in the design process involved a method called 'Topology Optimisation' (TO). This method allows the structure to use material only in locations that maximise efficiency, providing a theoretical optimum solution of a self-designed system. This technique works as follows:

- Solid surfaces of a continuum material are defined.
- The boundary conditions are defined (extent of material, supports).
- Loads are applied (only the leading action for this exercise, which was the wind for the bracing elements we are exploring this is dominate case).
- Stress analysis is performed, and areas of high and low stress are identified.
- Starting with a uniform thickness, material is removed from areas of low stress and added to high stress areas.
- This happens for many iterations until the system converges to a solution with a given material reduction target (for this case 10% of the original uniform surface volume).

This method is given a lot of freedom, and whilst the result is only a theoretical solution, it can be a useful indication of a preliminary layout strategy that will lead to the practical optimum.

Therefore, in order to convert this into an optimised 'stick model' solution, parametric modelling was used. In this model, the layout of the bracing system follows certain rules and satisfies the main architectural constraints (i.e. floor levels, column locations) but by varying a few design parameters, it is able to produce different layouts. The input parameters have been the number of braced bays, the height of each bay and the inclination of the diagonals as they intersect certain columns. Every time the input parameters are adjusted, a new geometry is generated and then analysed and evaluated based on predefined metrics (tonnage, deflections and strain energy) (Fig. 15).

This type of 'flexible' modelling allows the exploration of many more alternatives compared to the traditional way of modelling, where manual labour limits the number of options that can be explored. The bracing system was able to change from a conventional single bracing system, to cross-bracing or to a more complicated 'curved' arrangement that was similar to the one indicated by the topology optimisation study. In order to select the best option, genetic algorithm optimisation was used to come up with the best combination of input parameters which minimised the objective function (steel tonnage in this case). The output of this exercise was used as a base for the final detailed analysis of the structural system, for inclusion of all loading combinations and checks. The selected layout from this was very similar to the initial result of the topology optimisation process, giving more comfort that an option close to the theoretical optimum was selected.

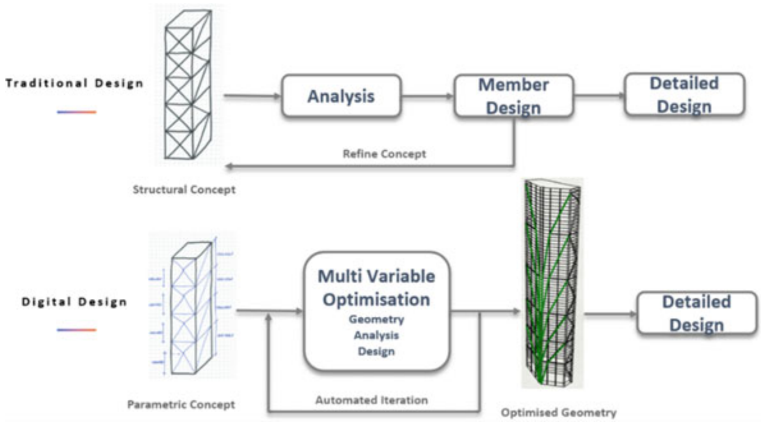


Fig. 15 Generative design workflow

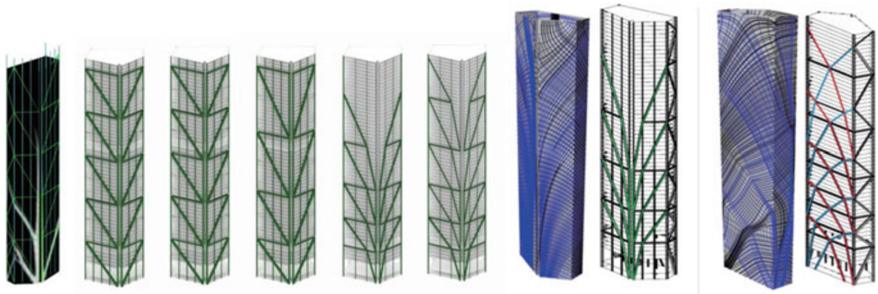


Fig. 16 Design process overview

The images below summarise the process, starting with the topology optimisation model to the left, exploring different bracing arrangements to manually reproduce this layout and then allowing the parametric model to explore thousands of layouts before converging to the final option. Plotting the principal stress paths on the tower envelope proves that the selected bracing layout tries to follow them closely. The architectural advantages can also be shown in the renders below, with a unique exoskeleton and minimised visual obstructions towards the top of the tower (Fig. 16).

6.4 *Case Study 4: Elizabeth House Arch*

The previous case studies present the individual aspects of parametric design; however, it is possible to link these elements together in an evolving design process. This was undertaken in the development of the structural system for Elizabeth House.

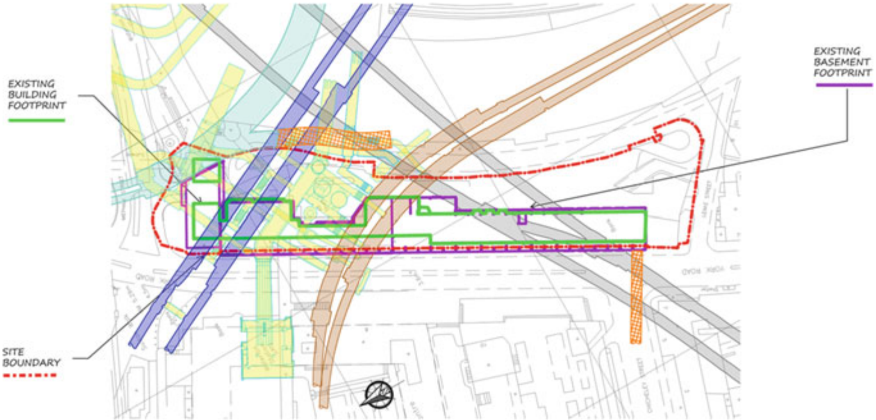


Fig. 17 Below ground constraints

Elizabeth House is a commercial office development in London, UK and is challenged due to a myriad of below ground constraints. The site is adjacent to Waterloo station and sits above the main London Underground station which connects to the overground train network. Located beneath the site therefore are a number of undergound platform tunnels, train running tunnels and a network of passenger concourse tunnels. Linking these are numerous service tunnels and ventilation shafts (Fig. 17).

The development aspiration for the site was to deliver 1.3 million square feet of commercial office space. Whilst the current seven-storey building is founded on a raft foundation, evenly distributing the load form the building on to the below ground assets, this system would not support the building massing required to deliver the require area. With a target building height of 30 storeys, a piled solution would be required to support the new structure. However, with the congested site constraints, the opportunity to install deep-piled foundations was limited to small areas located over 100 m apart. To solve this challenge, a transfer system was required to span the superstructure massing approximately 108 m clear over the below ground assets. However, removing too much weight from the tunnels would also be a problem causing them to move upwards; hence, a transfer of 108 m combined with some weight directly down onto a raft is required to effectively hold the tunnels close to their original position (Fig. 18).

6.4.1 Initial Idea Generation—Topology Optimisation

With numerous potential options for the transfer system, the first step was to undertake a number of topology optimisation exercises to identify what a natural system would look like and how, in the absence of any other constraints, a structural system would respond to the in ground constraints. Undertaken using the millipede plugin for Grasshopper, a number of different boundary conditions were analysed to gain an

Fig. 18 Piled foundation zones

understanding of the idealised geometry based on differing foundation solutions (Fig. 19).

Design Development—Parametric Optioneering Process

As the design progressed, a number of structural options were investigated for the main transfer structures. All of these options were modelled parametrically using Grasshopper to allow geometric manipulation of the structure within the architectural massing. This allowed rapid evaluation of the various options against a series of

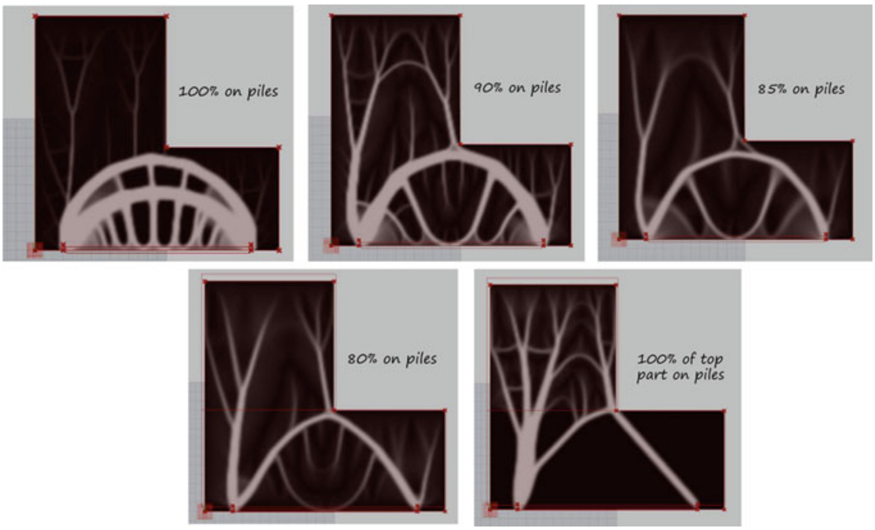


Fig. 19 Topology optimisation options

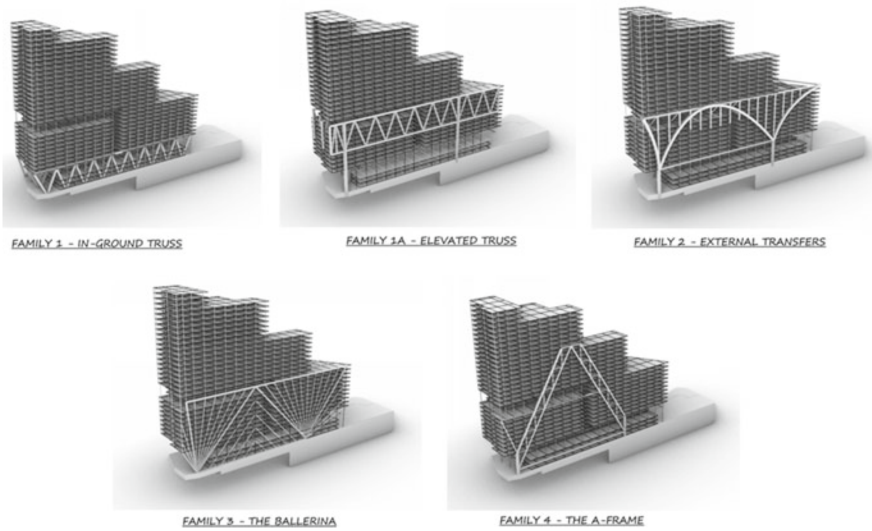


Fig. 20 Structural family options

criteria, including structural steel tonnages, architectural impacts and constructability issues. Four distinct structural 'families' of options were developed, with various options then investigated within the families. All these families shared a common objective—to transfer approximately 70% of the building weight over the tunnels and place back down approximately 30% of the building weight to hold the tunnels in position (Fig. 20).

With each of the options schemed in Grasshopper, it was possible to run an outline design for the main transfer elements which was linked to their geometry. This allowed rapid updates to structural element sizes and tonnages based on geometric changes and enabled the optioneering study to progress much more rapidly, and with informed data, than a traditional design options process. To accomplish this, the following steps were taken:

- A massing option was received by the architect.
- Floor surfaces were extracted based on levels schedule.
- The same structural grid (driven by the ground constraints) was projected on these levels.
- The selected transfer system was adapted to the massing option by finding the relevant intersection points.
- Manual modification of the transfer geometry was allowed by the script (inclination of diagonals, number of them, truss depth, etc.).
- Real-time analysis was performed by the Grasshopper plugin 'Karamba',[14] a parametric structural analysis tool for trusses and space frames.

[14] https://www.karamba3d.com/.

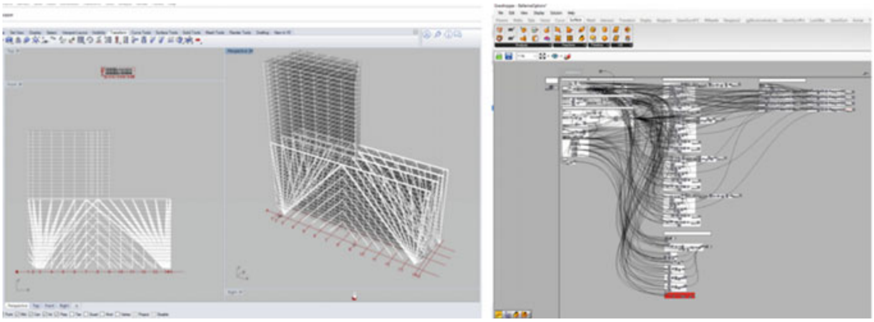


Fig. 21 Design optioneering

- Metrics were extracted automatically after each geometry change regarding tonnage, deflections, floor area, façade area, etc.
- Baked structural geometry was sent back to the architects for inclusion in the rendering process for visual impact (Fig. 21).

6.4.2 Generative Design Optimisation

As the design progressed, the A-frame option was selected as the most suitable when assessed holistically and was further developed in collaboration with the architects. As the architectural massing evolved to reflect planning and spatial drivers, further geometric updates were needed to the transfer systems to continue to integrate the structure into the architecture of the building. This development began to introduce elongated force-paths towards the support points.

To assess the most optimal geometric arrangement for the A-frame, a genetic algorithm was run to iterate numerous different options and zero in on the most efficient system. Key parameters within this iterative process were locked to maintain critical architectural and grid setting out, including:

- Node points within the system were locked to the grid intersections between the floor plates and the column grid.
- The floor-to-floor heights were locked.
- The longitudinal column grids were locked.
- Geometric symmetry was enforced left and right of the apex point of the system—important to enhance the space planning and character of the building, from both an internal and external perspective (Figs. 22 and 23).

The algorithm was run using the following steps:

- Focussing on one gridline at the time, the loads of the given mass were determined.
- Nodes were defined in the gridline/floor intersections that were able to change levels during the optimisation.

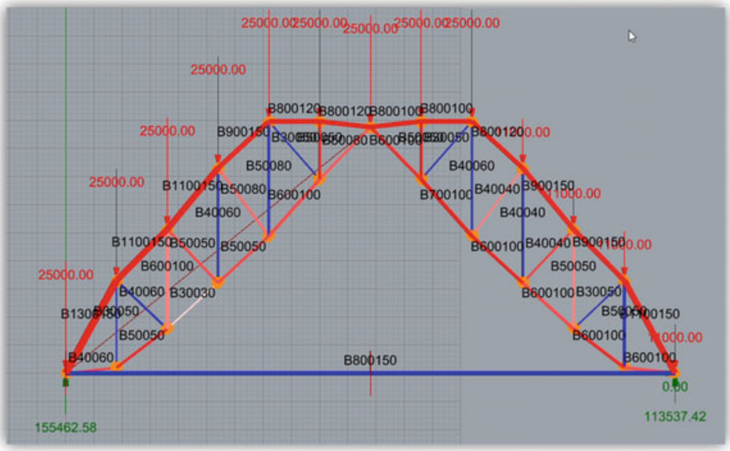


Fig. 22 Arch algorithm – automated design script

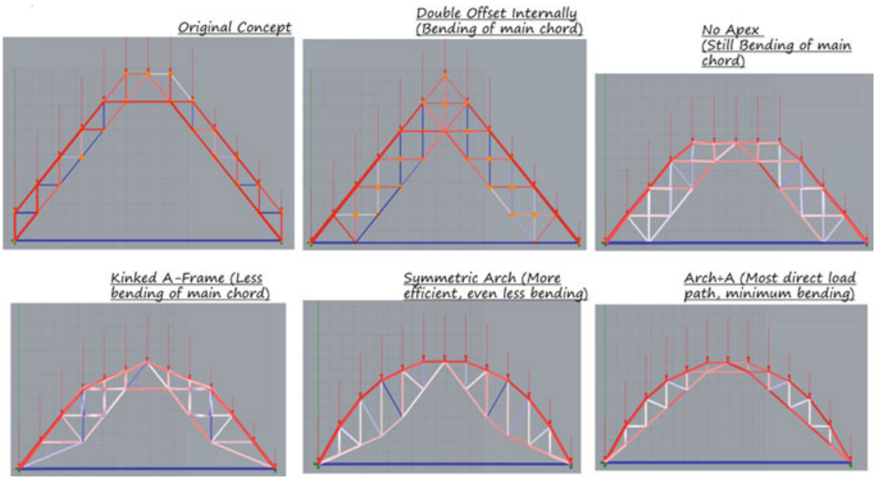


Fig. 23 Arch algorithm – geometric outputs

- Members connecting these nodes were generated based on predefined rules, ensuring a truss-like transfer system, regardless of the node locations.
- Real-time analysis and evaluation of metrics were performed by Karamba. Each time a node was changing levels, whilst moving along a certain gridline, a new finite element analysis was performed, and the efficiency of the system was evaluated.
- Genetic algorithms were used to explore all the possible combinations of node locations.

- The algorithm converged to node locations that formed a parabolic curve for the main chord of the trusses.

6.4.3 Foundation Design Optimisation

One additional discrete challenge which was solved using a parametric design process was the supporting foundation arrangement to the northern edge of the site. Whilst the available piling zones to the south allowed more scope for deep foundations, the planning requirements for the site drove the mass of the building towards the northern end.

The northern pile groups are constrained by a number of train and passenger tunnels and therefore have limited scope for pile sizes and numbers. The initial concept was based on the use of 1500 mm diameter piles; however, this limited the heights of the building, especially to the north-eastern corner where the area for piling was the least. To further optimise the potential load-bearing capacity, a generative design algorithm was run on the north-eastern pile cap to test whether varying the number, size and position of the piles would achieve a higher group capacity. To set up the algorithm, key steps were taken:

- A comparative table was set up with pile sizes and their respective capacity.
- The area was then defined within which piles could be placed.
- Key geometric rules were added, including minimum pile spacing as a function of diameter.
- Possible pile arrangements that maximise density were explored, resulting in an orthogonal and a hexagonal grid.
- Regardless of the grid selection, the whole grid was allowed to move in two directions and rotate.
- A trimming algorithm allowed only piles that were fully inside the allowable area to be accounted for in the design.
- Genetic algorithms were used to alter pile diameters, grid type, vertical/horizontal location and rotation, with the goal to maximise the pile group capacity (Fig. 24).

The resulting output was that by reducing the pile size to 1200 mm diameter and a best fit position for maximum piles, it allowed an additional two piles to be included in the pile group, which allowed an additional 10% load-bearing capacity from the overall group. This unlocked the restraint on the superstructure above and gave a more viable foundation design.

6.4.4 The Final Design

The final design for the transfer system, mega tied arches, allowed this complex site to be unlocked and yet retain an efficient and cost-effective structural system. The arch geometry and structural sizes respond directly to the massing of the building,

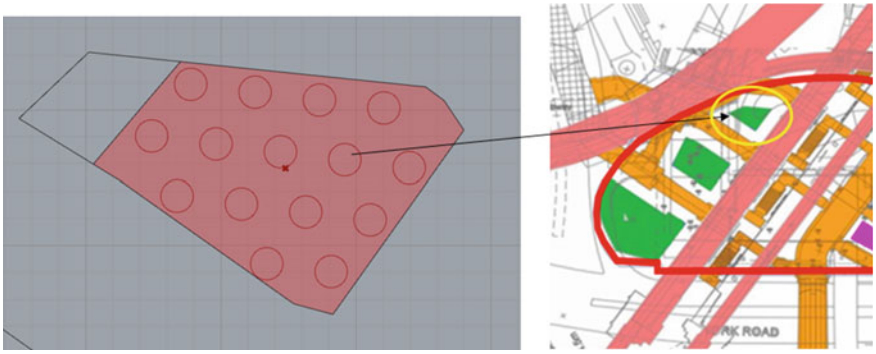


Fig. 24 Pile optimisation script

with three distinct systems embedded in on geometric arrangement. These consist of:

(1) A symmetric arch to support the lower mass of the building.
(2) An asymmetric arch to support the eccentric upper mass of the tower.
(3) A propped truss system to resist pattern and out of balance loading (Figs. 25 and 26).

Throughout the design process, parametric modelling and design techniques were used on both the holistic design and on targeted discrete aspects. This allowed the design to be integrated into the architecture of the building, which when complete, will result in an iconic development in the heart of London.

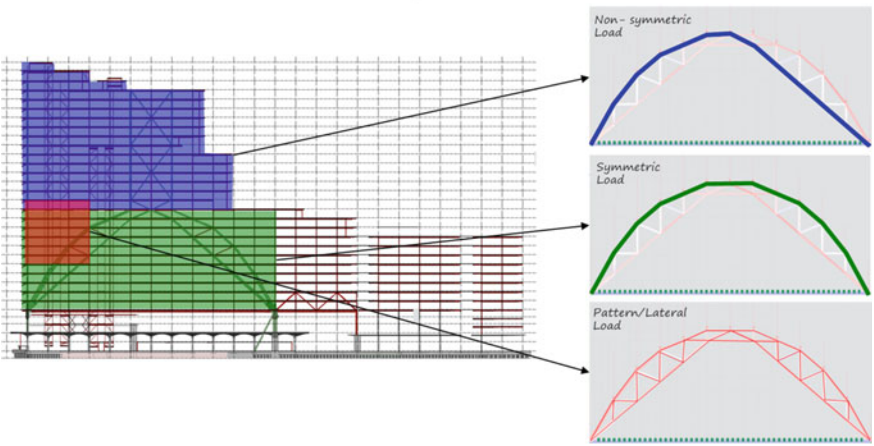


Fig. 25 Arch design

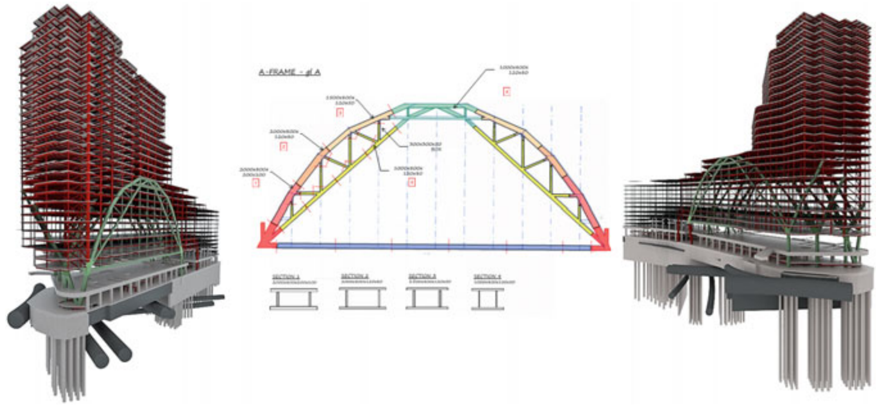


Fig. 26 Arch geometry

7 Lessons Learnt

Parametric modelling and design principles, and their application, are not without disadvantages. The techniques used can incur both design and technical issues which need to be acknowledged throughout the process to achieve the best outcome.

A Steep Learning Curve

To fully master parametric modelling, with the myriad of plugins and opportunities which the method can provide, is not an easy task. For new users, even those who are familiar with traditional 2D and 3D modelling packages, learning the skills to build through a design parametrically will take time and should not be rushed. Aside from the basic building blocks which are used to develop the models, understanding the interdependencies and relationships between differing variables requires a different way of thinking about design.

Luckily, there are numerous online and in person tutorials and courses available to both new and advanced users and active online forums where questions can be asked to resolve issues. Starting with simple models and growing the complexity and additional capabilities of the model would be the best route into the world of parametric design.

Black box engineering and design

As with all software, there is an inherent danger of ‘black-box’ design, i.e. an over-reliance on the outcome of any particular analysis and design package—in essence believing a solution is correct because ‘the computer says so’. This has the potential to introduce errors into the design, ones which can be costly and time-consuming to rectify later. Whilst this risk is present in most software packages, with the prevalence of open-sourced plugins available to enhance, the basic parametric tools increases the risk of potential errors. Issues can include:

- Incorrect analysis of stresses in materials (tension vs. compression) during analysis and design optimisation.
- Incorrect force distribution if boundary conditions are not correctly set.
- Node rotation issues due to member releases not set.
- No consideration of second order, but sometimes important affects such as member buckling, global buckling or local buckling or instabilities.
- Over implementation of optimisation, missing a critical check such as pattern loading.

To mitigate the risks of this, it is important to use technical engineering judgement across all aspects of a particular project. Any solution which is developed parametrically should still be verified against global force equilibrium and should have easily identifiable force-paths. Rough hand calculations can also be used to verify the basic magnitude of forces and verify the fundamental concept behind the more optimised design. Also, geometry and sizing derived through an optimisation and parametric process and simple analysis can be check by more complex analysis and design only software.

Lack of defined targeted outcomes

With a range of parameters which can be varied across a project, the potential outcomes can be numerous. As you introduce more variables to this already diverging process, it becomes difficult to identify what the ideal solution might be. To avoid endless iteration, it is therefore important to identify what is important to the project outcome. This could be a geometric target, minimisation of material quantities, finding the lowest embodied carbon solution or identifying the optimal end-user experience. With a solid definition of the critical metrics against which to test the varied outcomes, it becomes easier to discard the solutions which do not meet these metrics, and dive deeper into the more promising options.

Slave parameters

One potential pitfall across the generative design aspect is the issue of slave parameters. This is where certain parameters will always be linked to others, either through a geometric requirement or due to base design principles. In this instance, varying certain parameters will always result in the result for any slave parameters. Therefore, numerous iterations will give the same result and can run indefinitely without converging to a solution.

Constructability—can it be built?

Analysis and design software, whilst burdened by bounds of physics, are unrestrained by the need to construct the final design in an efficient and safe manner. With the endless geometric options provided by parametric design and the ability to fully optimise the material quantities in the finished building, this may not provide the most cost-effective and sustainable solution. Reducing steel tonnages to a bare minimum for instance is potentially counterproductive if the construction phase requires two or three times more temporary works to stabilise the structure until it is complete.

Further, a complex geometric solution may meet an aesthetic requirement, however, could add a number of months to the construction programme, incurring additional cost.

Avoiding a ‘wished-in-place’ design is therefore key to successful use of parametric design software and is essential during the early concept phases of the project, where the overall buildings form and geometry are established. Understanding the basic principles of construction and embedding these as constraints into the design as it develops are therefore important steps.

Are you asking the right question?

With the fundamental principle of variability of key parameters, one of the critical aspects of the methodology is to make sure that the right parameters are selected to both fix and to vary. In essence—are you asking the right question of the software before the iteration process starts? Do you have a full understanding of the project constraints, below ground risks, likely construction methodologies and budget limitations? Is fixing one variable likely to overly constrain the design? Is varying one parameter going to introduce unnecessary cost. There is not necessarily a right or wrong answer which can be outlined here to these questions, as these questions will need to be answered on a project-by-project basis. However, we would recommend that prior to the development of any models, a collaborative review is undertaken to identify all of the key variables and identify which ones have the potential to add value, which must be fixed (perhaps due to third party influences).

Imaginative and design thinking?

One potential drawback to parametric design and modelling is that it can constrain the historic thinking which has produced some of histories finest design examples. In both conceptual and optimisation design stages, the use of a parametric model will produce a number of different iterations and provide the designers with a number options to choose from—in effect a list of possible solutions to the question which has been asked. However, this has the potential to constrain the creative design process if rigidly adhered to. Across engineering and architecture, there are foundation design principles, be they technical or emotive in nature which are applied to all projects. Whilst the correct use of parametric modelling and design can enhance the creative design process, the designs produced should always be tested against the fundamentals and critiqued by colleagues and design partners to challenge the outputs. This will ensure that the final solution is designed as best for project rather than just selecting an option from a software generated list.

Qualitative Issues

Parametric design is often seen as able to provide a solution to a problem which has presented itself during the design process. However, it is not necessarily always the right tool. Certain design complexities or design development is qualitative in nature. As such, developing a parametric design script to apply to the design will not solve the complexity or develop a solution to provide an optimal outcome. Indeed, it may further complicate the design through adding costly complexity to the project.

In these instances, again, design experience is critical to identifying whether or not parametric design is the right solution or whether a more qualitative design process should be applied instead.

Diving into software too soon

One of the key risks to any design process is diving into the use of software to early on in the project. Even in traditional design processes, if the concept is not fully thought though from the outset, and the fundamental principles laid down, then any early modelling can be abortive or can give incorrect outputs for preliminary design quantities, causing errors in the initial project budgets. With parametric design, this issue can be exacerbated. If the constraints are not fully understood, or the parameters to be optimised are not fully thought through, including the upper and lower bounds for each of these variables, then there is a risk that the outcome of the parametric design process will not provide the intended outcome.

8 A Parametric Drive to Sustainable Design

As has been mentioned previously, the primary use of parametric design tools to date has been to define some fantastic geometrically complex buildings, creating landmark developments across the world. However, these tools are not often used in anger on the basic design activities, those bread and butter residential and commercial developments of which hundreds are in design and construction phases around the world at any one time. This is perhaps where there is the most scope for pushing the boundaries on sustainable design—creating more efficient and optimised structures to suit the everyday requirements of our communities. Even an average 5% saving in material quantities across these numerous projects could result in significant carbon savings worldwide.

There are a number of ways in which the use of parametric design can be used to further advance sustainable design principles—some of which are outlined below.

8.1 Material Optimisation

The optimisation techniques available in parametric design tools are outlined above and provide an opportunity to not just optimise the elemental design itself, but also to challenge the materiality of the structural elements which we use to design and build. Through amendments to the geometric form of elements, it is possible to identify more optimal force paths, connection points, spatial layouts and structural forms.

Parametric design also provides an opportunity to test different materials. For instance, what would a concrete frame look like in timber? Varying the design parameters and conceptual design algorithms, it is possible to flick between the two options

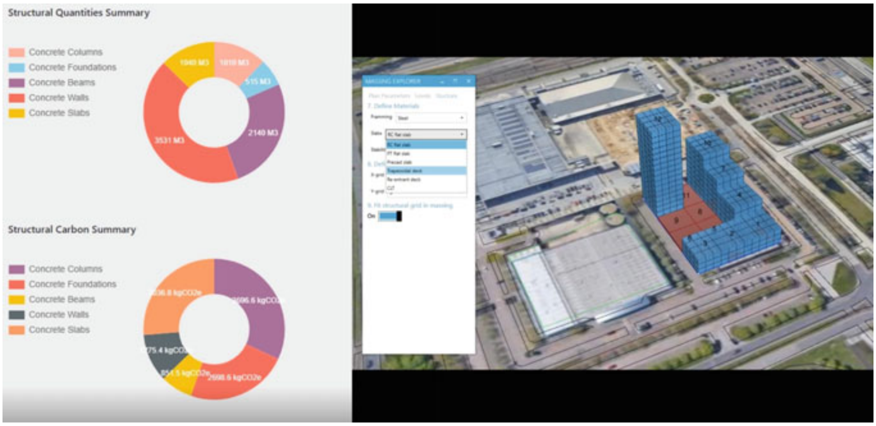


Fig. 27 Material optimisation (author original)

and identify the carbon quantities in both and indeed understand the spatial implications of switching between the two materials, in affect running two designs in parallel. This might be particularly useful when the optimum outcome might not be known until the project has been tendered, such as looking at two or more alternative materials (steel, concrete, timber) or looking at options such as volumetric modular vs. traditional building construction techniques (Fig. 27).

Whilst this is a simplistic example, using simple concept level calculations and ignores questions around aspects such as fire protection and cost, it demonstrates the potential to rapidly evaluate differing materials against a target outcome for the project.

8.2 Challenging Structural Form

Case study 2 outlines the significant benefits of using genetic algorithms to challenge the basic geometry in a residential column layout. Basic building geometry, usually based on experience and design judgement, can be further enhanced through the use of parametric design techniques.

Whilst an initial concept can be developed by hand, this should not preclude the spatial layout of the structure from being challenged. This can either be within the constraints of the architectural layouts, or even outside of them and challenging whether there is a better way to design a building. As demonstrated, the opportunities which are presented by parametric design methods in optimising the structural layouts within a building can result in more efficient design, using less materials, with faster and more concise construction programmes. All of these will contribute to reducing the embodied carbon content of the development and hence its environmental impact.

8.3 Visualisation of Sustainable Targets

As has been noted, as various parameters are optimised or altered through the parametric process, it is important to understand the key targeted outcomes for the project. With better understanding of the embodied carbon in various materials, it is possible to directly link carbon quantities to the parametric design, making the resultant an output of the design process. Various tools exist to accomplish this, including:

- Whole life carbon assessment for architects[15]
- Inventory of carbon and energy database—V3.0 (10 Nov 2019).[16]

The above resources provide guidance on calculating the carbon based on material quantities and can be used within parametric software to take the material outputs and convert them into a carbon content.

Using optimisation algorithms, it is then possible to create a feedback loop to optimise for the lowest embodied carbon option across a particular aspect of the project.

A word of warning however—this process needs to be a holistic review across the project—over optimisation of the structure for instance could have knock-on effects on the façade system, negating any carbon savings in steel tonnages for example.

8.4 Modern Methods of Construction and Componentised Design

There have recently been significant advances in modern methods of construction, using modular geometry to facilitate more off-site construction and allow faster on-site construction. In addition, the use of componentised design is also growing in certain sectors of the construction industry. Parametric design can allow future development massing and geometric layouts to be linked to certain components or modules. With this, it will be possible to develop unique building typologies using a standard set of modules or components, allowing mass of-site construction of elements and simpler and less constrained on-site delivery. These future methods will reduce material waste on site significantly, whilst also de-risking the construction process and speeding up the construction phase. Used intelligently, these methods will therefore have a significant impact on the embodied carbon content of new buildings and reduce the environmental impact of new construction.

[15] https://www.architecture.com/knowledge-and-resources/resources-landing-page/whole-life-carbon-assessment-for-architects.

[16] https://circularecology.com/embodied-carbon-footprint-database.html.

8.5 Integration of Existing Structure

Parametric modelling is particularly useful to integrate and reuse existing buildings, either wholly or partially. Reusing components of an existing building can significantly reduce the embodied and whole life carbon quantities in a new development and the parametric tools which have been outlined above can allow the identification of the optimal way of reuse.

Examples include the reuse of foundations—where the existing capacities are set as fixed parameters in the model, and the superstructure is optimised within these bounds. Similarly, reuse of existing buildings to extend them vertically and add floor plate capacity, again using the existing capacity of the structural systems to bind the parametric modelling process. These methods can help identify the opportunities available on a particular and aid in the decision-making process at the initiation of a project.

Taking this a step further, future opportunities will exist to mine the BIM data from buildings scheduled for demolition. Through limiting the model to only components which are available for reuse from previous projects (be they façade panels, MEP equipment or structural components), the design team is able to develop new and innovative developments without the need for newly fabricated materials—think of Lego building on a macro-scale.

8.6 Future of Materials

Material advances which have occurred over recent years, and indeed those yet to come, can take time to be adopted by the wider industry. Without extensive rework, it is often difficult to demonstrate what an alternative frame and material makeup might look like. The potential pros and cons can be difficult to explain with traditional design methods.

Parametric design, using manual optimisation, can allow options to be tried within a set massing and aspects such as material and embodied carbon quantities, along with geometric impacts such as floor-to-floor heights visualised and understood.

The ability to better understand the benefits of new materials will allow more comfort in their use to be gain by developers and contractors and will lead to more use of environmentally sustainable materials in future projects.

9 Concluding Thoughts

This chapter has outlined the opportunities, along with some practical examples, of how parametric design can be used to challenge geometry and materiality to drive minimisation of material quantities and more efficient geometric solutions. Whilst we have only outlined the possibilities here, with suggestions on areas to be investigates, we believe that parametric design carries the opportunity to have significantly positive impact on the embodied carbon quantities of the next generation of building.

As designers, we have a duty to drive sustainable design through all our projects, to lessen the environmental impact of the built environment and enhance the cities and towns in which we and our communities live. Parametric design gives us a set of powerful tools and design methods which can be used to challenge projects from the outset to ensure that we are delivering on our obligations to deliver a better world for future generations.

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Chapter 11
Construction Industry Transformation Through Modular Methods

Wahid Ferdous, Allan Manalo, Arvind Sharda, Yu Bai, Tuan Duc Ngo, and Priyan Mendis

Abstract Modular building construction has attracted significant attention from the construction industry in recent years. This type of construction system has been reasonably used in the Sweden, United Kingdom, United States and Japan, whilst becoming popular in Australia, China, Netherlands, Germany and Hong Kong. This chapter presents the benefits of modular construction over conventional construction systems such as high-quality control, rapid construction, risk minimisation, trades availability in adverse weather conditions, waste minimisation and mechanisation of the manufacturing process to overcome the current challenges. The design requirements of modular buildings for hydraulics, electrical, mechanical, heating ventilation and air conditioning (HVAC), fire, acoustics and thermal are briefly presented. The growth of modular construction market by region and application is reviewed, and the future global growth forecast is also presented. A comparative analysis of the cost involved in site-intensive and modular constructions is discussed to assist in understanding the wider benefits of modular systems. A number of case studies ranging from residential to commercial building projects using modular construction are presented. Finally, the potential of fibre composite materials to fabricate innovative construction modules is discussed. At the end of this chapter, readers will gain understanding on the benefits of modular construction and new innovations for transforming the construction industry.

Keywords Modular construction · Modular buildings · Offsite construction · Modular construction market

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_11

1 Introduction

Modular construction is an offsite construction process in which the building components are manufactured/fabricated in controlled factory environment. The prefabricated building components, also known as modules, are transferred to the construction site using flatbed truck and trailer. The modules are then assembled with suitable connection systems to form modular buildings. Depending on the degree of fabrication, the prefabricated modules are classified into three categories: 1D single element (2 points connection, e.g. beams or columns), 2D-panelised system (4 points connection, e.g. walls and floors) and 3D volumetric component (8 points connection, e.g. pods). This component-based design (splitting a product into smaller, more manageable parts) offers significant savings in the component production cost and the speed of assembly. Modular construction is primarily focussed on the panelised and volumetric construction as they encompassed 70–95% of a building. Design using modular construction requires proper understanding of modular production and installation. The chapter discusses the fundamental aspects of modular construction system.

2 Benefits of Modular Construction

Modular buildings are greener, faster and smarter over conventionally constructed buildings. This construction process is revolutionising the method that the world builds (Wuni & Shen, 2020). A brief overview on the three major beneficial aspects is discussed.

Greener: The factory-controlled manufacturing process produces less amount of waste and creates fewer disturbances at construction site. Buildings constructed by modular construction can be disassembled, and their used modules can be refurbished for another application. The reuse of modules can possibly minimise the demand for raw materials and that helps to reduce the total energy utilisation. The recycling process in factory environment is reducing waste generation and saving the building materials. Moreover, the possibility of moisture absorption by the modules in conventional construction can be eliminated as the building components are substantially manufactured in a controlled environment (i.e. without weather exposure) using higher quality materials (Ferdous et al., 2019).

Faster: The manufacturing of modules and site work occurs simultaneously, allowing 20–50% faster completion of the project work compared to traditional construction. The risk of weather delays can also be mitigated as approximately 60–90% of the construction work is completed inside the factory. The faster delivery of buildings is offering a quicker return on investment. Modular construction follows the same building codes and standards as conventionally constructed structures and can utilise the same traditional construction materials such as timber, concrete and steel. To ensure that fabrication, transportation, storage and installation occur in a

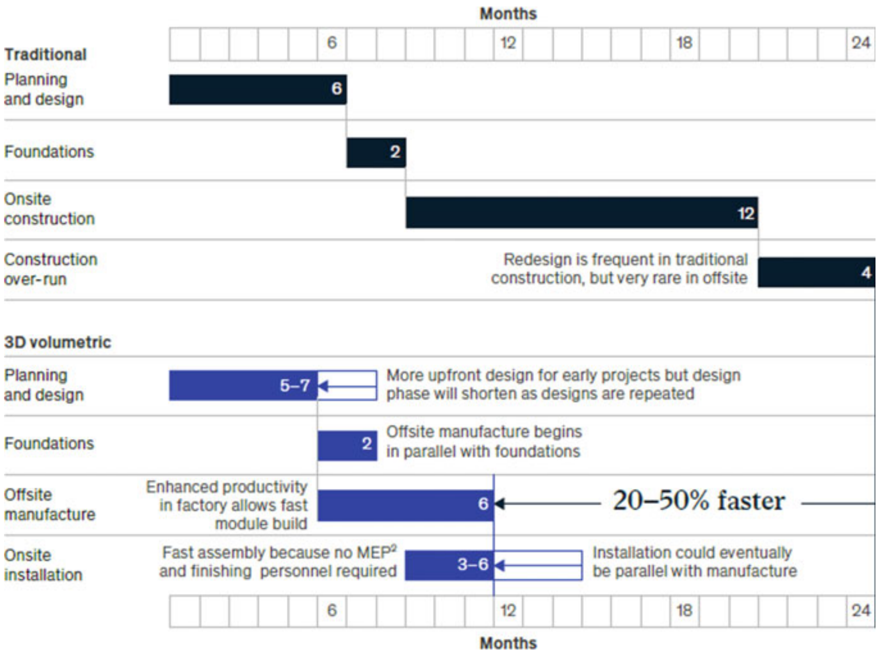


Fig. 1 Project construction duration: traditional versus modular (Bertram et al., 2019)

timely and cohesive manner; the contractors or suppliers should be involved during the design phase (Molavi & Barral, 2016). Figure 1 compares the completion time between traditional construction and 3D volumetric modular construction, which shows that an offsite manufacturing can reduce 20–50% construction time.

Smarter: The risks of accidents and associated liabilities for workers can be minimised by the indoor construction facilities and automation. The implementation of health and safety policies, procedures and risk assessment of standard manufacturing process is much easier than construction site. The quality of prefabricated modules is verified through non-destructive testing in a factory setting to prove that they pass and being certified for their design and performance requirements. Other than superior durability and higher quality, offsite construction greatly reduces on-site logistic volume, noise and overall local disruption. Only, a limited number of workers are required on site that reduces the project cost since a major part of the construction is completed off site. The consideration of high-performance design features, energy modelling and incorporation of solar or wind power can help to achieve net zero (Lawson et al., 2014).

In addition, the modular method of construction is often considered as safer (by relocating most jobs into a sheltered/controlled factory environment and eliminating most work at height) and of higher quality (better quality control of a production line). There also can be societal benefits of changing jobs from needing travelling worked temporarily on-site to being close to home.

3 Design Requirements of Modular Buildings

A reliable design guideline for modular structure is necessary to further reduce the overall project cost and completion time (White et al., 2015). In modular construction, typically, two design approaches such as load bearing wall modules and corner supported modules are followed for concrete and steel, respectively. The current design approach is considered traditional limit state design criteria based on strength and serviceability. When introducing new materials in modular construction, the overall public perception is that the modular components do not satisfy the minimum standard requirements as their long-term performance is still unclear. To ensure a safe design, all possible loading circumstances should be considered. The short-term loading generated during manufacturing, assembling and transporting modules may affect load-transfer mechanisms, the unavoidable fact which is different from the traditional construction.

Moreover, a different sets of equipment are required for on-site assembling when compared with traditional construction method. The influence of on-site installation must be taken into consideration. Because of this variability, the design guidelines for traditional construction might not be the best option for modular buildings. Therefore, developing suitable design strategies for modular structures is essential as the 80% of the building operational costs is dependent on the design stage (Bogenstätter, 2000). Handbooks were developed for the design of modular structures around the world (Bayliss & Bergin, 2020b; Lawson et al., 2014; Murray-Parkes et al., 2017; Smith, 2011). These handbooks are intended to provide technical guidance for modular construction and design to meet the expectation for different stakeholders. Although it is promoting the uptake of safe and high-quality modular structures, the design and selection of materials need to comply relevant standards and industry best practice. Table 1 summarised relevant guidelines and standards that are currently being used around the world.

The design of structure in a particular region is highly dependent on their temperature and moisture. To ensure efficiency and longevity of the structures, different building techniques including safe materials selection, cost-effective and energy efficient design approach need to be considered for different temperatures, moisture

Table 1 Relevant technical guidance and standards used for modular construction

Regulations	Services	Relevant codes/standards used in Australia
Design	Handbook, UK	The modular housing handbook—Bayliss and Bergin, 2020, UK
	Book, UK	Design in modular construction—Lawson et al., 2014, UK
	Handbook, USA	Prefab architecture: A guide to modular design and construction—Ryan E. Smith, 2011, USA
	Handbook, Australia	Handbook for the design of modular structures—Murray-Parkes et al., 2017, Australia

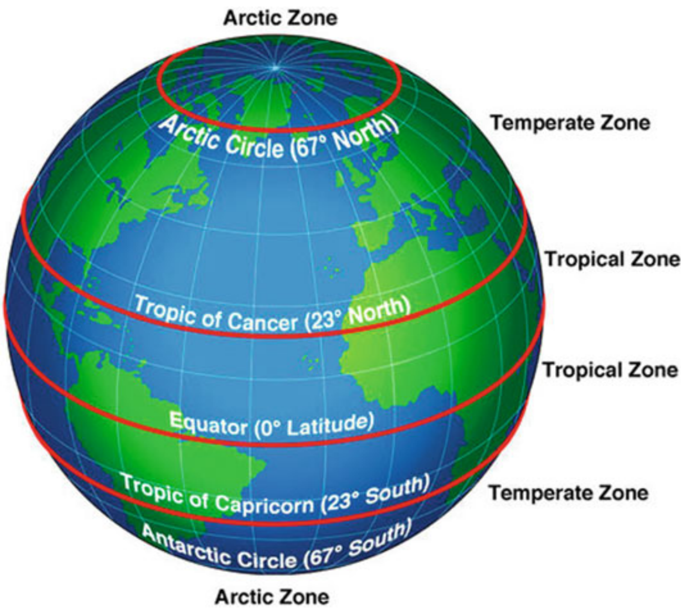


Fig. 2 Example climate zone map (CK-12, 2021)

and extreme weather. Understanding the climate, zone map is therefore important. Figure 2 is showing an example of the climate zone map for Australia, whilst the design requirements for different climate zone are provided in Table 2.

4 The Future of Modular Construction

4.1 Modular Construction Market

The global market size of modular construction is projected to increase to US$108.8 billion at a compound annual growth rate (CAGR) of 5.75% from 2020 to 2025 (Fig. 3) (Modular-Construction-Market, 2021). The North America, Europe and Asia–Pacific regions will continue to dominate modular construction market, whilst the interest will grow in South America, Middle East and Africa. The cheap labour and acceptance of lower quality buildings providing an effective barrier to entry in these markets. Modular construction can claim $130 billion of the market by 2030 in USA/Europe, bringing an annual cost savings of $22 billion that would help fill a productivity gap of $1.6 trillion reported in 2017 (Bertram et al., 2019).

The sustainable modular construction is estimated to dominate the market in near future (Modular-Construction-Market, 2021). Currently, steel holds the largest share in modular construction market due to its design flexibility, high strength,

Table 2 Design requirements for different climate zone (QLD-Government, 2021)

Climate zone	Tropical	Sub-tropical	Hot arid	Warm	Cold
Description	Warm winters, hot humid summers and high summer rainfall	Mild winters and warm humid summers	Cold winter nights and hot dry summers	Cool winters and warm summers	Mostly cold temperature during the whole year
Average temperature, °C	25–32	22–30	20–35	16–30	−3 to 10
Design aim	Cool the interior all year round	Provide some warmth for winter and cool the interior for summer	Complex design issues due to the seasonal extremes	Warm in winter	Warm in the whole year
Building materials	Lighter materials, such as metal and timber	Combination of lighter and denser building materials	Combination of lighter and denser building materials	Denser materials, such as brick and concrete	Denser and high insulation materials
Design consideration	Allow for good ventilation, high ceilings, well-insulated and ventilated roof	Allow for good ventilation, high ceilings, insulate walls	Allow for good ventilation, high ceilings, light-coloured walls and roof, reduce east- and west-facing windows and walls	Allow for good ventilation, high ceilings	Slippery and sloped roofs, right number of windows, lower ceilings, darker colour of roofs and walls

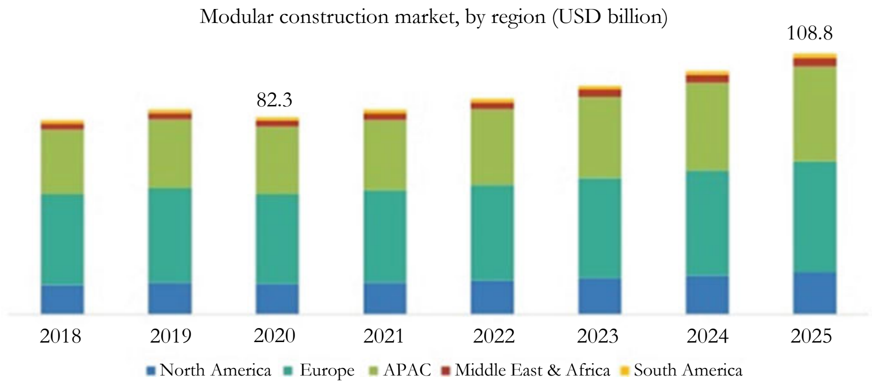


Fig. 3 Prediction of modular construction market by region (Modular-Construction-Market, 2021)

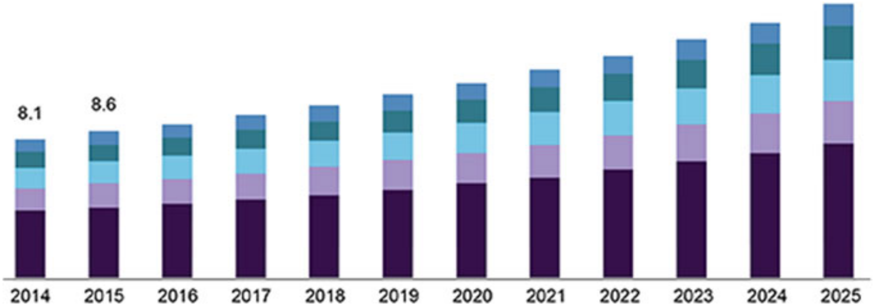
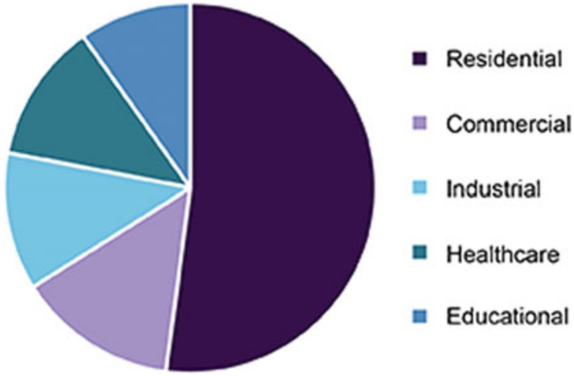


Fig. 4 Modular construction market size in the United Kingdom by application (USD billion) (Market-Analysis-Report, 2019)

Fig. 5 Global modular construction by application, 2018 (Market-Analysis-Report, 2019)



structural integrity and fire resistance that minimising maintenance cost. Moreover, steel frames are easier and safer over timber-framed relocatable buildings due to their superior structural integrity. The United Kingdom is one of the leading markets for modular construction that is projected to increase twice by 2025 compared to 2014 (Fig. 4). The largest application of modular buildings is within the residential sector followed by commercial, industrial, healthcare and educational sectors as shown in Fig. 5. However, the healthcare sector is predicted to be the fastest-growing modular construction market for the next few years (Modular-Construction-Market, 2021). The transportation route and method can play an important role for future growth of modular construction market.

4.2 Cost Analysis

High initial cost is required to establish manufacturing plant for prefabricated modules (Boyd et al., 2013; Rahman, 2014). Based on the opinion from 100 UK house-builders regarding modular construction, Pan et al. (2007) reported that the high initial cost is one of the challenges to promote modular construction. For example, Laing O'Rourke has invested 104 million pounds on a modular construction facilities, whilst L&G spent 55 million pounds for setting up a factory (Pinsent-Masons). Jaillon and Poon (2008) mentioned that the high initial capital is a major barrier to prefabrication in a dense urban area. Mao et al. (2015) indicated high initial cost is one of the top three major challenges for modular construction.

A proper planning, economic design process and advanced manufacturing can reduce the total cost of modular buildings. For example, automated manufacturing process for fabricating numerous modules simultaneously can save on materials, labour and transportation costs (Arashpour et al., 2018; Quale et al., 2012). The operational costs of a building can be minimised by microgrid integration and thermal comfort (Lešić et al., 2017). In addition, the low interest on borrowed capital, savings on consultants' charges because of standard modules, quick start-up of the owner's business are also expected to reduce the high initial cost of modular construction. Most importantly, the faster construction and lower on-site labour costs than conventional construction method can offset the high initial cost of modular construction. A comparative analysis between traditional and modular construction costs in different construction phases is illustrated in Fig. 6. This analysis showed that there is an opportunity to save up to 20% project cost if conventional construction is replaced by modular construction. On the other hand, the modular construction project cost may increase up to 10% if savings from labour cost are outweighed by materials or logistics costs. Another breakdown cost comparison between site-intensive and modular constructions based on the different activities is shown in Fig. 7. Depending on the design, materials and custom features, the cost of modular buildings can be approximately $2500 to $3000 per square metre (Schneider, 2020).

5 Case Studies of Modular Constructions

Currently, the modular housing is sharing 45% in Finland, Norway and Sweden, 15% in Japan, 10% in Germany, 6% in China, 5% in Australia, 5% in UK and 3% in US of the total new building construction (Bertram et al., 2019). Figure 8 illustrates the position of different countries in terms of supply and demand of modular structures. The both supply and demand for modular structures are increasing in Australia due to their high construction cost and great unmet demand for buildings. Similarly, the raising construction wages in skilled labours have driven a recent shift towards modular construction in the western United States. Approximately, 20–30 thousands units per year were built in Singapore, whilst 15 thousands new homes were constructed in 2018 using modular construction in UK (Bertram et al., 2019). With an increased housing demand and labour shortages in the construction trade, modular construction gains traction in markets with higher housing demands and labour shortages. To meet the UK's housing needs, another 300,000 units must be built every year. Surprisingly, the current supply and demand in Germany is

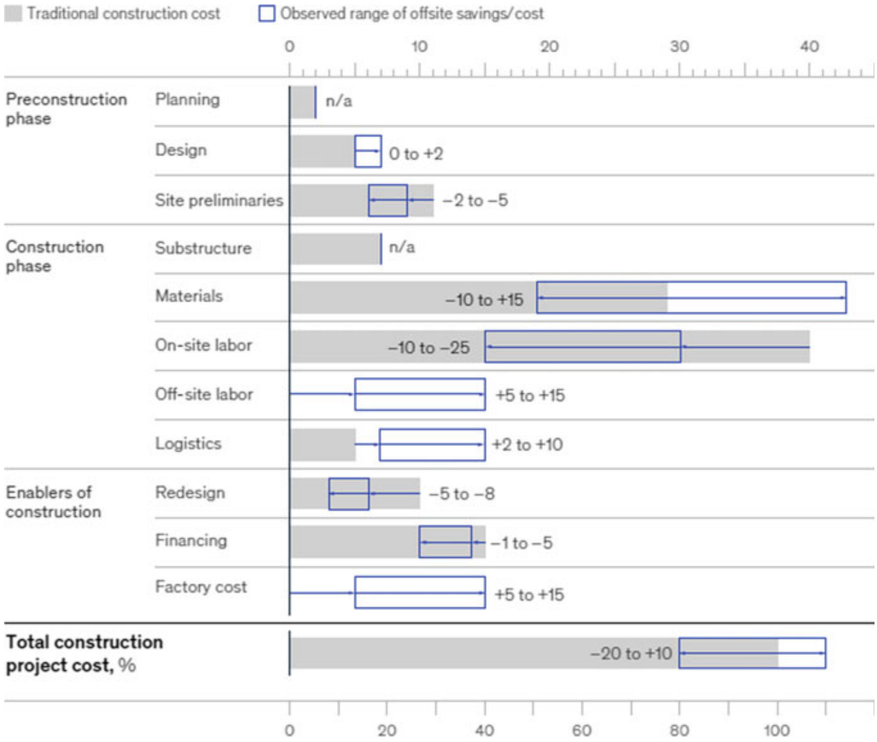


Fig. 6 Project construction cost: traditional versus modular (Bertram et al., 2019)

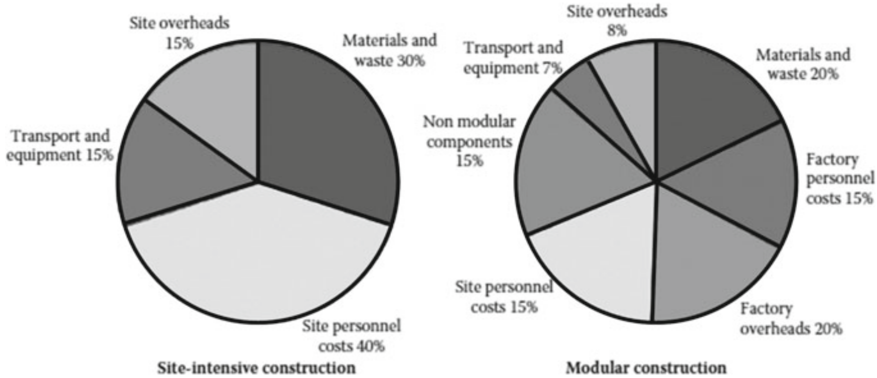


Fig. 7 Breakdown cost comparison: traditional site-intensive versus modular construction (Lawson et al., 2014)

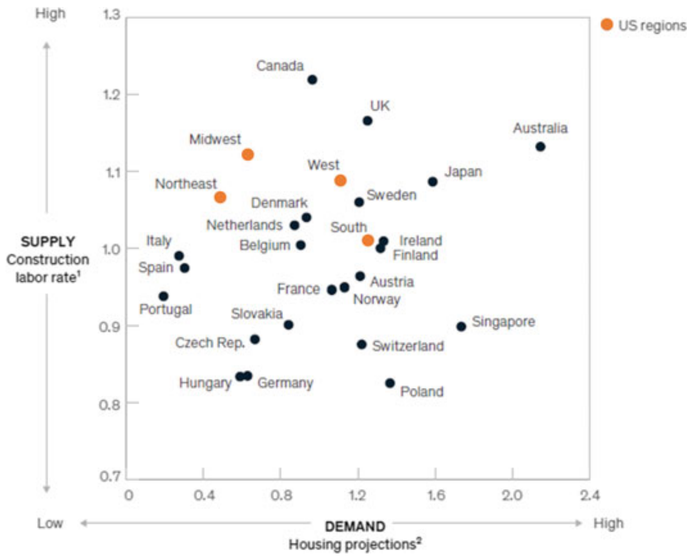


Fig. 8 Construction labour supply versus near future demand for new housing (Bertram et al., 2019). [1]Construction wage-to-national median wage and [2]2017–20 average housing projection as a percentage of national housing stock

appearing low. This is perhaps due to their construction strategy where the buildings are mostly constructed by private households that can make a difference in the dynamics of construction market. Technology advancements such as robotisation and 3D printing make modular construction more productive and environmentally friendly. By reusing and controlling construction space, modular construction reduces wastage of raw materials without compromising the integrity of the building. The growth of the market is driven mainly by infrastructure investments and government initiatives; however, the rising offset manufacturing investment and financial crisis may be challenges.

Residential and commercial are the two broad categories of buildings. The key difference between these two categories are provided in Table 3. A high number of residential and commercial buildings are constructed around the world using modular construction. The case studies for residential houses and commercial buildings are discussed in the following subsections.

5.1 Case Studies for Residential Houses

Residential houses are generally low-rise buildings. Sometimes, they can be constructed to fulfil different objectives. Marmol Radziner constructed a house in Desert Hot Springs, California using modular construction (Marmol-radziner, 2011).

Table 3 Difference between residential and commercial buildings

Key differences	Residential	Commercial
Purpose of construction	Designed to be lived in	Used for business activities
Building materials	Generally, timber frame construction	Generally, steel frame construction
Codes	Simpler and easier regulations than commercial	Stricter regulations than residential
Cost	More expensive due to the increase of overhead, labour and equipment cost	Less expensive due to bidding process and the use of specialised equipment
Example property	Living houses	Office buildings, apartment complex

This building was constructed on a five-acre land that includes two bedroom, two bath and capture the natural views of San Jacinto peak and the nearby mountains. The additional covered outdoor areas provided extra living spaces, and a separate modular carport allows the residents to leave the car behind as they approach into the building.

Atelier Tekuto designed the A-ring house in Kanazawa, Japan with the aim to reduce energy costs (Katherinev, 2009). To achieve this goal, the builders used special aluminium components that can reflect lights, enhance energy-efficiency and reduced energy costs. The water pipes are installed through the interior that is not only providing structural support but also acting as a temperature control system for heating and cooling.

Archipelontwerpers designed the Steel Study House II in Leeuwarden, The Netherlands (CAANdesign, 2015). The design concept of this building is based on the lightweight modular components that combines modern urban design with simplicity to build a cost-effective prefab housing project. This type of design generates less waste and represents the high potential of modular construction project.

The innovative floating home in Seattle was constructed in a nearby shipping yard before it placed permanently in Lake Union (Byers, 2015). This type of arrangements is offering unparalleled views for the residents. The lower level is constructed with ceramic panels and frosted glass, whilst ceramic surfaces and teak wood were selected for the upper level. The exterior materials were selected in such a way that ensures longevity and ease of maintenance.

Portable modular homes or relocatable homes are also available for supporting the needs for urban, rural and regional housing. This type of buildings is compact, cheap and lightweight (Roblin, 2010). Some special features such as overhead cupboards in kitchen, full carpet throughout, built in robes and stainless steel appliances are also available. A brief summary of the different types of modular residential houses is provided in Table 4.

Table 4 Summary of the case studies for residential houses

Objectives	Location	Special features	Example houses	References
House in desert	Desert hot springs, California, USA	Outdoor in-ground pool, fireplace, solar panels and sustainable design solutions		Marmol-radziner (2011)
Reduce energy costs	Kanazawa, Japan	Aluminium components to enhance energy efficiency by reflecting LED lights, interior water pipes offer a thermal radiation system for cooling and heating		Katherinev (2009)
Lightweight house	Leeuwarden, Friesland, The Netherlands	Built with lightweight components, generate less waste and are easier to construct than traditional homes		CAANdesign (2015)
Floating house	Lake Union, Seattle, Washington, USA	Offering unparalleled views		Byers (2015)
Portable house	UK	Compact living spaces, low cost, lightweight and portable		Roblin (2010)

5.2 *Case Studies for Commercial Buildings*

Modular construction is the most suitable construction method for structures with repeated units such as apartments, offices, hotels dormitories, hospitals and schools (Lawson et al., 2012). A large number of tall modular buildings have been constructed around the world in the past decade. The 57-storeyed J57 Mini Sky City was constructed in just 19 days in China (Caulfield, 2016). The modular construction method for J57 eliminated the use of up to 15,000 concrete trucks that reduced a significant volume of construction dust associated with traditional construction processes. Moreover, it has been claimed that the construction method also saved 12,000 metric tonnes of carbon dioxide emissions. The 208-m-tall building was fabricated using steel due to the design flexibility, strength, rapid construction and accuracy.

In Singapore, the Clement Canopy is a prominent modular building completed in 2019 (Pbctoday, 2019). Approximately, 85% work of each module was completed off-site before assembled onsite. This includes such as doors, window frames and glazing, painting, wardrobes and MEP (mechanical, electrical and plumbing) including sanitary and water pipes, which all are totally completed before bringing them on-site. This construction process reduced onsite waste by 70% and offsite waste approximately 30%.

In UK, the modular construction is becoming popular, and currently, more than 7.5% of the new homes are constructed using this method. The noticeable modular buildings are Croydon Tower in London (Price, 2019), Apex House in Wembley (Bayliss & Bergin, 2020a) and Victoria Hall in Wolverhampton (Brown, 2018). The pre-fitted, pre-wired and pre-plumbed modules (i.e. around 95% completed modules) were installed in Croydon Tower immediately after finishing concrete core. The lifting and placing of prefabricated modules in Apex House took only 10 min per unit. The rapid construction process saved the project completion time by 50%, compared to the equivalent steel-framed or concrete-framed tower. Instead, the ground floor of the Victoria Hall was site built, and the remaining floors being assembled using prefabricated modules.

In Australia, the Collins House (Thai et al., 2020) and La Trobe Tower (Online-Editor, 2017) are the significant prefabricated buildings. Each storey of Collins House contains a 150-mm-thick floor, precast post-tension beams and a prefabricated facade. Precast stairs were also built in factory. To avoid the usual disruption during day time, the construction of the 3D volumetric components with integrated facades for La Trobe Tower organised at night, whilst the internal fittings were completed during day time. This system reduced the construction time by 9 months.

In USA, the Tower B2 in Brooklyn (Farnsworth, 2014) and AC NoMad in New York (Morris, 2019) are the two significant modular constructions. Tower B2 was constructed with 930 prefabricated steel modules with 17% lower cost compared to conventional construction. Similarly, each steel module in AC NoMad comprised with guest room, flooring, bedding, even toiletries and the rooftop bar is also concepted using prefabricated modules. However, the public areas, such as the lobby and restaurant are constructed using conventional construction methods. A summary of the notable commercial modular buildings is provided in Table 5.

Table 5 Notable commercial modular buildings around the world

Height, (m)	No. of storey	Name and location	Year completed	Completion time	Service	References
208	57	J57 Mini Sky City, Changsha, China	2015	19 days	Atriums, apartments and office space	Caulfield (2016)
184	60	Collins House, Melbourne, Australia	2019	30 months	Residential tower	Thai et al., (2020)
140	40	The Clement Canopy, Singapore	2019	30 months	Commercial flat for residents	Pbctoday (2019)
135	44	Croydon Tower, London, UK	2018	35 weeks	Commercial flat for residents	Price (2019)
133	44	La Trobe Tower, Melbourne, Australia	2016	16 months	Residential tower	Online-Editor (2017)
109	32	Tower B2, Brooklyn, USA	2015	–	Commercial flat for residents	Farnsworth (2014)
109	26	AC NoMad, New York, USA	2020	–	Hotel	Morris (2019)
83	29	Apex House, Wembley, UK	2017	12 months	Student accommodation	Bayliss and Bergin (2020a)
77	24	Victoria Hall, Wolverhampton, UK	2009	27 weeks	Student accommodation	Browns (2018)

6 Innovations in Modular Construction

6.1 Opportunities with Composite Materials

Researchers around the world are now exploring the acceptability of fibre-reinforced polymer (FRP) composites and laminated veneer lumber (LVL) as alternative materials to replace timber, concrete and steels in modular building applications (Chybiński & Polus, 2021; Ferdous et al., 2018; Nguyen et al., 2014; Satasivam et al., 2018; Sharda, 2021). Griffith (Griffith) indicated that the lack of knowledge on the behaviour of new materials is responsible for underestimating their properties in prefabricated building components. However, in one particular example, FRP was used to construct a 5-storey office building justified the credibility of FRP composites for low-medium rise buildings (Keller et al., 2016). FRP modular buildings are expected to design by considering the load bearing wall module system. Therefore, the mechanical performance of a modular composite wall system ensures the suitability of this technology in modular building construction (Manalo, 2013). An investigation on the static performance of a modular FRP sandwich slab system showed that the bending stiffness can be engineered as per design requirements (Satasivam et al., 2018). The post-fire mechanical performance of prefabricated fire-resistant panels has indicated that the modular composite slabs are able to sustain around 50% of the structural stiffness and strength after 90 min of fire exposure (Zhang et al., 2018). FRP composites have also shown great potential to resist impact loads and corrosion (Fang et al., 2019; Zangana et al., 2020). These are some of the evidence that the FRP will take the lead for future materials in modular constructions.

6.2 Future Opportunities

FRP composites and laminated timbers are offering several advantages over the traditional construction materials. The challenges of using FRP and laminated timbers in construction need to be addressed that might open the door for future research opportunities. The long-term behaviour of composite modular structures under extreme loading conditions need to be investigated to ensure reliability and safety during the design lives. The short-term (e.g. transportation and handling) and long-term-imposed (e.g. fatigue and durability) action need to be considered for the design of modules.

The sustainability of modular structures and life cycle cost analysis is the two major areas where only limited information is available. The expected lower life cycle cost due to the use of FRP that requires less maintenance than traditional constructional materials may offset the high initial investment cost of modular constructions. The brittleness or low ductility of the FRP materials can be a challenge for utilising composite materials in construction; however, a suitable design guideline may overcome this issue. Modular building's structural integrity and performance are highly dependent on the inter-module connections. Some potential connections systems are exist, but developing a reliable connection system is still a challenge (Ferdous et al., 2019). The limited information on fire performance of the composite materials is also restricting their reliable application. In addition, the manufacturing of lightweight and durable modular units, smart connection system, suitable computational tools and reliable design provisions is the key challenges for next generation modular buildings.

7 Conclusions

Offsite modular construction has demonstrated several advantages over the traditional onsite construction in terms of minimising construction time, reducing construction wastes, improving quality within reasonable price and more importantly minimising negative environmental impacts. Despite having significant benefits of modular construction, the private companies still relies comprehensively on the traditional on-site construction method due to limited variety of design, complex approval processes, transportation difficulties, higher upfront costs and difficult financing. However, the modular construction increased significantly all over the world in the last few years. The acceptance and application of modular construction can be increased further with the development of design provisions and in using new generation materials that can exploit the many benefits of this type of construction system. Obviously, the shorter the construction period, the less the developer's carrying costs and the quicker the project will return a profit.

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Chapter 12
Concrete 3D Printing: Challenges and Opportunities for the Construction Industry

Ali Kazemian, Elnaz Seylabi, and Mahmut Ekenel

Abstract Construction 3D printing holds great potential for pioneering a digital transformation in the construction industry. This automated construction technology is introduced in this chapter, and relevant developments and advancements are presented. Next, major existing challenges of widespread adoption of this technology by the construction industry are discussed in detail. These obstacles and areas of uncertainty include the structural performance of 3D-printed elements, concrete reinforcement, process reliability and limitations, and regulatory challenges. Finally, different application domains and new possibilities which could be realized by this new construction method are discussed in detail to provide a comprehensive overview of the extrusion-based concrete 3D printing technology and its implications for the future of the construction industry.

Keywords 3D printing · Automated construction · Reinforcement · Regulations · Cementitious materials

1 Introduction

1.1 Digital Transformation in the Construction Industry

Digital transformation is a result of confluence of new technologies which promote connectivity, advanced analytics, automation, and advanced manufacturing (Siebel, 2019). This major paradigm shift is changing the dynamics in almost every major industry. Based on McKinsey's Industry Digitization Index, which involves 27 indicators for measuring the digital assets, digital usage, and digital workers in each sector,

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_12

construction is categorized as a sector with "low digitization" (Manyika et al., 2015). During the past decades, productivity in the construction sector has been stagnant, while other industries such as manufacturing have experienced significant improvements in the productivity. It is estimated that 5–10 times productivity boost is possible for some parts of the construction industry by adopting a manufacturing-inspired production system (Barbosa et al., 2017). Infusing digital technology, new materials, and advanced automation are key factors in realizing a much-needed productivity boost.

There are various ongoing efforts and technological developments toward digitization of the construction industry. For instance, building information modeling (BIM) is an important development which streamlines design and data collection and analysis by different stakeholders and teams within a digital platform. Recent efforts have demonstrated the benefits of adopting BIM technology, such as automated code-compliance checking, automated cost estimation, scheduling, clash detection between different disciplines, and energy analysis (Azhar et al., 2011; Davtalab et al., 2018).

Although some improvements are achieved by implementing technologies such as BIM in the construction industry, the manual processes involved in the construction phase are still a major obstacle toward realizing a manufacturing-inspired production system. Low construction productivity, growing labor costs, high accident rates, cost and schedule overruns, and poor quality are some of the consequences of these manual construction methods. Robotic construction seems to be a viable path toward digital construction, but it is yet to be proven practical before it is widely adopted by the construction industry.

1.2 Earlier Efforts Toward Automated Construction

Construction automation has remained a challenging topic of investigation for engineers for several decades. In 1980s and 1990s, Japanese construction companies were pioneering the research and development efforts on design and application of robots in their construction projects (Morales et al., 1999). These efforts were initially limited to experimentation with single-task robots and were mostly motivated by the shortage of skilled construction labor in Japan, and the low productivity observed in the Japanese construction industry. Examples of these single-task robots include concrete floor finishing robots, painting robots, and ceiling board installation robots (Castro-Lacouture, 2009). In late 1980s, these efforts aimed at developing integrated automated building construction systems (ABC), which resulted in multiple systems developed by different companies, such as Big Canopy by Obayashi and SMART by Shimizu (Morales et al., 1999). SMART was an integrated system designed to automate various activities such as steel frame erection and welding and wall panel installation. Big Canopy system included four tower masts and a massive canopy at the top, which lifted prefabricated material to the target floor. The control and maneuvering of the components were done using joysticks (Castro-Lacouture, 2009). These

ABC systems were used in several projects but were not continued after a few years. According to the Japanese Construction Mechanization Association, the failure of such construction automation efforts can be attributed to the significant research, development, and manufacturing costs of these systems which could not be recovered, as well as the overall inability of these systems to considerably reduce onsite labor requirements (Taylor et al., 2003).

1.3 Recent Developments

A more recent movement toward construction automation started with the invention of contour crafting (CC) in 1997 at the University of Southern California (Khoshnevis, 1998; Khoshnevis & Kazemian, 2020). CC uses computer control, material extrusion, and the superior surface forming capability of troweling to create smooth, accurate, planar, and free-form surfaces. It provides architects the flexibility to design curved surfaces as easily as traditional rectangular shapes (Fig. 1). By automating the construction process using CC technology and reducing the need for human labor, significant reductions in construction time and cost could be achieved while creating a safe working condition (Ghaffar et al., 2018; Khoshnevis et al., 2006). It is reported that only in the United States, over 1100 construction worker fatalities happen each year (United States Department of Labor). The high number of injuries and fatalities on the construction sites can be reduced by adopting automated construction systems, and assigning human workers to supervisory and machine control roles. Such improvement would be contingent on developing and following new measures to ensure safety during human-construction robot interactions. Another major distinction between CC and conventional concrete construction is eliminating the need for formwork to shape the fresh concrete, which makes the CC process significantly faster.

Fig. 1 3D-printed concrete element using CC technology (Davtalab et al., 2018)

Invention of CC later started the field of construction 3D printing (C3DP). Various similar large-scale 3D printing systems have been developed based on the extrusion of cementitious materials. Continuous mixers and concrete pumps are commonly used to deliver the printing materials to a robotic system which deposits cementitious layers according to the computer-generated commands after processing a 3D model. Different types of robotic systems such as articulated robots, and gantry, delta, and crane type robots have been used for layer deposition within the robot's build envelope (Hojati et al., 2018; Kazemian et al., 2017). Four examples of construction 3D printing systems are presented in Fig. 2.

During the recent years, there have been several other innovative approaches toward automated construction which rely on concepts other than extrusion of cementitious mixtures. D-shape (Colla & Dini, 2013) and smart dynamic casting (Schultheiss et al., 2016) are two prominent examples of these innovative automated construction systems. D-shape is a construction-scale particle bed 3D printing process in which layers of sand are deposited, and then, particles are selectively bonded using a binder material. After the fabrication process is complete, the residual

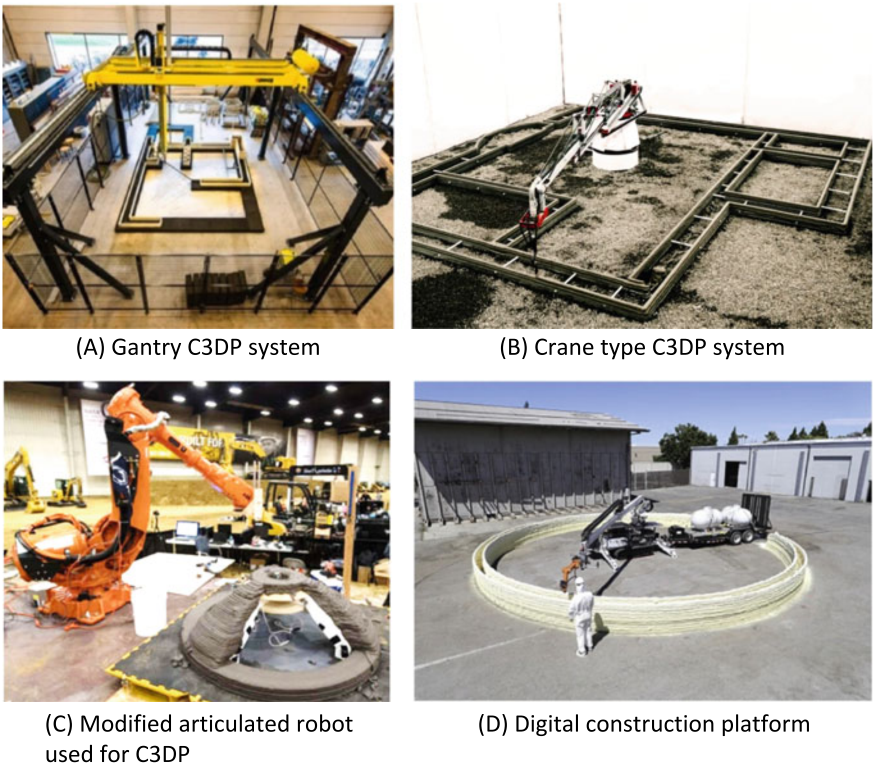

Fig. 2 Examples of different robotic systems used for construction 3D printing (Kazemian et al., 2017; Li et al., 2020b; Paolini & Rank, 2019; Zhang et al., 2019)

Fig. 3 Smart dynamic casting (Lloret-Fritschi et al., 2020)

sand is removed, and the object is infiltrated by additional binder, and finally, it is sanded and polished (Lowke et al., 2018). Smart dynamic casting (SDC) is a robotic slip-forming process where an actuated formwork, which is much smaller than the final produced element, is used to shape concrete. SDC requires precise control of material properties and rheology during the process (Lloret et al., 2015) and is able to produce bespoke reinforced concrete elements without any post-processing (Lloret-Fritschi et al., 2018). A concrete column fabricated by the SDC technology is shown in Fig. 3.

Among these recent developments and innovations, extrusion-based C3DP seems to hold great potential in revolutionizing the construction industry and being deployed in a massive scale in the near future. In the following sections, different aspects of this automated construction technology as well as recent advancements and existing barriers to its adoption by the construction industry are discussed in detail.

2 Current Status of the C3DP Technology

Two main scenarios can be considered for widespread adoption of C3DP technology by the construction industry: (1) Using concrete 3D printers in the prefabrication facilities to produce structural elements and (2) Using portable concrete 3D printers for onsite construction. Successful demonstration projects have been carried out for both scenarios. The first scenario, prefabrication, seems to be an easier starting point to facilitate adoption of C3DP technology by the conservative construction industry. Prefabrication facilities provide an ideal environment to implement a tightly monitored and controlled concrete 3D printing process which can operate continuously, with minimal human intervention. The same does not hold true for onsite construction where the ambient conditions (temperature, wind speed, humidity, and rain) can affect the process and impact the construction quality or even lead to process failure, such as collapse of freshly printed walls.

On the other hand, there are several disadvantages that can be attributed to the prefabrication 3D printing scenario. In this method, the production of structural elements is automated; however, transportation and assembly are still needed and can significantly add to the total construction time and cost. The onsite assembly of 3D-printed elements is still a manual and time-consuming task, which needs skilled workforce. These requirements are in conflict with the main goal of improving the construction productivity. In addition, to ensure a successful onsite assembly, tight quality control and high dimensional accuracy are required for the prefabricated 3D-printed elements. These restrictions do not apply to onsite C3DP, where a portable construction printer builds a structure in a single process and allows for minor process modifications. In addition, by shipping only one portable printer and needed materials to the construction site, a large number of structures can be constructed on the jobsite. Therefore, it seems that onsite C3DP is generally more advantageous in terms of productivity and process automation, while it is technically more challenging to design and implement a robust, portable, easy to set up, and reliable C3DP system for onsite applications.

In the following sections, recent developments and advances in printing materials, process quality control, and code compliance of 3D-printed structures are discussed in detail.

2.1 Printing Materials and Testing

Various materials such as clay, plastic, geopolymer, and sand have been successfully used for large-scale 3D printing (Chougan et al., 2020). However, Portland cement-based mixtures are the most commonly used printing material for C3DP. Portland cement-based concrete is the most widely used engineering material for conventional construction as well, with three primary reasons for its wide application: Excellent resistance to water, deformability in fresh state, and the fact that it is usually the cheapest and most readily available construction material. Unlike wood and ordinary steel, the ability of concrete to withstand the action of water without serious deterioration makes it an ideal construction material. Formability of cementitious mixtures in the fresh state enables engineers to form structural elements into a variety of shapes and sizes. Finally, the relatively low cost of concrete has significantly contributed to its wide application. The principal ingredients for mortar and concrete, namely aggregate, water, and Portland cement are relatively inexpensive and are readily available in most parts of the world. It should be mentioned that there are also other properties which are critical in some applications, such as fire and termite resistance of concrete (Kazemian, 2018).

Portland cement-based mixtures which are commonly used in C3DP have high Portland cement content, no coarse aggregate, and multiple chemical admixtures to modify the rheology and setting time of the printing mixture (Nerella et al., 2016; Kazemian et al., 2017). Considering the widely known negative environmental impacts of Portland cement production, high Portland cement content printing materials are not desirable from a sustainability standpoint. Extensive research is being carried out to eliminate or reduce the Portland cement content in the C3DP materials (Bhattacherjee et al., 2021; Bong et al., 2019; Panda & Tan, 2018). In addition, to improve the tensile strength and ductility of Portland cement-based printing materials, inclusion of discontinuous and uniformly dispersed fibers—such as steel and PVA fibers—has been studied by different researchers (Arunothayan et al., 2021; Bos et al., 2019; Ding et al., 2020).

There have been numerous studies on development and characterization of mortar and concrete mixtures for C3DP (Kazemian et al., 2017; Nematollahi et al., 2018; Panda & Tan, 2018; Sanjayan et al., 2018; Wolfs et al., 2018). With respect to the characterization of the fresh properties of printable cementitious mixtures, two categories can be recognized: (1) fundamental rheological properties and (2) performance-based workability tests. Fundamental rheological studies rely on measuring parameters such as yield stress and plastic viscosity of fresh printing mixtures and enable evaluation of the structuration rate and thixotropic behavior of different mixtures. Therefore, these rheological measurements provide a deep understanding of behavior of different mixtures over time and reveal the influence of different admixtures on the printing materials (Jeong et al., 2019; Perrot & Pierre, 2016; Roussel, 2018). The other approach for characterization of fresh properties of printing materials is based on performance-based testing, where the workability aspects, which are critical during the C3DP process, are defined and tested. Extrudability, shape stability, and printability timespan are some of the performance criteria which have been defined by researchers, and different test methods have been proposed for evaluating these workability aspects (Kazemian et al., 2017; Le et al., 2012). Shape stability is considered as the most critical property of a fresh printing mixture and is defined as the ability to resist deformations during layer-wise concrete construction. There are three main sources of layer deformation during C3DP: layer's self-weight, weight of following layer(s) which will be deposited on top of it, and the extrusion pressure (Kazemian et al., 2017). Addition of viscosity modifying agents (VMA) and nano-clay has been reported as effective measures to improve the shape stability of printing mixtures (Kazemian et al., 2017; Zhang et al., 2018).

2.2 Process Quality Control

In order to realize the full potential of C3DP and promote its wide application in real-life projects, robust and reliable processes should be designed such that variations in the ambient conditions or material properties do not lead to process failure (Ghaffar et al., 2018). Regarding the printing materials, in specific, some variations seem inevitable due to inconsistencies in the moisture content and grading of aggregates, as well as other sources such as imprecision of material dosing and measurement units. In C3DP, the stability of fresh concrete layers is an important topic, which needs process optimization accounting for different factors such as printing speed and material stiffening rate. Even at an optimized printing speed, however, variations in the rheological properties of a deposited layer could result in the collapse of freshly printed components and structures. Therefore, an inline real-time quality monitoring system is required to detect variations in the properties of the printing material during the process.

Kazemian and Khoshnevis (Kazemian, 2018; Kazemian & Khoshnevis, 2021) proposed and evaluated four different techniques for real-time extrusion quality monitoring. These four techniques are described in Table 1. In this study, change in the free water content was considered as the major source of variations in the printing mixture. A previously tested printing mixture was selected as the reference, and six levels of variation (error) in the free water content was intentionally applied to the mixture, resulting in a total of seven mixtures. These variation levels include ±5, ±10, and ±15 L/m^3 change in the water content of the printing mixture.

Table 2 presents the obtained results for the proposed real-time extrusion quality monitoring, where a higher sensitivity index shows a greater change in the measured parameters as result of material variations. The technique based on computer vision was proved as the most accurate and reliable extrusion monitoring technique, which was able to detect all the tested variation levels. These results imply the high potential of computer vision for C3DP process monitoring. In another study (Kazemian et al., 2019), the developed computer vision system was successfully used to develop a closed-loop extrusion system where the feedback by the vision system is used to automatically adjust the extrusion rate and constantly produce layers with consistent dimensions. Such intelligent extrusion systems could be used to improve the dimensional accuracy of 3D-printed elements and also eliminate the need for extrusion calibration and to enable multi-material 3D printing.

In a recent study, Davtalab et al. (2020) designed and implemented an automated layer defect detection system for C3DP. This automated inspection system builds upon a customized deep convolutional neural network which distinguishes concrete layers from surrounding objects by semantic pixel-wise segmentation. This model was trained, tuned, and tested using 1 million labeled images. Then, an innovative defect detection approach was designed and used to detect deformations in the printed concrete layers. The results showed a total accuracy of 97.5% and a miss rate of less than 6% for the defect detection model. The results of this study further highlight the great potential of computer vision and deep learning for quality control and inspection during concrete 3D printing (Fig. 4).

Dimensional accuracy of 3D-printed components and consistency of as-built dimensions with the initial CAD model are very important in the prefabrication construction. Other than computer vision, there are other well-established measurement approaches such as laser 3D scanning and structured light scanning which are frequently used in other fields. These techniques could be used to create a digital twin

Table 1 Proposed techniques for real-time extrusion quality monitoring

Technique	Hypothesis	Implementation notes
Agitator motor power consumption	By monitoring the changes in the electrical power consumption of an agitator motor, undesirable changes in the rheology of printing material could be instantly detected to prevent deposition of unacceptable layers	3D-printed blades were installed on a shaft connected to a DC motor. The design of the blades is similar to the continuous concrete mixers which are commonly used in construction, while the functionality of these blades is similar to a viscometer paddle. The power consumption of the DC motor is used as an indication of material viscosity
Extrusion pressure measurements	At a constant extrusion rate, monitoring the changes in the extrusion pressure could reveal the variations in the viscosity of printing material	A 0.5 mm thick resistive pressure sensor with an active sensing area of 38 × 38 mm, a microcontroller, and a customized 3D-printed nozzle was used to measured extrusion pressure inside the nozzle every 15 ms
Electrical resistivity measurements	Monitoring the changes in the electrical resistivity of printing material reveals the unacceptable changes in the water content of the printing material	To simplify the testing conditions, the electrical measurements were carried out on 100 × 200 mm cylinder specimens of fresh printing mixture. A preliminary experimental program was carried out to find the optimum frequency (1 kHz), amplitude (8 $V_{\text{p-p}}$), and waveform (sine wave), before the main experiments
Computer vision	By capturing and analyzing top-view images of the extruded layer using a camera, the layer width can be continuously measured in real time and compared to the target width, for automatic detection of over-extrusion or under-extrusion conditions	A computer vision algorithm was developed to detect the extruded layer and to measure the layer width in real time to compare to the target layer width and detect over-extrusion or under-extrusion conditions. To calibrate the system, layers with precise dimensions were cast and used

of the as-built structure and therefore enable real-time detection of geometrical inconsistencies. Buswell et al. (2020) discussed applications of digital measurement techniques for C3DP and the assembly of a set of 3D-printed elements. These researchers have suggested the application of these measurements during four different stages: before the printing process starts (for process and material assessment), during the process (to compensate for plastic deformation), after the printing process (for application of secondary processes), and after assembly of 3D-printed components (for documentation) (Buswell et al., 2020).

Table 2 Sensitivity index of the proposed techniques at different variation levels

Variation level (liter/m^3)	Proposed quality monitoring techniques			
	Power consumption	Extrusion pressure	Electrical resistivity	Computer vision
+5	x	x	x	2.8
−5	x	x	x	−2.4
+10	x	x	x	8.8
−10	4.9	✓	x	✓
+15	6.5	x	−2.9	15.7
−15	10.0	✓	x	✓

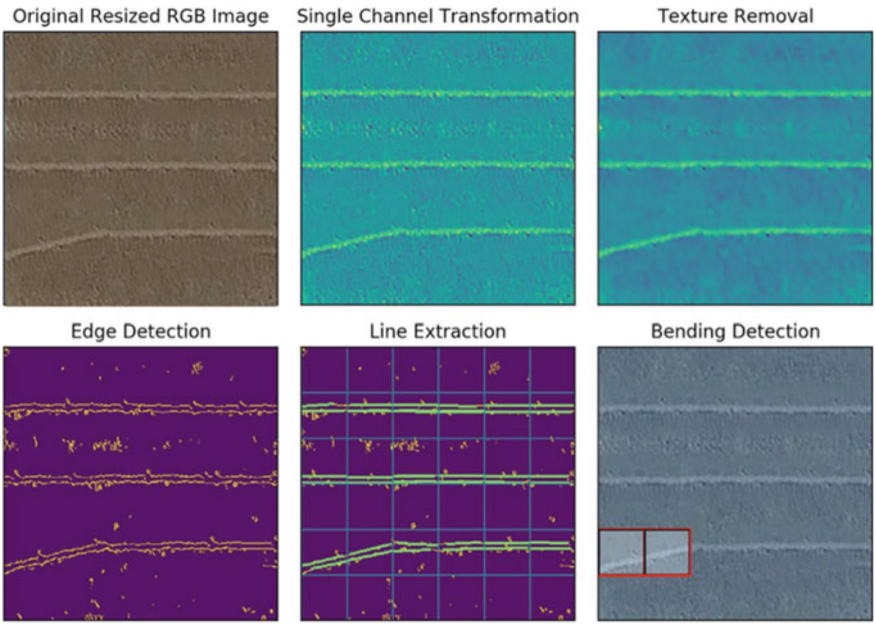

Fig. 4 Automated layer defect detection system (Davtalab et al., 2020)

2.3 *Design Code Compliance*

Design engineers and architects are usually guided by national and local design codes. The design codes become especially important when compliance with the legally adopted code is mandated by a jurisdiction having the authority to approve construction projects. In this section, "building" construction is used in specific to discuss code compliance of C3DP as a new construction method and the recent advancements. In some countries, such as most European countries, there are national building codes which are usually developed under central government supervision and enforced uniformly throughout the country by the central government. However, in other countries such as United States (US), since the power to regulate construction is vested in local authorities, a system of model building codes has been used. The international building code (IBC) and the international residential code (IRC) are the two model codes that have been developed to establish the minimum requirements to safeguard the public health and safety in building construction and are currently enforced throughout the US. To this date (2021), IBC and IRC do not include provisions for building construction using C3DP technology. Chapter 19 of the IBC refers to ACI 318 ("Building Code Requirements for Structural Concrete, 2019) for design of reinforced concrete buildings; similarly, ACI 318 also does not address building construction using C3DP technology.

Alternative Construction Methods and Building Codes: To accommodate new and innovative construction materials and methods, IBC allows the integration of alternative materials, designs and methods, systems and technologies not specifically addressed in the code, permitting manufacturers to demonstrate that their products comply with the intent of the provisions of the building code. To this end, Section 104.11 of IBC/IRC allows an alternative material, design, or method of construction to be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, provided that the material and method under evaluation is at least the equivalent of that prescribed in IBC/IRC in the following six parameters: quality; strength; effectiveness; fire resistance; durability; safety.

The building code compliance is typically accomplished through product testing in accordance with an established and peer-reviewed acceptance criteria (AC). The AC document outlines specific product sampling, testing, and quality requirements to be fulfilled in order to obtain code-compliance verification. The required tests are typically conducted by accredited laboratories, and the results are summarized in a research report made available to code officials, as set forth in Section 104.11.1 of IBC/IRC, which allows such reports to be issued by approved sources. The research reports are typically issued by certification bodies that are accredited as complying with ISO/IEC standard 17065 (2012a).

Besides testing in accordance with the AC requirements, an equally important aspect of product evaluation is the requirement for documentation of quality control measures during the manufacture of the materials. Among other things, the measures are intended to verify that the produced materials will match the performance as previously demonstrated by testing. As a means of verification, the quality system needs to be inspected by an accredited independent inspection agency conforming to requirements stipulated in ISO/IEC 17020 (2012b), as determined by a recognized accreditation body. The evaluation agency is charged with requiring that the inspection agency inspects each manufacturing location regularly, and not less than once per year, to provide assurance that the materials are produced and conform to critical performance and measurements set forth in quality documentation.

Acceptance Criteria AC509: Since building construction using C3DP technology is not within the current code provisions, AC509 was developed under Section 104.11

of IBC and IRC, with a final approval date of December 2020. AC509 applies to the automated C3DP technology, and cementitious mixtures used to construct interior and exterior concrete walls, with or without structural steel reinforcing, used as bearing walls, non-load-bearing walls, and shear-walls, in one-story or multi-story structures. The walls are to be constructed by extruded concrete layers to create two parallel outer face shells, then placing an especially designed concrete core (self-consolidating mixture) between the 3D-printed shells to form a solid wall. AC509 contains provisions for the evaluation of the material and durability properties of the printing concrete and the evaluation of structural performance of 3D-printed concrete walls. AC509 material tests are described in the following paragraphs:

- Concrete Compressive Strength and Slump Testing: AC509 requires a minimum of five replicate specimens for each printing concrete mixture design used for the outer face shells, and for the core, tested for compressive strength in accordance with ASTM C39 (2020) or ASTM C109 (2020). Prior to casting test specimens for compressive strength testing, the slump of concrete must be measured and reported for quality control purposes. AC509 requires a minimum average 28-day compressive strength of 2500 psi (17.2 MPa), and that the compressive strength be used for quality control purposes.
- Freezing and Thawing Durability: The purpose of this test is to evaluate the durability of each printing mixture, used for the outer face shells, and for the core, that is subjected to exposure or freezing and thawing conditions. Tests must be performed in accordance with Procedure A of ASTM C666 (2015) for a minimum of 300 cycles. AC509 requires that the average durability factor of all specimens after 300 cycles must be a minimum of 80.
- Shrinkage and Volume Change Testing: The purpose of this test is to evaluate the shrinkage-cracking response of printing concrete. AC509 requires that the tests are performed in accordance with ASTM C157 (2017) with the following acceptance conditions: The average strain measurements of all tests of printing concrete with fibers or with aggregate size larger than 0.5 inches at 28-days must be less than 0.065%, and all printing mixtures without fibers and with maximum aggregate less than 0.5 inches at 28-days must be less than 0.050%.
- Fiber Compatibility: Because presence of fibers in a printing mixture affects the performance of 3D-printed concrete walls, AC509 requires that fibers used in the printing mixture comply with a consensus acceptance criterion for the purpose of quality control.
- Test for Minimum and Maximum Extrusion Time Intervals: Performance of a 3D-printed wall may be affected by the time interval between extrusion of concrete from the printer nozzle. Therefore, AC509 developed a procedure to understand the effect of minimum and maximum time intervals between extrusions of cementitious layers on the bond between the extrusion layers. The specimens must be 3D printed with the same C3DP technology that will be used for full-size construction. Flexural bond tests must be conducted in accordance with Section 5.2 (Method A) of ASTM E518 (2015) on three replicate sets of specimens cast at both minimum and maximum extrusion time intervals between layers. Test results must show

that the tested flexural bond strengths at minimum and maximum extrusion time intervals are statistically equal. Otherwise, the difference in strengths must be considered by use of a reduction factor in structural design calculations. AC509 also requires that the average flexural bond strength and acceptable extrusion time intervals be reported in the final research report for jobsite inspection use.

In addition to the material tests, AC509 requires full-scale structural tests for each 3D-printed wall configuration, with or without structural steel reinforcement and for each printing mixture design to be tested to justify the design provisions. The following details must be considered while preparing the test plan: each printing mixture design, reinforcing details (rebar size and spacing), if applicable; variation in geometry of the 3D-printed outer shells (such as thickness and width of the extrusion layers) and the proprietary concrete core; minimum and maximum time intervals between extrusion layers to be evaluated. The following load tests are required by AC509:

- Wall Axial Compression Test: A minimum of six specimens, with three replicate specimens of two different wall heights, must be tested. One set of specimens must be of the maximum wall height with the minimum wall thickness to be evaluated.
- Wall Flexure Test: A minimum of six specimens must be tested. The specimen preparation and dimensions must be the same as those used in the wall axial compression test.
- Wall Static In-Plane Shear Test: A minimum of three replicate specimens must be tested for the thinnest wall width to be evaluated. If multiple wall thicknesses are to be included in the evaluation report, an additional three replicate specimens of the maximum wall thickness to be considered must be tested.
- Wall Connection Load Transfer Test: A minimum of three replicate specimens of the connection between the floor and the 3D-printed wall must be tested for the thinnest wall width to be evaluated in accordance with AC509 test provisions. If multiple wall thicknesses are to be included in the evaluation report, an additional three replicate specimens of the maximum wall thickness to be considered must be tested.

In addition, AC509 requires that a design criteria report be submitted by a registered or licensed design professional which must include complete analysis, and interpretation of the qualification test results demonstrating that 3D-printed walls can be designed in accordance with the applicable sections of the IBC. The design characteristic strengths used in the analysis and design must be qualified by the test data. Any deviation from design must be established in the analysis for inclusion in the final research report. Also, per AC509, where loading conditions result in combined transverse and axial loads, the sum of the ratios of actual loads over design loads must not exceed one.

Finally, the following building code-compliance requirements and limitations have also been included in AC509:

- The 3D-printed concrete walls are limited to non-fire resistance-rated construction unless qualified by testing in accordance with ASTM E119.

- At the moment, the 3D-printed concrete walls used as the lateral-force resisting system are limited to seismic design categories (SDC) A and B only until further research is available.
- The foundation, floor, roof, and their anchorage to the 3D-printed walls using code-complaint anchorage provisions are required to be submitted to the code official for approval and are outside the scope of AC509.
- The structural design equations for 3D-printed walls constructed with the specific C3DP technology are to be outlined in the final research report. If applicable, any deviation from code-calculated design to be included. If applicable, the reduction factors coming from different extrusion interval times must also be reported.
- Structural design calculations and details of the 3D-printed walls must be prepared by a registered design professional and submitted to the code official for approval. The structural calculations must also address design and detailing of openings and loads on headers.
- Exterior envelope requirements of the applicable codes have not been evaluated and are outside the scope of the final research report.

3 Existing Challenges and Future Prospects

3.1 Existing Challenges

In this section, some of the most important challenges facing C3DP as a construction method are discussed. Structural performance and reinforcement of 3D-printed structures and elements, process reliability and limitations, and regulatory challenges are three main existing concerns that need to be addressed in order to enable widespread use of this automated construction technology.

Structural Design and Reinforcement: To date, several attempts have been made worldwide to 3D print structures such as concrete buildings and bridges using C3DP (Kreiger et al., 2019; Salet et al., 2018). Due to the lack of the design codes to evaluate the performance and integrity of printed structures, physical experiments at different scales have been used to determine whether the printed systems meet the design criteria and resist the expected service loads. For instance, Salet et al. (2018) performed testing at three scales including material testing of printed concrete specimens to determine material properties, bending testing of a 1:2 scale bridge model to determine the structural performance of the bridge in the laboratory, and load-bearing capacity testing of the full-scale bridge before opening for public use. As another example, Nerella et al. (2019) performed micro- and macro-scale experiments to study the effects of printing direction and time interval between layers, and the introduced anisotropy and heterogeneity, on the mechanical properties of 3D-printed elements.

Different studies have shown that it is feasible for 3D-printed elements and structures to achieve adequate compressive strength capacity similar to the cast-in-place concrete. However, the tensile strength of cast-in-place concrete is significantly low, and 3D-printed concrete is not an exception. One approach to achieve the required performance in tension and bending is to reinforce 3D-printed concrete with steel rebars, similar to the cast-in-place concrete structures. Since automated rebar reinforcement for 3D-printed elements and systems is a complex task, most of the existing studies (e.g., World's largest 3D-Printed Building Completes in Dubai (https://www.dezeen.com/); Kreiger et al., 2019) have considered manual rebar installation, which can significantly diminish the central promises in automating and accelerating the construction processes. Therefore, a main question to be answered is how to enhance the ductile and strain hardening behavior of 3D-printed elements in tension while minimizing or eliminating the need for steel rebars (Ghaffar & Mullett, 2018). Classen et al. (2020) discussed existing methods for 3D printing of the reinforced concrete. Examples are manually post-installed or pre-installed reinforcement as discussed above, multi-arm 3D printing of steel reinforcement and concrete in parallel (Mechtcherine et al., 2018; Schutter et al., 2018), online reinforcement integration through placement of steel wires or cables within concrete layers (Bos et al., 2018a), automated installation of segmental reinforcing elements with locking mechanisms in parallel with the concrete 3D printing process (Khoshnevis & Bekey, 2003), and pre- or post-tensioned tendons to realize pre-stressed 3D-printed concrete behavior (Asprone et al., 2018; Bos et al., 2018b). Figure 5 presents two examples of these reinforcement possibilities explored by the researchers. Most of these methods are not fully automated and call for human intervention; furthermore, existing data on the structural performance of these reinforcement methods are limited. Therefore, extensive physical experiments are needed to investigate the effectiveness of these strategies in different applications and to use the achieved understanding in developing design codes for reinforced concrete 3D printing. It should be mentioned that use of innovative printing materials can be part of the solution to the C3DP reinforcement problem. For instance, using steel fiber-reinforced concrete (SFRC) as a self-reinforced printing material seems to be a viable solution, especially in the regions with moderate and low seismic activity. Steel fibers have already been

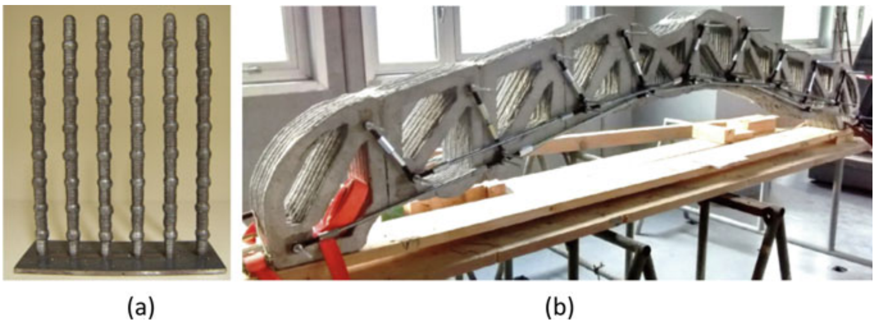

Fig. 5 **a** 3D-printed profiled reinforcement bars by Mechtcherine et al. (2018). **b** External steel reinforcement technique proposed by Asprone et al. (2018)

used for construction of various structures including rebar-free safety houses that meet FEMA requirements for EF5 tornados (Helix Steel). Engineered cementitious composite (ECC) is another fiber-reinforced high performance material with high tensile ductility which has great potential to reduce or eliminate the need for steel rebar reinforcement in 3D-printed concrete structures (Li et al., 2020a).

Moreover, for multi-hazard resilient housing and infrastructure development using C3DP, printed structures need to be designed to withstand the static and dynamic loads imposed due to extreme events, such as hurricanes and earthquakes. Today, no guideline exists for designing such 3D-printed structures, and the existing experimental data about their performance are minimal. Therefore, similar to cast-in-place structures, systematic, and holistic experimental programs should be designed to determine the performance of 3D-printed elements and structures against different design loads. The outcome of such experiments can be used to enhance existing computational frameworks for representing the behavior of 3D-printed structures at micro- and macro-scales. One important research need in this area is developing constitutive relations and the associated energy dissipation mechanisms to define the material stiffness, damping behavior, and anisotropy under both static and cyclic loading scenarios.

Process Reliability and Limitations: The second major existing challenge with respect to the industrial-scale implementation of C3DP is related to the process robustness. Despite some early regulatory efforts to address the quality control measures for C3DP (discussed in the previous section), currently, there are not any universally accepted technique and guideline for quality control and monitoring during C3DP. Failure or malfunction of the system components, variations in the printing materials, and the impact of ambient conditions are the most common issues which are observed in different large-scale 3D printing systems. Process failure due to material preparation and delivery equipment malfunction have been frequently reported, which is mainly because the existing commercial equipment is not specifically designed for the C3DP application. For instance, most of commercial continuous mixers are designed for highly flowable or self-leveling mixtures, and when used with a viscous printing material, the mixing quality and consistency of the produced material are not acceptable. After the mixing stage, in order to deliver the freshly mixed mixture to the concrete 3D printer, a commercial pump (such as a progressive cavity pump) is commonly used. These pumps usually have limitations with respect to the size and percentage of aggregate that can be used in the mixture, as well as the ability to process fiber-reinforced mixtures. The pumpability requirements for a printing mixture can be considered as the major reason for the widespread use of mixtures with aggregate size of less than 5 mm in C3DP. The reduced aggregate size and percentage also leads to an increase in the Portland cement content of printing mixtures—usually in the range of 500–900 kg/m^3 (Kazemian et al., 2017; Murcia & Reda Taha, 2020; Zhang et al., 2018)which has a negative impact on the cost, sustainability, and dimensional stability of the printing material. Therefore, to resolve some of the existing challenges, customized material preparation and delivery systems specifically designed for C3DP are needed. These systems should be able to process mixtures with different type, dosage, and size of aggregate and fiber.

Regulatory Challenges: Another major challenge facing C3DP as a new construction method is related to the construction regulations. One main barrier is the approval of 3D-printed structures where building officials need to determine if the proposed design complies with the intent of the provisions of the legally adopted building code. As mentioned before, currently, IBC and IRC do not include provisions for building construction using C3DP technology. Therefore, a major hurdle in building code compliance is the lack of legally adopted regulations that can be used for project approvals by building departments and building officials in charge of plan checks. Since predominant building and residential codes in the US do not cover this construction technology, two pathways are available:

- The building code must incorporate the technology into the building code through the public hearing process of International Code Council (ICC), or,
- Building code compliance is shown, based on Section 104.11 of IBC or IRC.

The first case may be accomplished if mandatory language design code books and material standards can be developed and adopted into building codes through ICC public hearing process. This could be accomplished by the American Concrete Institute (ACI) committee on 3D printing with cementitious materials, ACI 564, by developing design codes or material specifications using mandatory-code-language. The second case requires that the proponent of the alternative material and technology, in this case C3DP technology, demonstrates building code compliance via acceptance criteria and a resulting research report under Section 104.11 of the IBC.

A second regulation barrier could be lack of jobsite inspection details for C3DP technology. Section 110 of the IBC requires that construction or work for which a permit is required must be subject to inspection by the building official, and such construction or work must remain accessible and exposed for inspection purposes until approved. In addition, some works require detailed scrutiny, but the building official cannot stay at one job all day; therefore, special inspection provides additional surveillance in accordance with Chapter 17 of the IBC. To this date, Chapter 17 of the IBC does not contain any provisions for C3DP technology. Therefore, the inspection process for 3D-printed structures are based on the decision of the individual jurisdiction in charge of overseeing the construction.

Acceptance criteria AC509 provides suggestions for the consideration of building officials for special inspection of C3DP. AC509 suggests that special inspection must be in accordance with Sections 1705.1.1 and 1705.3 of the IBC during the mixing, printing, and placing of the 3D-printed concrete shells and the concrete core. In addition, the report applicant must submit inspection procedures to verify proper usage. The inspection must include verification that the concrete compressive strength and flexural bond strength are consistent with the published code-compliance research report. Concrete cylinders of the outer face shells and core are to be field cured in accordance with ASTM C31 (2019) and tested in accordance with ASTM C39 (2020). Testing of flexural bond strength in accordance with ASTM E518 (2015) must be compared with published values in the code-compliance research report with a maximum variability of 10 percent. It should be mentioned that currently there is no ASTM standard specifically developed for construction-scale 3D printing. However, the newly formed ASTM F42.07.07 subcommittee is tasked with addressing the construction applications of 3D printing technology.

3.2 Future Prospects and Potential Applications

In addition to the improved productivity, C3DP also offers new possibilities for design and construction of structures. By eliminating the need for formwork, C3DP allows for fabrication of complex geometries which were impossible or very difficult to create using traditional concrete construction techniques. This unprecedented design freedom offered by C3DP enables architects, designers, and structural engineers to explore new possibilities and adopt innovative techniques such as topology optimization (Vantyghem et al., 2020). In topology optimization methods, a material distribution problem is solved to create an optimal geometry, resulting in a more efficient use of materials. The algorithms can achieve cost minimization as well as performance maximization based on structural requirements (Vantyghem et al., 2018). To this aim, Vantyghem et al. (Vantyghem et al., 2020) presented a digital design-to-manufacture process that combines topology optimization, C3DP, and post-tensioning. The feasibility of this process was demonstrated by fabrication of a post-tensioned girder with optimized geometry (Vantyghem et al., 2020).

Another interesting possibility which can be realized by C3DP is use of functionally graded materials (FGM) in structures. C3DP makes it possible to dynamically mix, grade, and vary the proportions of printing material ingredients, resulting in gradual change in properties and optimized designs with an efficient use of construction materials and reduced waste (Oxman et al., 2011). By changing the dosage or type of aggregate, fiber, cement, admixtures, and other ingredients during the process, properties such as density, modulus of elasticity, mechanical strength, impact resistance, and thermal conductivity of the printing material can vary according to the actual “local” loading, insulation, and deformation requirements (Ahmed et al., 2020; Kazemian et al., 2019). In a recent study, Ahmed et al. (2020) designed and implemented two systems to enable graded functionality in C3DP. The first system was based on the selective addition of fibers and lightweight aggregates to the printing mixture in a second stage mixing process at the print head. The other system was based on the addition of particles in between the layers of printed concrete. Functionally graded specimens were fabricated in this study using each system to demonstrate the possibilities with respect to the use of FGMs to achieve an optimized design and construction using C3DP (Ahmed et al., 2020).

In terms of applications, C3DP is best described as a platform technology which can be adopted in various domains. House construction, disaster relief (shelter construction), infrastructure development (towers, bridge, etc.), and construction of habitats and settlements on other planets such as Moon and Mars are some of the applications for which demonstration projects have been carried out using C3DP technology (Khoshnevis & Kazemian, 2020; Khoshnevis et al., 2016; Kreiger et al., 2019; Salet et al., 2018). For each application category, the specifications and requirements for a suitable C3DP system could be different in terms of the robotic system configurations and printing materials. Furthermore, for industrial-scale adoption of the technology in each category, economic considerations and overall process efficiency play an important role. For instance, C3DP is currently used mainly for automated construction of building shell, which is only portion of the total house construction process, therefore diminishing the attractiveness of this construction method for developers and builders. Integrating different tasks such as roof construction, insulation, plumbing, and finishing into the automated construction process can significantly increase the viability of C3DP as a commercial construction method and promote its widespread adoption by the industry. In addition, a well-studied and effective automated reinforcement approach could be a key enabler for utilization of C3DP in numerous applications.

4 Conclusions

Construction industry is known as a “low digitization” sector suffering from poor productivity and has not yet undergone digital transformation, as opposed to other major industries such as manufacturing. Although some improvements have been achieved by implementing technologies such as BIM, the manual processes which are involved in the actual construction process are still a major obstacle against a digital revolution in construction. Robotic construction seems to be a viable solution which is yet to be proven reliable and practical. In this chapter, some of the major historical efforts on developing integrated robotic construction systems were briefly reviewed. Then, construction 3D printing (C3DP) was introduced as a more recent and high potential automated construction technology, and relevant developments and advancements were presented. Printing materials, quality control, and code compliance of 3D-printed structures are three important aspects of C3DP as an emerging construction method, which were discussed, and the ongoing activities promoting advancement of C3DP in each area were reviewed. On the other hand, the existing barriers and challenges against widespread adoption of this technology by the construction industry are noteworthy. Lack of sufficient data on the structural performance of 3D-printed structures, concrete reinforcement, process reliability and limitations, and regulatory challenges are examples of existing barriers which were discussed in this chapter. By addressing these shortcomings through extensive research and testing at different scales, and advancing toward a fully automated construction process (by integrating various activities such as reinforcement), industrial-scale adoption of C3DP for many applications such as house construction, disaster relief, and infrastructure development would be facilitated.

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Chapter 13
Material Design, Additive Manufacturing, and Performance of Cement-Based Materials

Biranchi Panda and Jonathan Tran

Abstract Important developments in additive manufacturing of concrete (AMoC) have been achieved in the past decades. Like other additive manufacturing processes, interdependence between material design, process effects, and part performance exists in AMoC. In this chapter, material design of various cement-based materials amenable for extrusion-based additive manufacturing, rheological responses that are influential in ensuring printability, and the performance of such novel materials is discussed. The need of adequate rheology to successfully develop printable concrete and tailoring mix design by addition of various admixtures is also presented. These results demonstrate that thixotropy of building materials is key for AMoC. The mechanical performance of AMoC is further discussed including interlayer bond strength and its consequence in terms of anisotropic properties. Finally, material development challenges for large-scale AMoC are discussed with new strategies to produce sustainable yet printable mixes.

Keywords Material design · Additive manufacturing · Cement-based materials · Extrusion rheology · Low carbon cement · Geopolymer

1 Introduction

Digital concrete fabrication including additive manufacturing of concrete (AMoC) has attracted the attention of academia and industry in recent years, due to its advantages of less labor requirements, and absence of formwork (Buswell et al., 2018). The process, first pioneered by Berokh Khoshnevis and branded initially as 'Contour Crafting', is the direct transfer to concrete of the well-known fused deposition modeling (FDM) process typically carried out with thermoplastics (Khoshnevis

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_13

et al., 2006). The term ‘Concrete Printing’, and/or ‘3D Concrete Printing’, was originally the name given to the process developed at Loughborough University to differentiate it from contour crafting (Lim et al., 2012). Literature reviews several reviews of AMoC that covers 3D printing processes, wide range of materials, properties of 3D printed materials, and some computational modeling of the process (Bos et al., 2016; Mechtcherine et al., 2019; Paul et al., 2018; Sanjayan et al., 2019; Tay et al., 2017; Wangler et al., 2019a). Despite availability of reviews, limited information is available on the topic ‘process-material design’ relationships of AMoC. The main of this chapter is to provide a review of building materials design for extrusion-based AMoC process considering process capabilities and limitations.

2 Extrusion-Based Concrete AM Process

In order to provide a baseline description of AMoC processes, extrusion-based gantry printing process is described as the paradigm approach to which other concrete printing processes are compared. Figure 1 shows a typical gantry-based concrete AM system developed at Indian Institute of Technology Guwahati, India.

In AMoC, the part building process starts with CAD modeling of the structure which is further processed as stack of sliced layers, and unlike other 3D printing processes, the layer thickness in concrete printing varies from 5 to 40 mm depending

Fig. 1 3D concrete printer facility at Indian Institute of Technology Guwahati, India. (author’s original)

on nozzle size and material flow rates. The digital processed file is then converted into machine language such as G-code and send to a numeric controller that translates the language into *X*, *Y*, *Z* motion. In most commercial 3D printers, the material delivery process is carried out by a grouting pump, but in some research laboratories, a plunger based or an extruder (Fig. 2) is used due to low cost and ease of extrusion. The advantage of pump-based delivery system can be reckoned as continuous supply of large volume of material, which is not possible in case of plunger extruder due to limited storage capacity of the barrel. However, for laboratory trials, such systems are very much helpful as miniature samples can be easily printed by extruding small volume of material. It is important to note that the material delivery mechanism is completely different in both the extrusion systems and according the material design need to be decided. More discussion about mix preparations is presented in the following sections.

The extruded layers get deposited layer by layer, and therefore, the printer (*z* axis) moves in vertically upward direction as the print bed remains stationary in this process. If the part design has any overhanging features, it is commonly not possible to print without support materials (Albar et al., 2020). An example is shown in Fig. 3, where additive manufacturing of overhanging structures is attempted by temporarily

Fig. 2 Extruder-based 3D concrete printing (author's original)

Fig. 3 Additive manufacturing of overhanging concrete structures at NTU Singapore (author's original)

providing support with help of other mechanical systems. In addition, some recent work shows that by optimizing the overhanging angle and using rapid hardening mixes, it is possible to print complex structure without the need of support materials (Sika Concrete 3D Printing; The Large-Scale 3d—XtreeE—3D Printed Wall).

Robotic AM systems are also available and used by some industries for concrete printing of complex geometrics. The process of a robotic AMoC is almost similar to a gantry-based 3D printer except the complex path programming method owing to higher degree of freedom of the robots. The material deposition occurs through a nozzle connected with a concrete pump, and in case of special concrete extrusion, advanced nozzle can be mounted considering the maximum payload capacity of the system. The main disadvantage of robotic printing system is the sizes of the printed structures which are constrained by the reach of the robot's arm, and therefore, advanced mechanical systems are now being developed which combines the benefits of both gantry and robotic 3D printers.

3 Material Design, Extrusion Rheology, and Early-Age Properties of Additive Manufactured Concrete

3.1 Background

AMoC differs significantly from traditional casting processes by virtue of the importance of control of the yield stress, and especially with respect to its evolution over time. More specifically, the requirements of material delivery and placement are rather similar to some processes seen in traditional construction processes, but the absence of a traditional formwork requires an additional aspect that of controlling structural build-up to ensure structural stability during production (Mechtcherine et al., 2020). In the printing process, appropriate workability is required to ensure extrudability, shape stability, and buildability after deposition. More specifically, to achieve printable concrete, it is needed to balance among these critical printing requirements. Workability of freshly printable concrete is commonly evaluated using slump test, flow test, or V-funnel test. In the slump test, workability is evaluated through the slump, which is the slumped height of concrete paste relative to the height of the cone after demolding. Additionally, V-funnel is used to evaluate flow ease by the flow time. Flow test, also called slump flow test, spread-flow test, or mini-slump test is the most widely used to measure workability of printable concrete because it is simple, fast, economical, and reliable. Rheological parameters such as static/dynamic yield stress and plastic viscosity obtained from rheological tests are also considered important properties to evaluate flowability of fresh concrete. For instance, static yield stress needs to be sufficiently low for being pumpable and high enough for carrying self-weight. Regarding the effect of mix compositions, the selection of fine aggregates in terms of shape, size, and dosage needs to be taken into consideration to achieve printability through a specific size of a nozzle.

In AMoC process, the extruded layers are hardened by hydration reaction of the material, and therefore, it is very important to design the material so that it can harden rapidly while retaining the nozzle shape. In case of extrusion by pump, the material design is even more challenging as it needs to be very fluid during pumping, and after deposition, it should be stiff enough to hold its own weight and the load of other layers (Rahul et al., 2019).

After successful extrusion, buildability of fresh concrete must be ensured, which can be described as layer build-up capacity of the material. Layer build-up capacity depends on shape stability of each filament, which is also an essential prerequisite for build-up capacity. As discussed above, fresh concrete is required to have appropriate workability to meet two competing requirements, i.e., 'extrudability' and 'buildability'. From the standpoint of rheological behavior, these two requirements depend on thixotropic properties of cement-based materials which is governed by flocculation mechanism. Thixotropy' is shear thinning property of building materials. This behavior allows breakup of the material under shear and their reformation when shear force is removed. Shear thinning results in smooth extrusion of material, while the reformation ability helps in shape retention of the extruded filament.

In a nutshell, following critical properties should be satisfied for an extrusion-based AM process (Le et al., 2012a).

(a) Extrudability: It refers to ability of the material to be extruded out continuously from a nozzle or orifice.
(b) Shape retention: This property indicates shape stability characteristic of the extruded filament according to nozzle opening shape and size.
(c) Buildability: Buildability of a material indicates the ability of material to be buildable layer by layer without failure of the bottom layer and the entire structure during printing.
(d) Open time: It indicates the material workability (the ability to work with concrete) time for which it is extrudable.

There are no standards to measure these properties, and therefore, depending on the material processing technique, researchers have developed 3D-printable building materials by optimizing the mix design with the help of different admixtures. In the following section, two most common approaches of material design have been discussed for realizing extrudable 3D-printable mixes.

3.2 Material Design Approaches

The most widely used building material for AM-based applications involves the use of blended materials to obtain required recipe fulfilling the abovementioned criteria. Literature reveals that yield stress and viscosity (Bentz et al., 2018; Nair et al., 2019) have been often used to measure 3D printability, and some researchers have focused on thixotropy (Chen et al., 2020a; Kruger et al., 2019) aspect of building materials including other rheological properties.

Thixotropy property allows building material to become less viscous when subjected to an applied stress, and on removal of stress, the material turns in to more viscous fluid which can produce stable filament. The low viscosity property will ensure smooth and continuous flow during the extrusion, if the material is extrudable. Thixotropy characterization can be done by measuring structural breakdown and viscosity recovery as these two phenomena mimics the extrusion-based AMoC process. The material is usually sheared at high shear rate in structural breakdown protocol mimicking extrusion or pumping process. Two important parameters such as thixotropy index and breakdown time are calculated in this test which indicates the ease of material pumping or extruding from a nozzle. Similarly, in the recovery test, viscosity values before and after extrusion are compared to ensure the material has ability to recovering initial high viscosity (after extrusion) for better shape retention and buildability property.

While measuring yield stress and viscosity, researchers have used (static) yield stress as an indicator of extrudability and viscosity to indicate shape retention of the extruded filament. The structural build-up measured by increasing yield stress of material is often used to explain buildability of the structure. Therefore, by combining yield stress and viscosity, it is thus possible to confirm printability properties of building materials. There are various methods available in the literature to measure these rheological properties; however, the choice of test method selection depends on the type of 3D printer and extrusion process. Researchers using a pump to deliver the material have conducted additional characterization to check pumpability of the material, which may not be recommended if a regular piston is used for extruding the material, instead of using pumping mechanism.

The material design for AMoC can be broadly categories into two groups: (1) the ‘infinite brick extrusion’ and (2) layer pressing strategy. The consequences of these strategies on the extruded material properties are described by Roussel in Carneau et al. (2020) with in the first case a high initial yield stress layer (around 1000 Pa) which takes the form of the nozzle. And in the second case, a layer with a low initial yield stress (around 100 Pa) whose section can vary by playing with the printing parameters. More details about 3D-printable materials and mix design optimization are discussed in the following sections.

3.3 Effect of Material Design on Extrusion Rheology and Early-Age Properties

The development of AMoC materials can be considered as multi-material blending, and among all, ordinary Portland cement (OPC) remains popular material choice due to presence of inherent thixotropy. The origin of thixotropy as mentioned by Roussel et al. is due to colloidal flocculation and hydration reaction. However, recently, there is an increasing interest in studying the properties of sustainable printable concrete in which OPC is partially replaced by supplementary cementitious material (SCM), including fly ash (FA), silica fume (SF), ground blast furnace slag (slag), and rice husk ash (RHA). The effect of mix design on rheology (required for additive manufacturing) and early-age properties of different concrete is discussed in this section.

3.3.1 Research on 3D-Printable OPC-Based Mixes

The addition of SCM into OPC-based cementitious materials can affect the extrusion rheology depending on the properties of SCM. Panda and Tan 2019) investigated the rheological property of cementitious materials with different replacement levels of FA and SF. The results show that increasing FA content up to 80% led to the decrease in static yield stress due to ball-bearing effect, whereas the effect of SF addition up to 5% resulted the opposite effect. SF particles have large surface area with an ideal thixotropic material behavior. As reported in Panda and Tan (2019), the addition of SF improved the structural build-up rate (steeper slope), and similar results were also reported by Yuan et al. (2018), who observed that the addition of 5% SF nearly doubled the build-up rate compared with pure cement-based mortar, due to ionization of SF surfaces and potential ion bridging effect that promoted C–S–H gel formation (Panda & Tan, 2019). The structural build-up rate can be linked with material buildability, and it can be further improved with addition of chemical admixtures.

Muthukrishnan et al. (2020) have investigated the effect of RHA on the fresh properties of printable cementitious materials, and flowability was found to be decreased for 20% cement replacement by the RHA. Interestingly, the green strength (at 15 and 30 min) was observed to increase significantly with the addition of RHA, which could be explained by the filler effects of RHA particles promoting cement hydration, and the densification of cement transition zones resulting from free water absorption by porous RHA particles. Like structural build-up, material green strength indicates load bearing capacity of the extruded layers. To improve green strength, packing density and material cohesion property need to be improved which can be achieved by optimizing the mix design. The applications of statistical methods such as analysis of variance (ANOVA) analysis can be helpful in this regard, as Liu et al. (2019) adopted it to investigate the effects of different composites (cement, sand, FA and SF) on the rheological properties, and their modeling results showed when the volume fraction of sand was fixed at 0.235 or above, replacing cement with FA had minor effects on the static yield stress of fresh mortar. A reasonable explanation for this could be under the high-volume fraction of sand; the static yield stress was mainly governed by the interlocking and friction resistance. A similar study was also conducted by Tay et al. (2019a) who investigated the relationship between the mix components (such as water, FA and SF) and workability of fresh mortar via ANOVA analysis.

In recent years, more focus has been given on improving the material rheological properties by addition of nanomaterials and other admixtures. Panda et al. (2019b) studied the effect of nanoclay on the rheology of high-volume FA cementitious materials, and they found that nanoclay addition up to 0.5% can significantly increase both static yield stress and viscosity which resulted in higher buildability property (see Fig. 4). In another study, the structure build-up rate of cementitious material with nearly 70% FA was improved by 50% with the addition of 0.5% nanoclay. The increase in rheological properties can be explained by the electrical attraction force induced by the oppositely charged nanoclay surface, which densified the microstructures (Ma et al., 2018). Depending on the type of additives, in some cases, there is an optimum dosage of the additives to be added into OPC-based sustainable concrete.

Fig. 4 3D printing of high-volume fly ash mortar with nanoclay inclusion (author's original) (Panda et al., 2019b)

van den Heever et al. (Heever et al.) studied the effect of nano-silica carbide (nSiC) on the yield strength development of OPC-based material incorporated with FA (20%) and SF (10%). Interestingly, despite the positive correlation between nSiC dosage and yield stress, the increasing dosage of nSiC resulted in a decreased value of A_thix (rate of yield strength development at structuration stage) indicating the buildability was negatively influenced by nSiC.

Some studies were focused on the effect of fiber addition on properties of 3D-printable concrete as fiber inclusion not only produces ductile behavior but also increases the buildability of the material in the early age (before setting). Figueiredo et al. (2019) investigated the effects of PVA fibers on the shear yield stress and bulk yield stress of the cementitious materials with FA or slag. In most cases, the increased fiber content had a positive effect on both bulk and shear yield stress. The increase in bulk yield stress suggested an improved buildability, while higher shear yield stress due to the friction of fibers and concrete matrix indicated a lower pumpability. Similar results were also reported by Weng et al. (2018), who found the addition of 1 vol% PVA fibers promoted both flow resistance and thixotropic behavior of fresh mortar with at most two-third of cement replaced by FA.

3.3.2 Research on Low Carbon Cement Mixes

In recent year, 3D-printable low carbon building materials are getting increasing popularity compared to other cementitious materials due to demand in achieving sustainable built environment (Dey et al. 2022). Here, different green building materials and their respective advantage for AMoC is discussed.

Additive Manufacturing of Geopolymer

The term ‘geopolymer’ was first introduced in the literature in 1978, characterizing a new class of materials with the ability to poly-condense at low temperatures like ‘polymers’. This process involves the chemical reaction of aluminosilicate materials (e.g., fly ash, metakaolin, granulated blast furnace slag, and silica fume) with alkali activators. When mixed with the alkaline activators, setting and hardening take place, yielding a material with good binding properties. The binder constituents of geopolymer materials such as FA, slag and SF can significantly affect the printability properties of mixtures along with dosage of alkali activator. In a study by Panda et al. (2019c), the static yield stress and viscosity of geopolymer mortars were found to have increased by 80% and 20%, when the slag content was increased from 15 to 40%, respectively, and it was attributed to the angular shape of slag particles that enhance the yield stress through interlocking effects. The improvement of yield stress can allow deposition of more layers. Alghamdi et al. (2019) investigated rheological properties of sodium-alkali-activated FA-based materials and found that by replacing FA with limestone, material shear yield stress, and viscosity significantly decreased. The addition of slag can also affect structural build-up rate of FA-based

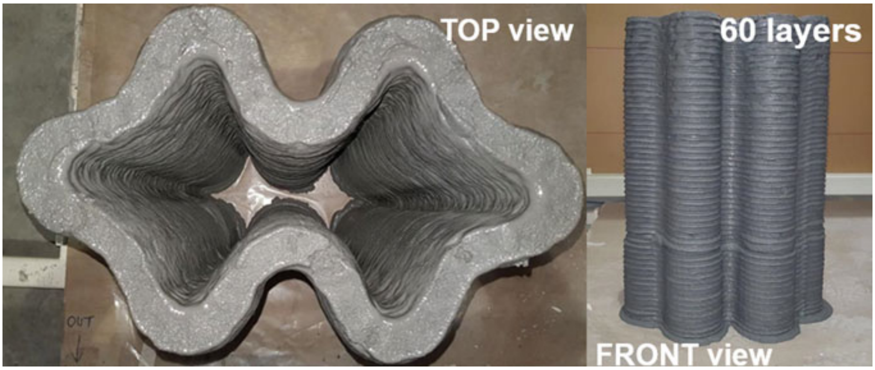

Fig. 5 Additive manufacturing of fly ash-based geopolymer (author's original)

geopolymers by accelerating the mixture (Saha & Rajasekaran, 2017), and on the other hand, SF addition can promote the thixotropy of geopolymer. Alkali activators can also play a critical role in the rheology of geopolymer as alkali-based solution activates the polymerization process which controls stiffening of the material. Based on Panda et al. (2019d) study on the effects of molar ratio and activator-to-binder ratio on the rheology of geopolymer material, it was noticed that increasing molar ratio (MR) from 1.8 to 2 resulted in significant increase in both static yield stress and viscosity, which can be explained by higher activator viscosity having higher MR. It was also concluded that regardless of MR, the static yield stress and viscosity consistently decreased as the activator solution-to-binder ratio increased, which was mainly attributed to the decrease in particle concentration. Thus, it is recommended to properly tailor the activator-to-binder ratio as it can affect the rheology of geopolymer for 3D printing. Figure 5 shows an example of 3D printed geopolymer composite, optimized for 900 mm print height.

Apart from binder and activator, researchers have supplemented additives like nanoclay for improving printability of geopolymer, as reported in Panda et al. (2019d) and Chougan et al. (2021). Other additives such as sodium carboxymethyl starch (CMS) and hydromagnesite seeds have also been incorporated into geopolymer mixtures and investigated. According to Sun et al. (2020), the addition of CMS (up to 8%) promoted both yield stress and viscosity at different rates, which could reduce the risk of segregation while avoiding filament collapse. However, the porosity of printed filaments rose with increasing CMS dosage, leading to weak internal structures and lower strength. On the other hand, the addition of 1–2% hydromagnesite seeds was found to exert minor influence on the rheological properties of the alkali-activated slag binders (Panda et al., 2020). Different fibers also have been incorporated to tailor the rheological behavior of printable geopolymers (Al-Qutaifi et al., 2018).

Additive Manufacturing of Limestone Calcined Clay Cement Material

Limestone calcined clay cement (LC3) is a low carbon cement material, and due to higher structure built-up rate capability (Beigh et al., 2020), this material is found to be an excellent choice for 3D printing applications. Chen et al. (2019) investigated green strength (early-age property) of LC3-based concrete with different grades of calcined clay and found that with higher proportion of hydraulic cement concrete resulted shorter initial setting time and higher growth rate of green strength indicating an improved buildability. This result could be explained by the higher surface area of metakaolin particles such that these fine particles provide nucleation sites to accelerate early-age cement hydration (Lothenbach et al., 2011). Meanwhile, some extra MK particles in the matrix accelerate the phase transition from flocculation to structuration (Chen et al., 2019), resulting in a decreased setting time.

Additive Manufacturing of Calcium Sulfoaluminate Cement (CSAC)

Calcium sulfoaluminate cements (CSACs) are a promising low-CO_2 alternative to ordinary Portland cements and are as well of interest concerning their use as binder for waste encapsulation. A study from Huang et al. (2019) suggested the buildability of cementitious material containing CSAC is influenced by the percentage of CSAC in the binder. They found an evident positive correlation between the ratio of CSAC replacing OPC and structure build-up rate at structuration stage. This result could be explained by the positive effect of CSA on hydration kinetics of hydrates and the formation of network between needle-like AFt and rod-like gypsum, which increased interparticle frictional force. The fresh property of CSAC-based materials for printing purposes can also be tailored via the supplement of additives. According to Chen et al. (2020a), the addition of bentonite (up to 3%) could significantly improve the thixotropic behavior and increase material viscosity simultaneously. The optimal bentonite dosage was determined to be 2% since the significant increase in viscosity due to excessive amount of bentonite could cause blockage in the nozzle. The optimal dosage of additives again highlights the necessity to balance viscosity (ease to transport) and green strength development (less filament deformation) via careful monitoring of additive supplement. A comprehensive study conducted by Ding et al. (2018) showed increasing dosage of hydroxypropyl methylcellulose (HPMC) and lowering water/cement ratio (W/C) could both reduce the setting time, whereas the addition of HPMC and the increase in sand/cement ratio (S/C) had negative effects on the flowability of sulfoaluminate cement (SAC) mortar simultaneously. A higher S/C ratio led to increased friction forces between grains which decreased the fluidity of fresh material. The addition of HPMC resulted in the formation of 3D network gel due to its gelation behavior, and the resulting thickening effect increased the resistance against penetration (Poinot et al., 2014), thus decreased the setting time. Besides, the interlocking effect of gel originated from HPMC also accounted for the negative correlation between flowability and addition of HPMC (Ding et al., 2018).

In another study, Chen et al. (2020b) studied the effects of retarders (borax acid and sodium gluconate) and diatomite on the rheological properties of SAC materials for 3D printing. The addition of either borax acid or sodium gluconate resulted in lower yield stress and plastic viscosity, whereas the addition of diatomite showed adverse effects. A lower percentage of retarder within cementitious matrix increased the free water content between particles, thus stimulating the formation of flocculation network that accounted for the increase in yield stress. On the other hand, the high water absorption of diatomite due to its large specific area and superficial Si–OH groups increased the frictional force between cement particles, thus giving higher values of rheological properties.

Additive Manufacturing of Other Low Carbon Building Materials

This category mainly refers to processing of earth-based material and cementitious materials incorporated with recycled waste materials, including glass and plastics. The research works on feasibility of printing cementitious materials with recycled glass were pioneered by Annapareddy et al. (2018) and Ting et al. (2019). According to Ting et al. (2019), completely replacing sand with waste glass as raw ingredient could significantly decrease the static yield stress that made material less buildable, and adversely impacted the hardened mechanical property. For materials with natural sand fully replaced by recycled glass, the material properties could be influenced by gradation of glass particles. In specific, a higher percentage of super fine glass (0.15–0.71 mm) in the mixture improved thixotropic property and static yield stress (better buildability), whereas filament with majorly medium-sized glass (1–1.7 mm) exhibited lower compressive strength due to the increased void contents. Besides, the replacement of fine glass was also found to yield a higher risk of bleeding and segregation in fresh mortar (Taha & Nounu, 2008, 2009), which is linked to the occurrence of blockage in 3DCP. A few research papers are found to be focused on development of 3D-printable light-weight mortar followed by earth-based building materials. Research pioneered by Perrot et al. (2018) focused on the fast development of early strength in pure clay-based soils for 3D printing. Their solution was to incorporate soils with alginate, which is an alginic salt processed from cell walls of brown seaweed and can be used as a fast-setting binder. Some recent research on development of 3D-printable foam materials focuses on foam stability issue which is very important in extrusion-based concrete printing, and in this regard, different mixing style and admixtures are opted to tailor the mix design amenable to 3D printing (Cho et al., 2021; Markin et al., 2019; Mohammad et al., 2020; Wang et al., 2020).

3.4 Mechanical Performance of AMoC

In traditional casting method, mechanical properties of hardened concrete mainly depend on mix compositions and casting procedure. Meanwhile, those of printed concrete are determined by the mix components and printing strategy such as printing path direction, extrusion pressure, and time interval (Panda et al., 2017, 2019a). In AMoC, layer-by-layer deposition process and time gap between layers are the leading causes for anisotropic behavior (Sanjayan et al., 2018; Wolfs et al., 2018; Zareiyan & Khoshnevis, 2017) and depending on material structuration (hardening) rate, decreasing trend of bond strength was found with increase in time gap between the layers (Tay et al., 2019b). Additionally, mechanical characteristics and durability of printed components could be affected by large voids which are formed between filaments and layers as shown in Fig. 6. To improve the mechanical properties, many attempts have been made to print reinforced concrete using steel rebar, rods, wires, fibers, and mesh (Asprone et al., 2018). However, extensive quantified characterization of their performance is generally still lacking and requires further research.

Directional dependence of mechanical performance such as compressive, flexural, and tensile strengths is observed in almost all studies on AMoC, which is an unavoidable feature of the extrusion process (Le et al., 2012b; Nerella et al., 2019; Wolfs et al., 2019). Le et al. (2012b) observed that the degree of anisotropy in compression tests is less pronounced than that in flexural tests. Besides, there is not much difference in compressive strengths between cast and printed specimens, but a significant discrepancy is found in flexural and tensile strengths. The great difference in flexural strengths at different loading directions results from underperformed interlayer bond

Fig. 6 Voids in 3D-printed concrete at NTU Singapore (author's original)

strength, which is the reason for the high degree of anisotropy in flexural strength tests.

The bond mechanism between new and old concrete interfaces experiences three stages, namely adhesion, friction, and mechanical interlock (Momayez et al., 2005). In particular, the adhesion resistance of the interface, which is considered a chemical bond, mainly depends on the physical and chemical characteristics of the mixture compositions. Following that, the frictional mechanism acting against slip at the interface appears right after the adhesion mechanism disappears. Finally, after the adhesion and friction actions, the mechanical interlock acts to boost bond strength depending on the roughness of the surface (e.g., size and shape of aggregate particles, surface texture, etc.). It is confirmed that apart from the adhesion resistance, the bond capacity is fundamentally dependent on the mechanical interlocking which contributes to extra resistance for the interface bond strength.

Interlayer bond strength is one of the key aspects of AMoC (Kruger & Zijl, 2021). To evaluate bond performance, bond test methods can be categorized into four main groups based on the reviews in existing studies, including shear test with different test protocols (direct shear and slant shear), indirect tensile test, known as flexural test, and prismatic or cylindrical splitting tests; direct tensile test; and pull-out test. It is worth noting that there is no reasonable concordance between the results obtained from different test methods; therefore, it is not possible to compare them. In these types of tests, the authors also observed that the splitting tensile and pull-out tests are considered efficient and straightforward test procedures to obtain consistent and conservative results. In the AMoC, three prevalently used methods to determine the interface bond strength of printed elements are found in the literature review, including flexural strength tests, direct tensile test, and splitting tensile tests. More details about theses testing methods and results can be found in Babafemi et al. (2021).

3.5 Material and Machine Design for Large-Scale AMoC

Literature reveals most of the AMoC was limited to lab scale printing and testing for evaluating 3D printability of building materials. A few academic researchers (Bos et al., 2018; Weng et al., 2020) and some pioneer construction companies (Apis cor, 2021; COBOD, 2021; Winsun, 2021) have demonstrated successful fabrication of large-scale AMoC; however, the term 'large scale' is not defined properly in the literature. In this section, some important challenges related to material development is discussed while highlighting the need of new print head design for large-scale AMoC.

Considering different types of material design of large-scale AMoC, it can be well summarized that increasing structural built-up via addition of accelerators is the most popular approach. Structural built-up of building materials is an important property which has been characterized by various rheological tests (Jeong et al., 2019; Marchon et al., 2018; Perrot et al., 2016; Reiter et al., 2018) with respect to time, and it indicates buildability of the 3D structures. This property is not only useful in AMoC but also in other digital fabrication techniques (Wangler et al., 2016) such as slip dynamic casting and hardening of material have been controlled with accurate dosage of chemical additives. Increasing of structural built-up via adding accelerators needs complete understanding of material chemistry, selection of a proper accelerator, its reaction mechanism, and dosage control. Currently, there are many guidelines available in the literature (Boscaro et al., 2021; Reiter et al., 2020; Wangler et al., 2019b) for selection of appropriate chemical admixtures to retard or accelerate the concrete. However, controlling the dosage and mixing technology is the critical challenge for large-scale AMoC.

The dosage of these admixtures mainly depends on material chemistry and required structural built-up rate. Different binder systems need different admixtures, and their dosage can be tailored based on target buildability property. Admixture compatibly is also one of the well-known issues in building materials, and therefore, it is necessary to always optimize the mix design with proper understanding of multi-component materials behavior. In large-scale AMoC, two different types of material design schemes have been noticed such as:

(1) AM of rapid hardening concrete: In this approach, low viscosity retarded concrete (mortar) is extruded, and in the print head, appropriate amount of accelerator is added to deposit rapid hardening mortar.
(2) AM of high thixotropic (zero slump) concrete: Here, a high thixotropic mix is extruded, and accelerator may or may not be added, depending on material mixing process.

The first approach is commonly found for large-scale AMoC via pumping low viscosity mortar, but the key challenges are print head design and dosage control with respect to printing parameters. There are many advanced print heads developed in this regard for accurate control of mixing of retarded mortar with other chemical admixtures. During mixing, residence time plays a main role, and Boscaro et al. (2021) have pointed out measurement of this residence time distribution for smart dynamic casting which can be applied to other digital fabrication processes.

On the other hand, extruding high thixotropic mix may not need addition of accelerator for batch mixing conditions as more layers can be deposited (without failure) due to the high thixotropic nature of the material, but extruding such stiff material requires high pumping pressure. In case of continuous mixing, accelerator addition is required for large-scale AM as material in the bottom layer may not be able to resist the load of more layers despite the high thixotropy nature of the mix. The AM of such high thixotropic mix sometimes causes poor surface roughness due to low slump character. Figure 7 shows examples of AMoC carried out by some academic research institutes using high thixotropic mixes.

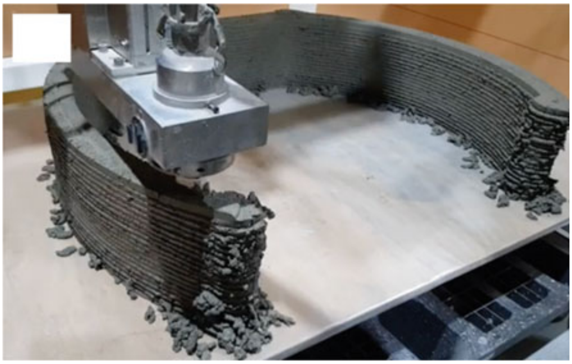

Fig. 7 Example of highly thixotropic concrete 3D printing at NTU Singapore (author's original)

4 Conclusions and Future Directions

The additive manufacturing of concrete presented in this book chapter can be grouped under the term of digital fabrication processes, and this disrupting technology can reduce the need for formwork, while allowing fabrication of highly complex geometries without formwork. A major challenge in this process is the development of material with a contradicting criterion such as low viscosity during extrusion and high yield stress after the extrusion. To fully exploit the potential of additive manufacturing, low carbon materials and structures can be designed, and numerical simulation can greatly contribute in this regard to analyze material flow, buildability, and structural capability of the optimized structure. In addition to low carbon materials, functional materials can be developed using nano/micro-particles and graded functionally can also be achieved by mimicking bio-inspired structure. While developing innovative materials of additive manufacturing of concrete, now, the focus should shift to development of new standards of testing material fresh as well as hardened properties.

Concrete additive manufacturing system development in terms of higher degree of automation (from mixing to material deposition) is also required with in-line process monitoring capabilities so that material and printing process can be optimized simultaneously. In a nutshell, in AMoC material behavior, part design, printing process parameters, and other aspects need to be considered collectively for producing robust concrete components.

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Chapter 14
A Procedure Model for the Development of Construction Robots

Thomas Linner, Rongbo Hu, Kepa Iturralde, and Thomas Bock

Abstract Due to a constantly growing interest in construction robots, guidance on the design and management for its development process is needed to employ the best practice know-how and accelerate efficient development and marketisation. The development of construction robots usually involves stakeholders from the construction sector, non-construction sectors, and investors. A systematic design management method can help to integrate the needs and aims of different stakeholders and team members during the development process. Therefore, a procedure model for the development of construction robots is proposed as an integrative guidance on how to systematically conceptualise engineer requirements and to design, develop, implement, evaluate, manage, and mature the designs of construction robots. Several recent projects have been used by the authors to test and verify parts of the proposed cyclic method. In addition, the authors explain how the proposed model has been composed of an adapted set of proven principles and methodologies from the systems engineering and management field and highlight the specific concepts for developing and testing the construction robots. The application of the procedure model revealed that the concept and method are feasible and, in principle, can provide a comprehensive and practical guide on the steps forward. A unique characteristic of the proposed procedure model is the core principle which allows the evolvement over time with each cycle of use. In addition, interchangeable elements can be inserted into the procedure model depending on the region, type of robot, and technical readiness level.

Keywords Construction robotics · Modular/multitask construction robots · Modular robotics · Affordable robots · Construction automation · Systems engineering · Technology management · Procedure model

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_14

1 Introduction

It can be observed that a development and integration of "soft" information-driven technology for on-site construction dominated research and development activities in the field of on-site construction automation and robotics for over a decade. Examples of the "soft" information-driven technology include building information modelling (BIM) (Goulding et al., 2015), scheduling and construction process optimisation techniques (e.g. Wang & Rezazadeh Azar, 2019), sensing systems (e.g. Kim et al., 2019), and unmanned aerial vehicles (UAVs) (Zhou & Gheisari, 2018). Recently, there is a noticeable renewed interest in the development of "hard" physical–mechanical robot systems for the execution of specific tasks on the construction site. This has manifested through an increase in academic research activity (Cai et al., 2018), joint industry-academia collaboration projects (e.g. Cordis, n.d.), the emergence of start-ups (e.g. Bunkeberg Systems AB, n-Link, Fastbrick Robotics; O-Matic Intelligent Robot Ltd., Construction Robotics, Autonomous Solutions Inc., Kewazo, Built Robotics, Levaru, OutoBot, ROB Technologies, Tmsuk Co. Ltd., Constructions-3D, German Bionic, Okibo, etc.), and a strong and growing interest of large, established organisations (e.g. Construction Industry Council Hong Kong, Excellence Group, Bouygues Construction, Thyssenkrupp, Country Garden Group, Hilti AG, Takenaka Corporation, Hitachi Construction, Hip Hing, Yau Lee, Züblin, etc.) towards the development of construction robots.

1.1 The Need for a Domain-Specific Procedure Model

Construction robots are robots designed to execute one or multiple construction tasks on site. In contrast to more complex approaches, they do not attempt to automate or robotise large parts of the construction site to avoid the need for extensive modifications or upfront investment. In this context, the authors realise the need to develop a generic development method that allows the diverse stakeholders to be involved in the development of on-site construction robots to streamline their activities along a common and simple set of steps and tools in an efficient and cyclical way. The development of construction robots usually involves stakeholders from the construction sector (e.g. contractors, developers, planners, engineering firms, etc.), the non-construction sectors (e.g. robotics, manufacturing, etc.), and the investment community. A systematic design process can help to integrate the needs and objectives of the different stakeholders and team members during system development. More importantly, the domain-specific procedure model for the development of construction robots can boost the efficiency of systems engineering and reduce redundant efforts and unnecessary waste of resources in the development process.

1.2 Construction Robots: State of the Art

Based on four decades of experience, the term, single-task construction robots (STCRs), was first defined by Bock and Linner (2016), who sub-categorised the robots by typology, mechanical configurations, and, most importantly, task categories. The STCTs were divided into 24 different categories, for instance: reinforcement production and positioning robots (an example would be a robot for positioning heavy reinforcing bars from Kajima Corporation) or bricklaying robots (an example would be the Hadrian bricklaying robot from Fastbrick Robotics) or facade coating and painting robots (an example would be the facade painting robot SB-Multi Coater from Shimizu). The initial boom of STCRs happened in the 1970s, driven by the Japanese construction industry. In the 1980s, a combination with parallel developments was supposed to achieve complete, integrated on-site factories (Linner, 2013). From the mid-1980s onwards, the global interest in STCRs decreased gradually. Bulky and expensive systems, difficult on-site navigation and logistics, a narrow scope of tasks, inflexibility, incompatibility with on-site work organisation and professional qualification, low usability and insufficient inter-robot coordination capabilities revealed the immaturity of the systems (Cousineau & Miura, 1998). By 2010, most STCRs had disappeared from the market. Only a few organisations such as Takenaka Corporation (Arai et al., 2010), Obayashi Corporation (Furuya & Fujiyama, 2011), Kajima Corporation, Nihon Bisho Co., Ltd., Hanyang University (Gil et al., 2016), Samsung Construction (Cho et al., 2009), Hitachi Construction (Kitahara et al., 2018), and Shimizu and the Fraunhofer Institute for Factory Operation and Automation (IFF) (Elkmann et al., 2002) maintained development activities, with the majority focussing on façade maintenance and inspection systems.

However, since the mid-2010s, development activities are gaining traction again. On the application side, this is mainly driven by the need to upgrade the energy performance of buildings in Europe (an extremely labour-intensive task), a global necessity to remove asbestos from existing structures, and a demand for enormous quantities of high-rise buildings all over East Asia. On the system side, the renewed interest stems from major advances in physical–mechanical robot technology in other automation-driven industries such as the automotive industry. Robots in general became lighter (Hirzinger & Albu-Schaeffer, 2008), more flexible (Perzylo et al., 2019), their parts modular and interchangeable (Giusti & Althoff, 2018), more user friendly (Bicchi, 2015), and significantly cheaper. Almost all around the world now, there is infrastructure for a mature robot component supply and networks of firms that can handle system integration for the design of location and industry-specific manufacturing solutions from standard robotic components.

Simultaneously, the above-mentioned soft information-driven infrastructures (in particular BIM-driven approaches that integrate fabrication and machining knowledge; see, e.g. Hamid et al. 2018), that were the focus of R&D for the last 20 years, can now serve as an integrating backbone, allowing for the coordination of on-site robots with humans, other systems, logistics and supply, and overall scheduling systems and processes on the construction site. In addition, an increased use of prefabricated elements on construction sites (e.g. Bock & Linner, 2015) and advances in material science - lighter, easier-to-use materials (see e.g. Bremner, 2008) reduce task complexity on site, which creates and facilitate preconditions for the design, development and use of robots. Nevertheless, a number of challenges remain. Labour shortage, labour cost, demands for quality and safety, stakeholder networks, predominant materials, construction practices and legal frameworks, and technology access and supply infrastructures differ significantly between regions all around the world and demand individual, bottom-up solutions. These circumstances impede the systematic build-up of knowledge and create redundant development efforts. Additionally, they hinder the quick scale up after development, which is demanded by investors.

1.3 Beyond the State of the Art and Research Question

The authors focus their recent research on developing and evolving a design replicable process for construction robots. This process combines the needs and know-how of stakeholders, considers best practices, and allows to benefit from the opportunities of "soft" infrastructures and scalability. The main question is how the development procedure of construction robots can be facilitated and formalised, while considering the following issues: simplicity (i.e. low complexity, custom-made kinematic components, standard components, etc.), high scalability (i.e. easy adaptability to a range of tasks, for instance painting, coating, or drilling), and cost effectiveness. An appropriate development process needs to be generic in its nature and to provide enough flexibility to work in different regions around the world, as well as for different construction task categories.

1.4 From STCRs Towards Modular/Multitask Construction Robots (MTCRs)

As conventional construction machinery is more widely used by replacing some specific construction tools, one could argue to develop not only STCRs but rather multitask construction robots or even a construction robot platform with interchangeable modular end-effectors for certain types of tasks. For example, the autonomous mobile robot for interior finishing developed by Bock is composed of a locomotion unit as the platform and has one single-task working end-effector on top, but it is capable of exchanging end-effectors for not only the installation of interior wall modules and raised floor units, but also for cleaning, tiling, painting, and other tasks (Bock, 2004).

2 The Procedure Model

Procedure models are defined sequences of project development activities which are widely used in various industries and domains. Besides the generic procedure models, systems engineering methods specifically designed for certain industries were also applied to best suit the features and needs of these industries and domains. Due to the growing interest worldwide in developing physical–mechanical robot systems for executing on-site construction tasks in recent years, a domain-specific procedure model customised for developing construction robots is needed as well. Therefore, a procedure model with a specific focus on the development of construction robots is introduced based on the experience and wisdom gained in several best practice research projects conducted in recent years (for instance the BERTIM project which focussed on developing a prefabricated solution or the CIC project which focussed on a multifunctional façade and exterior finishing robot or the HEPHAESTUS project which aimed to increase market readiness and acceptance of key developments in cable robots and curtain walls with a prototype cable robot designed to build, repair, and maintain a building façade, and many more).

2.1 Procedure Models in Other Industries and Domains

Both systems engineering methods and management systems seek to provide to some extent generic best practice guidelines on how to successfully develop, implement, and improve new technical systems that meet the needs of users and make predictable impacts. Systems engineering methods such as the V-model approach (Firesmith, 2013), which is used for simultaneous validation and verification of development phases, as well as test phases in a sequential manner (disciplined model, where a next phase only starts after completion of the previous one) and the NASA systems engineering method (NASA, 2008) are usually of a generic and cyclic type and applicable to a variety of tasks and industries. However, systems engineering methods specific to certain industries such as IT and software-intensive technical systems (e.g. Holtmann et al., 2017), mechatronics products, systems development (e.g. Gausemeier et al., 2014), machine learning, and artificial intelligence applications (e.g. Shearer, 2000) have also proven useful to integrate dedicated and domain-specific knowledge. Newer approaches to systems engineering also address the increasingly multidisciplinary nature of systems to be developed (Crowder et al., 2016), their increasing modularity and flexibility (e.g. Baldwin & Clark, 2000), the steadily growing need to systematically include stakeholders (Lu et al., 2017) and users (Ritter et al., 2014) into the design process, and the need to manage and to continuously improve the target systems (Fujimoto, 1999).

While systems engineering methods usually have a narrower focus on the development process, the complementary management systems have a broader orientation, which considers the whole organisation, business strategy, leadership, operation, and performance measurement and improvement. ISO has developed a series of Management System Standards (MSS) from its generic MMS high-level structure (ISO/IEC Directives, Part 1, Annex L, 2010), such as the ISO/IEC 20000-1:2018-09 standards series for service management (ISO/IEC 20000-1:2018 and ISO 13485:2016 for the development and quality assurance of medical devices). Xue et al. (2014) have reported about the increasing need to integrate systems engineering approaches with higher-level management techniques when developing technologically sophisticated systems. In the context of systems engineering, the concept of technology readiness levels (TRLs) and system and integration readiness levels (SRLs/IRLs; e.g. Sauser et al., 2006) are used to track the maturity of the implemented sub-systems, their interfaces, and integration with each other. The concept of system architecture (e.g. according to ISO/IEC/IEEE 42010:2011-12), referring to the structure of the target system, can be seen as a static representation of the systems engineering and management process, which usually aims at defining, detailing, and evolving the architecture of the system in question over time.

As described previously in the introduction of the chapter, "hard" physical–mechanical construction robots experienced a significant loss of interest—both on the market and in R&D—after the boom in the 1970s and 80s. Since then, only limited attempts were made to explain the concepts and processes of successful examples. Bock (1988) introduced the technology-focussed concept of robot-oriented design (ROD) aiming at a parallel and co-adapted development of both the elements of the actual robot and its surroundings (processes, logistics, work design, building component design, etc.). Hasegawa et al. (1992) introduced guidelines on how to modularise construction robot applications. Maeda led and reported on the development of a series of construction robots for different tasks (e.g. Maeda, 1994), but did not attempt to synthesise these findings into a generic, structured development process. Bock and Linner (2015) provide a general overview of design and management tools needed to develop automation and robot applications for construction, however, no concrete guidance on the development of construction robots. Several researchers reported the successful use of workflow diagrams and techniques to design and optimise the work progress (e.g. Kitahara et al., 2018) and translated the solution subsequently into a specific robot design—a key element in construction robot design. However, integrative and comprehensive guidance on how to systematically devise, strategically align, engineer requirements, design, develop, implement, evaluate, manage, and mature designs of construction robots (i.e. their system architecture), and the respective TRLs, IRL, and SRLs are missing at present. In the view of the authors, this gap can be closed most efficiently by providing a practical, hybrid guidance system, situated between and seamlessly integrating systems engineering and management system methods—namely a procedure model for the development of construction robots.

2.2 *Procedure Models for the Development of Construction Robots*

The basic structure of the procedure model is explained in Fig. 1. With its basic structure, it follows the Deming cycle for continuous improvement (Layer 3) and allows to start the cyclic development process at any stage and to apply it even to existing and, to some extent, to matured construction robot designs. In the eyes of the authors, these aspects of continuous improvement and flexible starting points are crucial in the light of the current state of play in the field of construction robots; since, at present, there is limited feedback from the market and continued and successful long-term use, it is—in contrast to more established industry fields–very difficult to specify the right requirements, system architectures, work processes, and business models straight away. Instead, a cyclic and iterative approach is required that allows

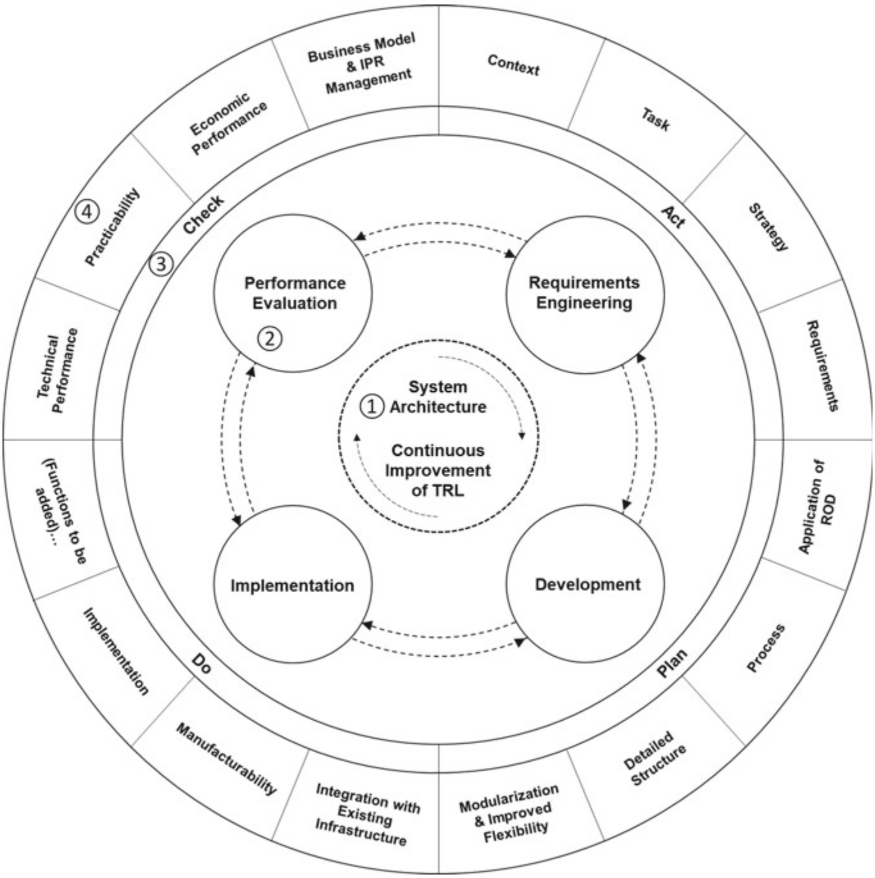


Fig. 1 Procedure model for the development of construction robots (*source* T. Linner and R. Hu)

the developers, start-ups, or companies using it to start at a specific stage and to tailor the efforts for each cycle to the specific capabilities and resources they have at hand when starting a cycle. Core elements of the procedure model are the four primary process steps (Layer 2) at the centre (requirements engineering, development, implementation, performance evaluation, inner circle), each being comprised of a selected set of activities, tasks, and outlined requirements (Layer 4). Both the primary elements (Layer 2) and the individual activities (Layer 4) are discussed in greater detail in the following sections. Specifically, the sub-activities listed in the outer circle incorporate construction robot-specific knowledge that the authors of this chapter have gained through their involvement in numerous development projects of construction robots. The continuous evolvement of the system architecture and its TRLs (Layer 1: System architecture) state the primary aim of the proposed process (Linner et al., 2019).

As with any systems engineering or management approach, the verification (providing initial formative feedback that key elements work in practice) and validation (summative and quantitative feedback from large-scale application and testing) of the method are critical. Cases of sustained market application of construction robots are rare. Thus, a matured validation (i.e. evaluating statistically relevant application data or comparing different development methods of use cases) is not feasible currently. However, the authors were able to verify individual elements and larger parts of the procedure model cycle, in addition to the successful interaction of selected elements in a series of very recent construction robotics development projects. The procedure model cycle can be seen as an open and expandable system (e.g. new primary elements can be added to the inner circle and new activities to specific sections of the outer circle), presenting an initial configuration which can evolve over time with new experience and input from formative testing in upcoming projects where it is applied.

2.3 Verification and Validation of the Model

The following projects contributed to the verification of parts and elements of the cycle:

- **Development of a façade processing robot for CIC (CIC robot)**

  The authors developed a highly scalable and cost-efficient façade processing robot for high-rise buildings in Hong Kong. The project allowed for a first complete pass through one procedure model cycle. The first semi-functional prototype of the multifunctional façade processing robot was built and tested in a laboratory as a proof of concept. At present, a follow-up project is planned which will allow for two additional run-throughs (second cycle: extended prototype + improved business model; third cycle: fully functioning site system + market introduction). The project was commissioned by the Hong Kong Construction Industry Council (CIC) in Hong Kong and evaluated the current on-site construction operation and identified the existing bottlenecks that can be enhanced by implementing robotics and automation. As a result, a range of robotic applications that are tailor made for Hong Kong public housing industry were recommended and hierarchically categorised. The proposed multifunctional façade and exterior finishing robot aims to inspire the construction industry to initiate and explore innovative robotic solutions with its main functions (exterior painting, concrete wall grinding, and water tightness inspection).

- **Development of a cable-driven panel installation robot in the project HEPHAESTUS**

  In this project, the authors are responsible for the development of a multifunctional end-effector for a robotic system for façade panel installation (Iturralde et al., 2020). The process allowed the verification of selected parts of the requirements engineering, development, and implementation sections. The project was funded by the EU under Horizon 2020 and explored the innovative use of robots and autonomous systems in construction, a field where the incidence of such technologies is minor to non-existent. The project aims to increase market readiness and acceptance of key developments in cable robots and curtain walls. The project prototype cable robot is designed to build, repair, and maintain a building façade. HEPHAEASTUS cable robot is for the automated positioning and assembly of façade panels on the site for empowering and strengthening the construction sector in Europe.

- **Development of innovative façade renovation solutions in the project BERTIM**

  In BERTIM, the authors are responsible for the development of automated and robotic solutions for the building renovation process with prefabricated modules. The prefabricated solution will provide the opportunity to renovate improving energy performance, air quality, aesthetics, comfort, and property value at the same time, while ensuring low intrusiveness during renovation tasks. The project allowed a verification of selected parts of the development and implementation sections, i.e. the application of the ROD activity, the detailing of the structure (with a focus on manufacturing and installation processes), and integration with existing infrastructure. Moreover, the whole product life cycle was integrated with a software (RenoBIM 4.0) that links the information of the existing infrastructure, BIM, and the robotic manufacturing and installation processes. This project was funded by the EU under Horizon 2020.

- **Development of a scenario development technique for on-site construction robot technology**

  In collaboration with the University of Hong Kong, the authors developed a scenario technique for forecasting technology trends in specific construction industries. The project provided feedback on how to structure the initial phase of the requirement engineering section. This project was financed by the German Academic Exchange Service and the Research Grants Council of Hong Kong.

- **Development of robotic solutions for elevator system installation by LEVARU**

  The start-up LEVARU aims to automate the process of aligning elevator guiderails during elevator installation. The development has run through several cycles as the problem was first defined, and a solution for adjusting guiderails with a robot was developed. Industry insiders provided feedback, which helped to specify the problem further and to improve the solution. Entrepreneurial aspects led to further conceptual alterations in favour of an assistive system, indicating the position of the guiderail in real time. Having a lower degree of automation reduces development time, time to market, and risks involved.

Furthermore, future validation studies can be conducted with the developed robot systems. For example, a real-world pilot project can be conducted among two competing teams, where one team employs the robot system and the other uses the conventional construction method to execute the same task. Through this process, key performance indicators (KPIs) of each method (e.g. speed, quality of the work done, resources consumed, costs, etc.) can be analysed to compare the advantages and disadvantages of the two methods.

In addition, it must be mentioned that the procedure model for the development of construction robots is composed of an adapted set of established principles and methodologies from the systems engineering and management field as its core and combined with a set of activities enlisting concepts specific for the development of construction robot. These concepts represented in Layer 4 were developed as stand-alone elements and tested by the authors in their construction robot-focussed research work, robot development projects, and consulting activities (see, e.g. Bock, 1988; Linner, 2013) prior to their combination into the procedure model cycle and prior to their more integrated application in the projects covered in this chapter.

The primary elements their sub-activities and sub-concepts are described in the following sections. The development process of the façade-processing robot for the Hong Kong CIC (CIC robot) is serving as the primary example for explanation and verification since the project is the closest to the market and allowed performing and testing for one complete cycle, where needed, other projects and works will be referenced for individual elements, activities, concepts, or other aspects.

3 Requirements Engineering (Act)

This phase of the procedure model for the development of construction robots is intended to systematically establish the context and cornerstones for the development. It is divided into four main steps: (1) the analysis of high-level context and industry trend of the use case; (2) gradually narrow it down to a selection and decomposition of the actual task for the robot; (3) once the task is defined, a business strategy and stakeholder network can be developed; (4) based on this, the system requirements and performance indicators can be defined.

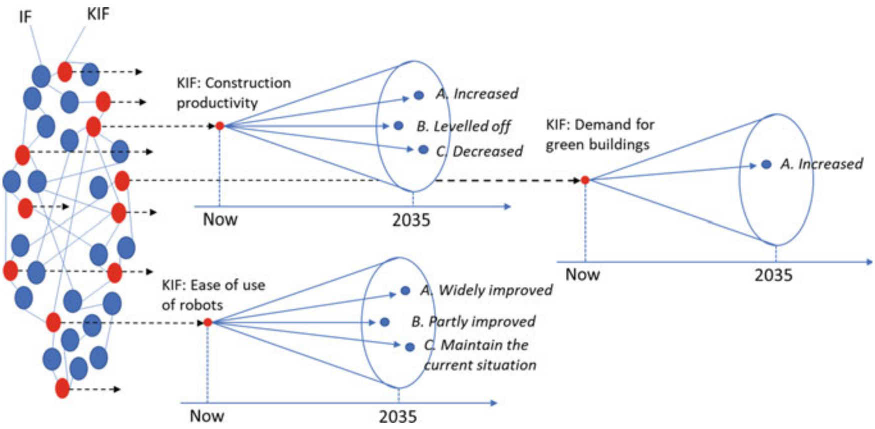


Fig. 2 Use of scenario technique to forecast automation and robotics trends in Hong Kong's construction industry (*source* T. Linner)

3.1 Context: Scenario, Technology, Stakeholder, and IPR Analysis

Firstly, the context within the industry use case setting needs to be analysed (i.e. within the country and/or the particular region). A methodology to forecast technological trends and high-level requirements in a confined industry setting such as Hong Kong was developed by the authors in a series of publications (e.g. Pan et al., 2018a; cf. Fig. 2) based on the scenario technique by Gausemeier et al. (1995). On the basis of this analysis, the forecasted trends can be used to narrow down the scope of the project (e.g. feasibility of different types of automation, etc.), and an initial high-level analysis of stakeholders and the IPR context (existing IPR, IPR regulations, etc.) can be carried out. The authors have provided guidance on conducting stakeholder and IPR analysis prior to the development of robotic or mechatronic systems in Linner et al. (2017).

3.2 Task: Selection, Analysis, and Decomposition of the Task Area Foreseen for the Construction Robot

Secondly, the robot's task or task category must be carefully identified. Helpful task categories for construction robots have been provided by Bock and Linner (2016). In the development of the CIC robot, several activities were conducted. This includes an online survey for previously identified stakeholders ($n = 36$) in combination with an in-depth process analysis on site (workflow, techniques, regulations, interviews with workers and site managers, etc.; $t = 4$). The outcomes were reported in a separate publication (see Pan et al., 2018b).

3.3 Strategy: Business Strategy and Scalability

Based on the selected task category, the initial business strategy can be developed. In this stage, it is key to identify the cost drivers in conventional task execution and to find ways to alter the task composition and execution efficiently for the robot. At this point, the business strategy should also identify potentials for quick scale up. Ideally, the selected task appears in high quantities or very frequently within the company or industry in question. The application scope can be increased by analysing whether the selected task (e.g. the kinematic motions) occurs similarly in other trades or even industries, in order to generate additional applications and market cases. High-rise façade processing tasks such as painting occur in a very similar form in precast element production or in shipbuilding.

3.4 Requirements: Co-creation, Requirements, Indicators

In the identified context, a combination of the selected and analysed task and the initial business strategy form the case for tangible use for the actual system development process, besides the definition, detailing, and prioritisation of the requirements. A systematic requirements engineering process can be conducted in numerous ways (see e.g. Pohl & Rupp, 2015). A direct, fast, and very efficient way to define and prioritise the key system requirements is to conduct this process as part of a series of co-creation workshops together with the potential key stakeholders. Usually, these workshops can also be used to test the first assumptions about business models and discuss future cooperation among key stakeholders. The practical application of the requirements co-creation method in the case of the CIC robot is described in Pan et al. (2018b).

After the prioritisation of the requirements, measurable indicators for a successful translation into system functionality and system performance must be defined. In the example of the CIC robot, the first stage prototype should provide information regarding processing speed, cost, manufacturability, and flexibility performance, including indications of possible challenges for future continuous on-site operation. Complex automated systems with several sub-processes need to be broken down into several steps, which then can be analysed separately. Methods such as axiomatic design (Suh, 2001) can be a helpful tool to avoid interferences or contradictions when defining the requirements and solutions. This method has proven useful in the BERTIM project, where it helped to create a set of solutions. The automated and robotic process was divided into four different stages: data acquisition, layout definition of the modules, manufacturing, and installation. The preliminary definitions were weighted and evaluated using multi-criteria decision-making (MCDM) called COPRAS (Kaklauskas et al., 2006). This method allows determination of the suitability of the construction robot solution in each procedure model stage, depending on the key functional requirements. The iterative evaluation enables constant improvement, while a MCDM can serve as a sub-system to evaluate the procedure model in every stage.

4 Development Sequence (Plan)

This stage serves to define and detail the initial concrete model of the system architecture. In the author's view, the first important step is conducting a ROD analysis in order to determine how complexity can be distributed between both the building system and the robotic system. Based on this, detailed operation sequences for the robot and the execution of the task can be developed. This is used to determine the (kinematic) structure of the robot. Although modularity should be kept in mind from the very beginning, it is possible only now to develop it as first detailed regarding modularity and flexibility.

4.1 Application of Robot-Oriented Design (ROD)

To translate system requirements into concrete system functionality and design, first of all an in-depth ROD analysis is required. This is necessary to determine how the complexity of the robot can be decreased by shifting some complexity to the overall system (e.g. the building system). For the CIC robot, the façades of the local public housing estates (primary use case) were thoroughly analysed in terms of geometry, variance, accuracy, manufacturing processes, etc. The analysis showed two things: (a) the robot can be designed according to the dimensions of the typical elements, which can be used for orientation and as a repeating operation sequence block; (b) redesigned precast elements could significantly reduce the degrees of freedom the robot requires. A subsequent discussion with the previously identified stakeholders led to the decision to pursue only option (a), whereas option (b) was dropped because it would have required changes across the value chain, which would have been hard to implement (Linner et al., 2019). Apart from the formal design of elements the construction robot interacts with, accuracy is an important parameter for ROD. This issue has been addressed in BERTIM (Iturralde et al., 2017). If the production accuracy of construction elements is higher, tolerances become smaller, and thus, potential reworking is reduced. For ROD, the feasible accuracy of the robot determines the tolerances of the objects it is handling—the more accurate the robot is, the lower the tolerances can be (see Fig. 3).

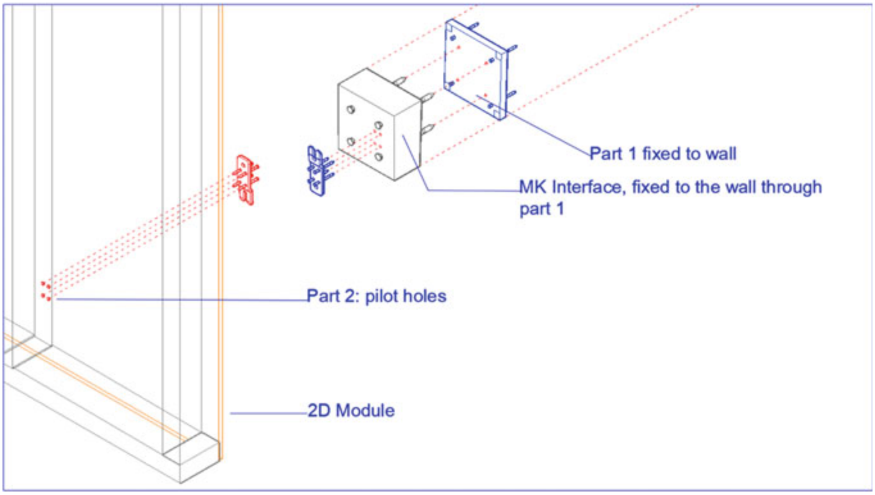


Fig. 3 ROD concept applied in the BERTIM project (*source* K. Iturralde)

4.2 Processes: Determine Operation Sequences and Processes

On the basis of the results of ROD and the determined requirements, assembly line planning can take place. The term “assembly line” is intentionally used to emphasise the construction process and should be perceived as a production process. The robot is inserted into an assembly line-like process in a factory environment (i.e. the construction site) with the usual means of production: human resources, equipment, material, etc. In this context, the following aspects must be considered when drafting the operation sequences and sub-activities of the robot and its surrounding elements:

1. Consider sequencing and material flow of all involved elements (e.g. it is more challenging to supply paint or other material continuously according to the consumption of the robot on a construction site than in a factory.).
2. Determine and implement the productivity focus in line with the previously specified performance indicators: focus on speed, labour reduction, cost reduction, safety, or all.
3. Consider ease of use and the movement/logistics of the robot: transportation to site, installation, operation and maintenance/repair, de-installation, etc.
4. Determine a feasible degree of automation considering human factors (i.e. which skills and new work profiles may be needed)
5. Determine the implication across the value chain (i.e. to what extent does the operation of the robot within a specific trade affect other trades or processes before and after the application of the robot).

In case of the CIC robot, the operation sequence was synchronised with the structure and shape of typical façade panels in Hong Kong public housing

Fig. 4 During the development of the CIC robot, all operations needed from setting up the robot on site, operating it along the façade, to the removal of the robot from the site were carefully planned (*source* R. Hu)

(Fig. 4). All operations required—from the set-up to operating on the façade to the de-installation—were carefully planned and represented in operation sequence diagrams. A variety of options for the paint supply of the robot were developed in close collaboration with key stakeholders.

The initial degree of automation was kept low (with the option to increase over time) and facilitated by a modular strategy. The positioning of the system on the façade panel will be manual, and only painting will be performed automatically.

In BERTIM, the main issue regarding the robotic installation is the placement of a connector on the existing infrastructure (Iturralde et al., 2016). If the modules require high precision, the connector needs to be installed very accurately; otherwise, the modules do not fit. This is also a relevant issue for new construction. In BERTIM, two strategies were developed, as shown in Fig. 5:

- Strategy 1 (left): The connector (Part 1) is placed on the existing infrastructure with low tolerance. Similar to "traditional" approaches, this is done using measuring devices to acquire reference points on the building.
- Strategy 2 (right): The connector (Part 1) is placed on the existing infrastructure with high tolerance. In this case, an interface, the matching kit (MK), corrects possible deviations.

Which strategy eventually requires more time or effort needs to be determined in the procedure model for STCR development. The accuracy of the STCR is the main factor in this case. In the Hephaestus project, five different conceptual scenarios for the complex automatic installation process of façade elements by a cable-driven robot

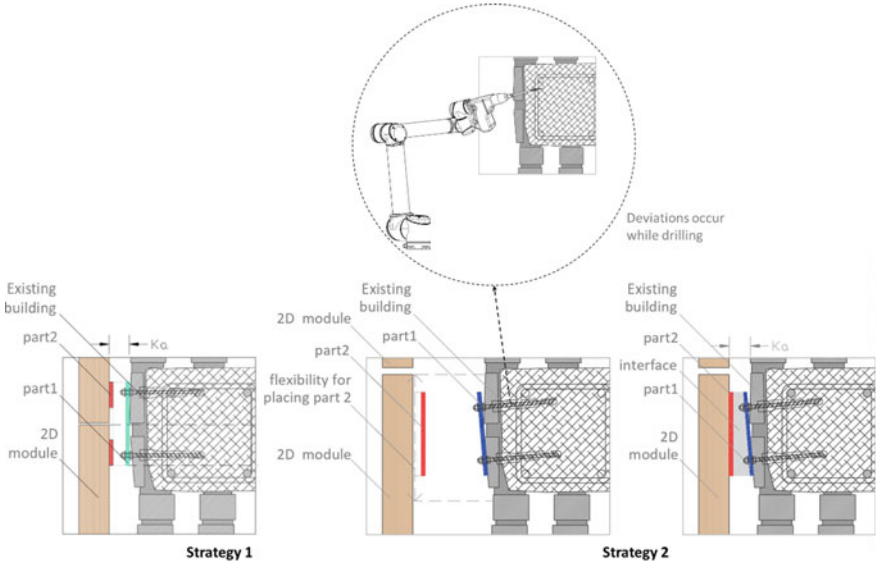


Fig. 5 Subsequent step determines the kinematic configuration of the robot (*source* K. Iturralde)

were introduced early on. Results of the assessment in terms of accuracy, safety, and installation time are published in Taghavi et al. (2018b).

4.3 Detail Structure of Construction Robot

With the operation activities, sequences and degrees of automation detailed, the mechanical–physical composition of the robot (i.e. basic kinematics)—a key step in designing the system—can be determined and drafted. For the CIC robot, the operation sequence for each panel could be simplified to a degree that allowed the use of a simple gantry-type Cartesian system (see Fig. 4). By using only linear axes, the integration of industrial robots in the system design could be avoided. As a consequence, the complexity is significantly reduced, which in turn makes the system significantly cheaper. In this context, it is also required to determine the basic physical–mechanical sub-systems of construction robots, which is usually comprised of (1) the actual robot base body or frame, (2) the locomotion unit (e.g. ground based, rail based, cable suspended, cable stayed, etc.), (3) the end-effector, and (4) the material and tool supply system.

Next, the sensing and feedback composition of the robot (i.e. the basic sensing, positioning, and alignment solutions) can be determined. In general, digital sensing systems for construction environments are difficult to design and operate and are a substantial cost factor. Where possible, physical–mechanical sensing elements should be used instead. For the CIC robot, a sensor system for positioning could be avoided by manual operation of the robot gondola in the initial version. The fine positioning is done by a mechanical template that aligns the robot along the typical cantilevering elements of the façades. Finally, the feasibility regarding dynamics and statics (payload, net weight, etc.) needs to be detailed.

4.4 Modularisation and Flexibilisation

Modularity is one of the initial guiding principles when cycling through the proposed procedure model. After detailing the basic structure, the detailed concepts for modularity and flexibility of the robot system can be developed.

Determining the levels of inbuilt and modular flexibility, the modularisation of the base body, the tool change strategy, and the modularity of the end-effectors are key in this context. The carrying frame (base body) of the CIC robot was designed to allow easy adjustments to slightly varying heights and length of the façade panels. The kinematic structure ensured the flexibility to process deviating façades (e.g. windows and cantilevering elements). In addition, a set of modular end-effectors was designed to cover nine relevant tasks for processing and finishing exterior façades (Fig. 6). Keeping investors and scaling up in mind, tool change allows the robot to be adapted for additional repetitive on-site tasks (e.g. for other building types or even in other industries such as shipbuilding). Given the available resources for demonstration purposes, only one end-effector for painting was prototyped in the first procedure model cycle. Considering modularity and flexibility early on facilitates efficient refinement and expansion in later procedure model cycles (Fig. 7).

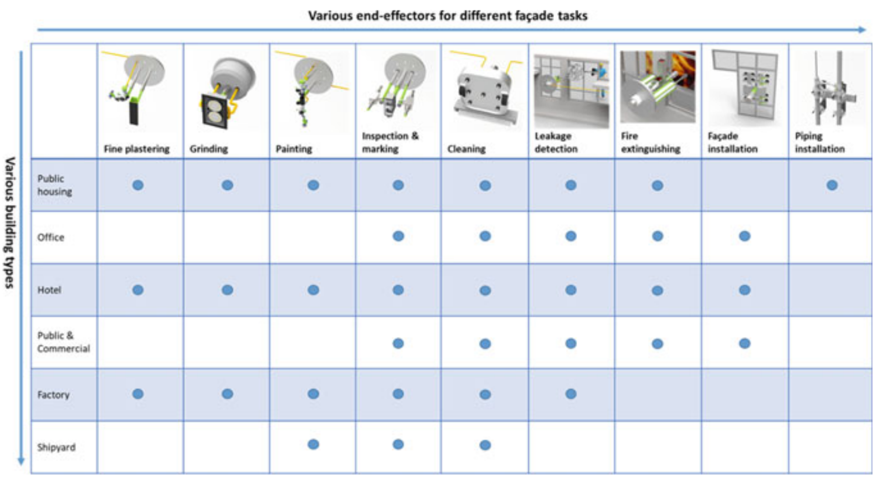


Fig. 6 Set of modular end-effectors was designed allowing the robot to be adaptable to larger quantities of repetitive tasks (*source* R. Hu)

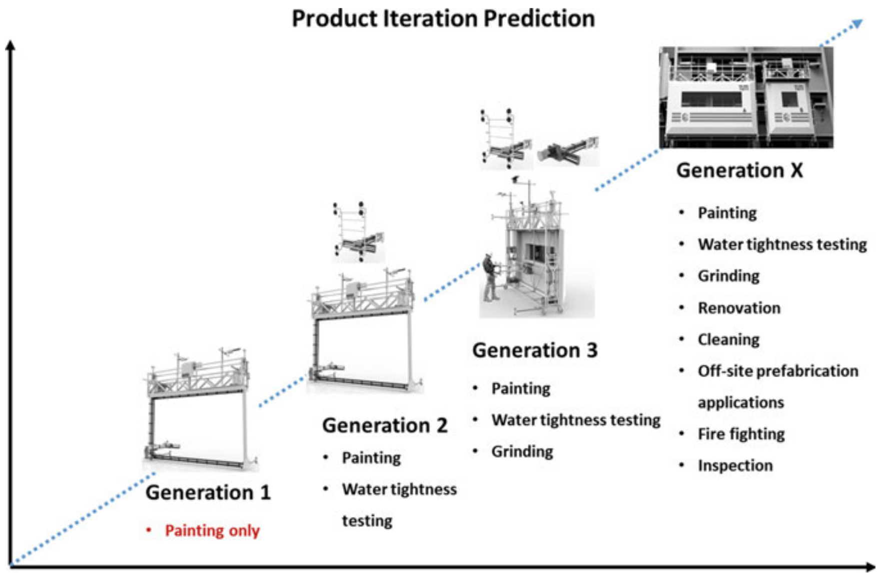


Fig. 7 Projection of future expansions of the robot developed for CIC Hong Kong, which are enabled by modularity of the underlying system (*source* T. Linner and R. Hu)

5 Implementation and Prototyping (Do)

After having detailed task sequence, structure, composition/design, and modularity of the robot, the first implementation can be addressed. This phase of the procedure model for the development of construction robots is usually resource and time intensive. With the task sequence, structure, composition/design, and modularity concept of the robot detailed, the first implementation and prototyping cycle can be started. This phase of the procedure model is usually resource and time intensive. It comprises detailing the integration with larger existing infrastructures, development towards higher manufacturing readiness levels, and the implementation as either a mock-up, a prototype or as the final product—depending on maturity and previous procedure model cycles.

5.1 Detailing of Integration with Existing Infrastructures

As mentioned before, ICT infrastructures such as BIM have made great strides in the last decade. They have huge potential to facilitate the integration of construction robots with other systems, processes, and humans on site and therefore overcome

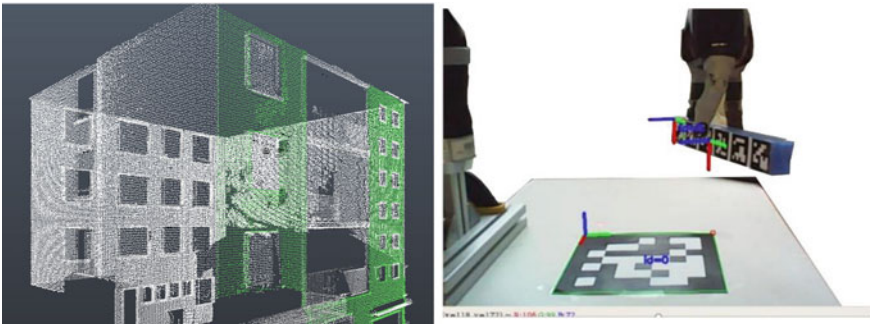


Fig. 8 Left: Point cloud of an existing infrastructure (*source* K. Iturralde). Right: Using ArUco markers for determining the location of the construction robot (*source* K. Iturralde)

many of the current drawbacks. Ideally, a digital infrastructure allows the integration of construction robots into a digital twin of the construction site, simplifying scheduling, planning operations, programming movement and motion, etc.

Digital surveys can provide information about the geometry and material composition of the environment. The construction robot requires this information to interact with the built environment. Depending on the degree of automation, the data can be processed automatically via algorithms to achieve spatial recognition. The robot can gather two main types of information: (a) coordinates or distances and (b) images. Coordinates can be provided by scanners (see Fig. 8 left). Images can also provide digital information of the existing infrastructure. The recognition can be facilitated by using fiducial markers (see Fig. 8 right). Each type has its merits, depending on the scenario.

The findings from BERTIM suggest that, depending on the requirements, a construction robot can operate even with little available data (see Fig. 8 right). The necessary accuracy level could require positioning calibration during operation. In Hong Kong, an ongoing transition to BIM as the industry standard suggested to work towards an interoperability with the CIC robot. BIM can then serve as the backbone for an integrated service platform (ISP) for construction robots, allowing for automated scheduling, planning, and operation monitoring of the tasks to be executed (see Fig. 9).

Aside from ICT and BIM, other types of emerging infrastructure such as sky factories or larger robot system platforms warrant further analysis.

5.2 *Manufacturability*

The design generated in previous procedure model cycles must be suitable for a cost-efficient production. This requires determining the manufacturing readiness level (MRL). The necessary resources and the cost of the robot should be minimised,

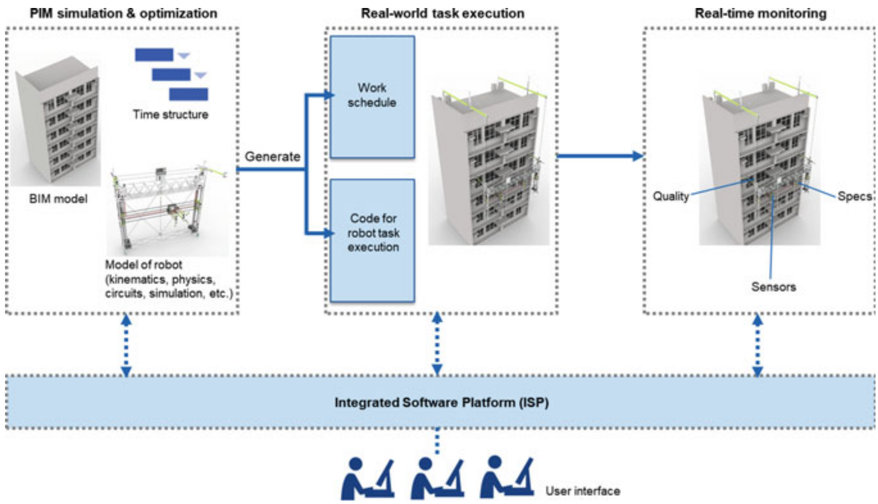
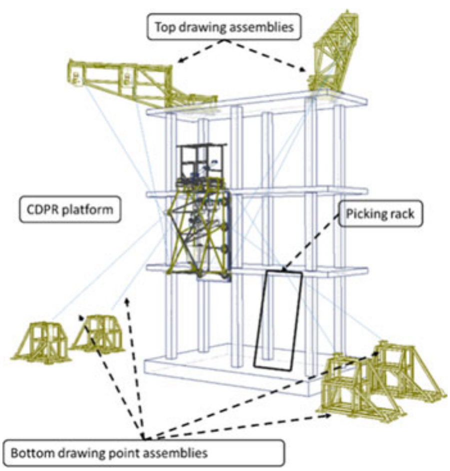


Fig. 9 Having the BIM infrastructure as the backbone, an integrated service platform (ISP) for construction robots can be created to allow for extent automated scheduling, planning, and monitoring operations executed by the construction robots (*source* T. Linner and R. Hu)

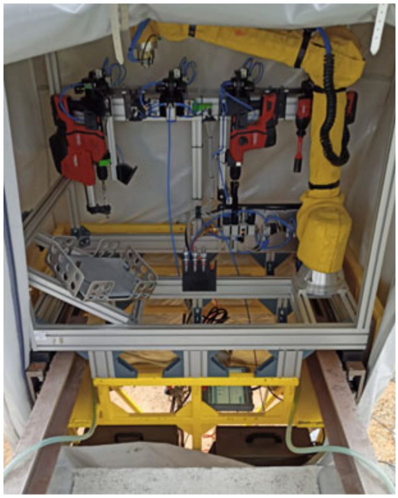
while ensuring robustness for on-site operation. Therefore, construction robots are ideally composed primarily from linear axes or other relatively cheap and standard automation components, while avoiding the costly integration of industrial robots. The latter tend to be significant cost drivers. Nonetheless, their application (e.g. as part of an end-effector) may be reasonable, depending on the situation.

The operation sequence of the CIC robot was partially simplified, which allowed it to be built entirely from standard linear axes and drives (Fig. 10). Thus, it is not only possible to create a cost-efficient bill of materials (BOM), but it also facilitates the set-up of a manufacturing system for the robot. In HEPHAESTUS, a hybrid approach was selected: the main kinematic structure of the robot system is made

Fig. 10 In the context of the facade processing robot developed for CIC, the operation sequence and the composition of the robot were simplified in previous steps that allows the robot to be built fully from standard linear axes and drives (*photo* R. Hu)



Overall cable-driven robot system



End-effector utilising and industrial robot as a sub-system

Fig. 11 Left: HEPHAESTUS cable robot overall system with an example of a prototype building and curtain wall system, suitable for robot assembly (*source* K. Iturralde); Right: Hephaestus cable robot end-effector (*photo* K. Iturralde)

up of a cost-effective cable robot system, and a small (6 DOF) industrial robot is utilised as a sub-system of the end-effector. This hybrid "macro/micro" positioning approach was selected (Fig. 11). A simple, cost-effective cable robot system serves as the macro-kinematic structure, while a light end-effector system with a small industrial robot handles fine positioning (Taghavi et al., 2018a).

5.3 Simulation and Model-Based Systems Engineering

Apart from physical prototyping, simulations as "digital prototyping" are also widely used in many domains including the construction industry. The development of simulation environment is especially useful for early-stage verification, and the development of construction robots is no exception. Notably, the simulation environment for the development of construction robots integrates models of the robot components, models of construction processes and other equipment, and models of human beings and collaborative processes, all integrated and coordinated by process information modelling (PIM), which is a process-based database platform concept based on BIM technology, providing a collaborative strategy of planning, designing, producing, assembling, and managing the entire project life cycle (Pan et al., 2018c). The advantages of simulation and model-based systems engineering are manifold, including but not limited to the following aspects: (1) it is more cost effective than testing with physical mock-up and prototypes; (2) the deployment speed is much faster than the conventional physical prototyping process; (3) the whole or parts of the digital prototype are flexible and easy to modify for new simulations. Therefore, simulation and model-based systems engineering is widely used in various scenarios in the construction sector including the development of construction robots, although the physical prototyping activities cannot be completely replaced due to their high credibility and tangibility.

5.4 Utilisation of Digital Twins, Data Processing, and AI

Digital twin technology emerged over the recent years as a dynamic model for data-driven management and physical system control in the fields of product manufacturing and operations. In the context of the construction industry, the notion of digital twin is not clearly defined and widely applied, although there have been some meaningful attempts to integrate it into the construction sector most recently (Sacks et al., 2020).

Therefore, the following simplified model for using sensing technology, data processing, and AI in the development process of construction robots can be proposed as a component of the procedure model. In the planning phase, all the components and parts of the robot are designed and parameterised, supported by capable BIM technology that can manage the geometry, system coordination, and path planning of the robot. Subsequently, the work process of the robot and the programming languages used for coding the instructions (e.g. Python, C+ +, Java, etc.) are defined. In the next phase of factory production and construction site operation, the automation software (e.g. LabVIEW, ROS, TwinCAT, etc.) is chosen to implement real-time control for multiple PLC, NC, CNC, and robotics run-time systems. Meanwhile, the data processing hardware (e.g. microprocessor, single-board computer, controller, sensors etc.) is integrated, which later receives real-time data from the construction site, processes them, and produces time/vector-controlled execution instructions to operate the actuators and kinematics of the robot to conduct certain task on the construction site. As the process of development progresses, the uncertainty will decrease, and the robustness of the construction robot system will improve (see Fig. 12).

5.5 Implementation

In contrast to other industries such as manufacturing, there is only limited experience about the behaviour of construction robots in the field. Consequently, iterative prototyping and testing are of the utmost importance. Prototypes can be used to generate information from stakeholders at all levels (workers, site managers, contractors, robot system suppliers, the public, etc.). Where initial prototyping should be

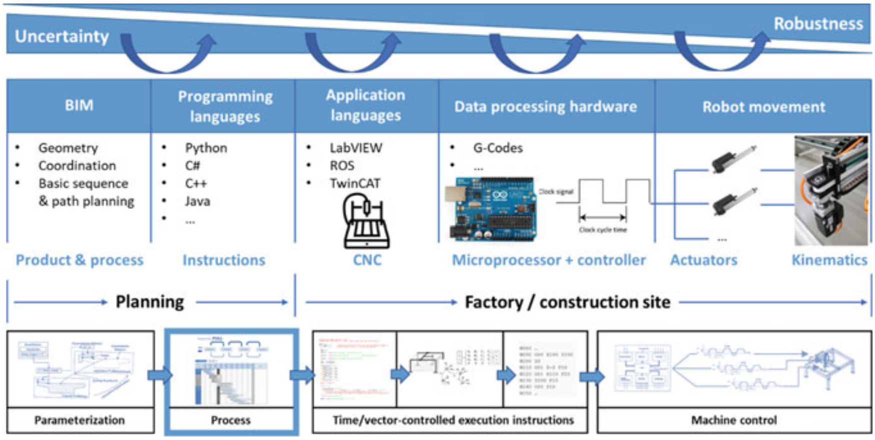


Fig. 12 Sensing technology, data processing, and AI application in the development of construction robots (*source* T. Linner and R. Hu)

focussed on technical performance, later stages should be accompanied by a study design that allows valid feedback from users and potential interference with the on-site ecosystem. NASA's TRL concept provides good guidance. It suggests three successive test phases (laboratory testing, testing in relevant/simulated environment, testing in real-world environment) before the development of the final "mission ready" system.

The prototype of the CIC robot was designed to yield information on (a) processing speed; (b) system flexibility; and (c) system cost. Additionally, feedback regarding the manufacturability of the system by local companies including general feedback from stakeholders such as contractors and developers was acquired. Live testing and demonstration of the cable-driven robot system in HEPHAESTUS (Fig. 11, left) will later be carried out on a three-storey construction site in Madrid, Spain. Initially, each sub-system will be implemented individually, followed by the integration and testing of the entire system. For LEVARU, the robot system was first prototyped as a 1:2 scale mock-up, before the concept was altered to a human-guided on-site-assistive device. A device to display the position of elevator guiderails in real time was prototyped and successfully tested in a laboratory environment, reaching TRL 4.

Moreover, it is not unusual that new, unexpected obstacles appear during the implementation process. In BERTIM, testing revealed a problem of major deviations when the construction robot was grasping objects, which affected the placement accuracy and therefore the entire assembly process. This can be considered a typical challenge in unstructured environments such as construction sites, where objects are not referenced. To eliminate this problem, visual systems were introduced to detect the object and its exact location. The robot was then able to correct the planned path and to place the object accurately (Iturralde et al., 2019).

6 Performance Evaluation (Check)

The prototype must be developed in conjunction with the study design. To obtain information on the performance characteristics and to evaluate the system, testing must be designed to generate the necessary data and feedback for verification against the performance indicators from the requirements engineering phase to start the next procedure model cycle.

Performance indicators should be tailored to the specific project (e.g. the deployment region), the available resources for the procedure model cycle and the desired TRL. Three performance categories (technical performance, practicability and usability, and economic performance) are key for construction robots. Based on the qualitative and quantitative data, the performance evaluation yields and the initial business strategy, defined in the requirements engineering phase, can be detailed towards a business model. In parallel, an appropriate strategy to deal with potential intellectual property (IP) needs to be developed or updated.

6.1 Proof of Concept: Laboratory Testing and Public Demonstration

As for the CIC robot development, the prototype tested in the laboratory served as a perfect example to successfully verify the concept, kinematics, and partial functionality of the robot. Based on the laboratory testing, the prototype (currently equipped with four degrees of freedom and later to be extended to five) is able to move its end-effector to cover the majority of the façade surface, and it has the potential to switch its end-effector from one to another in a short period of time. In the simulated painting testing (using a laser pointer instead for the simulation), the robot can complete the painting simulation of one 1:2 scale façade wall panel in as fast as 150 s. Furthermore, the actual prototyping cost provided the data that can be used to estimate the fully functional prototype costs and will be useful as a guideline for future cost–benefit calculation. In addition, it was understood from the prototyping process that in the future iterative development, the weight of the robot needs to be effectively reduced to relieve the burden of the existing building structure and avoid alterations to the existing hoisting of the suspended platform system. Ultimately, the prototype was successfully exhibited and demonstrated in the Construction Innovation and Technology Application Centre (CITAC) in Hong Kong (see Fig. 13, top). This provided not only a live demonstration to the engineers and professionals but also raised public awareness of construction robotics. In conclusion, the first project phase provides precious knowledge and experience for the activities in the next project phase (e.g. performance testing, usability testing, etc.). In the HEPHAESTUS project, as previously mentioned, the prototype of the system was transported and assembled on a three-storey construction site in Madrid, Spain, and was tested for real-world performance thereafter (see Fig. 13, bottom).

Fig. 13 Top left and right: prototype of the CIC robot (*photo* R. Hu); bottom: prototype developed and tested in the HAEPHAESTUS project in Madrid, Spain (*photo* K. Iturralde)

6.2 Practicability and Usability: Stakeholder and User Feedback (Co-Creation 2)

Besides the technical performance, it is important to evaluate the practicability and usability performance of the system. The development team of the CIC robot carried out initial explorative usability testing in the laboratory. Testing revealed that the calibration of the robot after emergency stops may cause severe maintenance issues in real-world operation. During an exhibition at the Construction Innovation and Technology Application Centre (CITAC) of the CIC, additional explorative feedback from stakeholders and potential investors could be acquired. This can be considered as a second co-creation phase in which stakeholders and users collaborate to refine practicability and usability requirements. Due to the previous acknowledgement that there is virtually no data for the on-site performance of construction robots, co-creation shall be considered as the key.

6.3 Economic Performance: Cost–Benefit Analysis (CBA)

The economic performance can efficiently be tested through a CBA that uses data obtained from technical, economic feasibility, and practicality/usability testing and evaluation (Warszawski & Rosenfeld, 1994). Both CBA and cost-effectiveness analysis (CEA) are useful tools to measure, to evaluate the investment potential of a product, and to guide investor decision-making on how to allocate research funding in a prospective project (Boardman et al., 2018).

Therefore, a simple and practical framework for conducting the CBA of STCRs was developed based on the case study of the cable-driven façade installation robot in the HAEPHAESTUS project. Figure 14 shows the general steps applied in this CBA framework. Using this framework, key financial indicators such as benefit–cost ratio (BCR), return on investment (ROI), payback period (PBP), net present value (NPV), and break-even point (BEP) for local hourly wage were calculated. In addition, the results showed that the façade installation robot in the HEPHAESTUS project is theoretically worth investing in the UK and generally in most developed countries. This CBA framework is highly adaptable and reproducible which allows researchers, engineers, investors, and policy-makers to easily follow and customise it to assess the economic performance of other construction robot systems (Hu et al., 2021).

6.4 Business Model and IPR Management

The first procedure model cycle for the CIC robot assisted to clarify the relationships of the involved stakeholders and to determine that the contractors can act as users and operators of the system that either buy the robot from a local (e.g. Shenzhen, China)

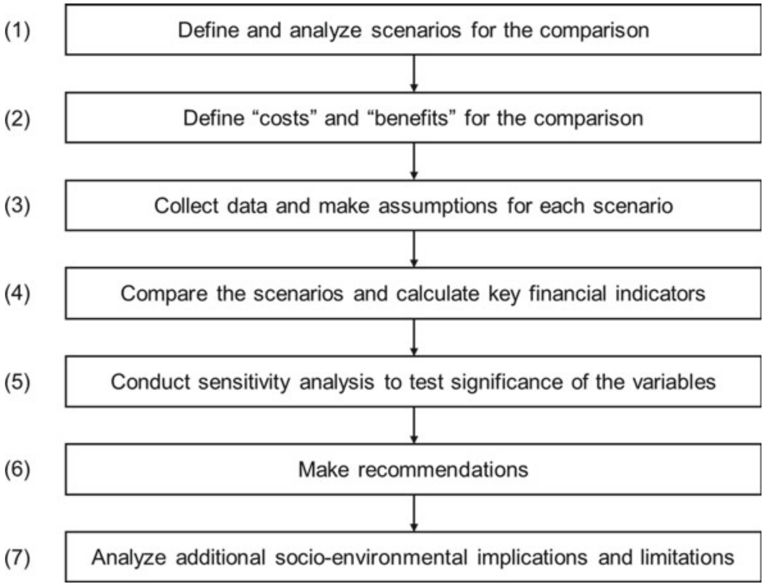


Fig. 14 Common steps in this framework for conducting CBA of construction robots (*source* R. Hu)

system manufacturer or think about acquiring and incorporating a small robot manufacturer into their business. Various stakeholders such as contractors, robot system manufacturers, and developers qualify as investors. Once CIC saw the emergence of a team of stakeholders to jointly invest in a second procedure model cycle, CIC in their role as a construction industry association pursued the filing of a patent to be able to license it in a facilitating manner to the co-investors for cycle 2 and or other players in the future.

7 Conclusion and Outlook

Nowadays, there are still some barriers to overcome when introducing construction robots to the construction industry. Firstly, the construction industry is still a quite rigid ecosystem with various fragmented stakeholders, which have different interests and sub-ecosystems. That is why there are often incompatibilities with existing practices and current construction operations occurring when it comes to integrating construction robots to the industry. To integrate a construction robot, it is necessary to address various interests with an overall systematic approach and to structure the development of such systems in a targeted manner. It is crucial to address the various needs already in the development phase. Moreover, other barriers which could be addressed already in the development phase are, for instance, the high cost and financial commitment or the difficulty of use (not easily understood) or the low technology literacy of project participants (need for retraining of workers), and more (Mahbub, 2008). The procedure model represents a proper guidance for developing construction robots and eventually get them on site with the acceptance of all involved stakeholders in the construction industry to overcome some of the aforementioned barriers.

The procedure model for the development of construction robots was proposed as an integrative and comprehensive guidance or handbook on how to systematically develop construction robots step by step, eventually pushing them to the market. Five recent projects were used to examine and verify different parts of the proposed cyclic procedure model. The procedure model consists of an adapted set of proven principles and methodologies from the systems engineering and management field, associated with a variety of activities employing specific concepts for the development of construction robots, which had been tested by the authors in the recent projects. The application of the procedure model demonstrated the ability to guide the development of the method. A unique characteristic of the proposed procedure model is that it has the capability to evolve with each cycle of use because of its module principles. With the increased application and iterative verification and validation over time, the proposed procedure model for the development of construction robots will mature and contribute benefits to the ever-improving construction industry.

Among these analysed projects, HEPHAESTUS can be considered as an exemplary case study of employing the procedure model for the development of construction robots. Specifically, in the "Act" stage, the status quo of the façade installation business and the potential large demand of automation in the construction sector were analysed. In the "Plan" stage, five different conceptual scenarios for the complex automatic installation process of façade panels by a cable-driven robot were introduced and assessed in terms of accuracy, safety, and installation time. In the "Do" stage, a hybrid "macro/micro" handling approach was selected. A simple, cost-effective cable robot system serves as the macro-kinematic structure, while a modular end-effector system with a small industrial robotic arm handles tasks such as drilling and fine positioning. Thereafter, a prototype of the robot system was built for testing in the next stage. In the "Check" stage, the prototype was transported and assembled on a three-storey construction site in Madrid, Spain, and was tested for real-world performance. Simultaneously, a simple framework for conducting the CBA of construction robots was designed, and the robot system developed that the HAEPHAESTUS project was analysed and compared to the conventional façade installation method. Additionally, the results showed that the HEPHAESTUS robot system is, in general, more competitive than the conventional method in the UK, as well as in most developed countries.

In the follow-up project of HEPHAESTUS, more activities of the procedure model cycle can be further explored, such as exploring other possibilities of task execution based on the modular robot system (Act), incorporating ROD philosophy in the building supply chain (Plan), integrating advanced construction technologies including BIM and digital twins (Do), evaluating the practicability and usability with key stakeholders (Check), exploiting business models and IPR management towards marketisation (Check), and creating technical standards for certain types of robots (Check). With further research and development, the HEPHAESTUS robot system and the procedure model for the development of construction robots can enhance and grow over time.

Acknowledgements This research was supported and partly financed by the following entities and projects:

1	Development of a façade processing robot for CIC. This project was commissioned by the Construction Industry Council, Hong Kong	CONSTRUCTION INDUSTRY COUNCIL 建造業議會
2	Development of a cable-driven panel installation robot in the project HEPHAESTUS: this project has received funding from the European Union's H2020 Programme (H2020/2014–2020) under Grant Agreement Number 732513	
3	Development of innovative façade renovation solutions in the project BERTIM: this project has received funding from the European Union's H2020 Programme under Grant Agreement Number 636984	
4	Development of a scenario development technique for on-site construction robot technology: this project has received funding from the German Academic Exchange Service (DAAD Grant No. 57217359) and the Research Grants Council of Hong Kong (Reference No. G-HKU704/15)	DAAD
5	Development of robotic solutions for elevator system installation by LEVARU: the authors thank the LEVARU team for their kind cooperation	LEVARU

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Part III
Practical Strategies for Innovation in Practice

Chapter 15
Some Changes Are Invisible to the Eyes: Transformation of Business Models, Organizations, and Cultures

Olivier Lepinoy, Giso van der Heide, and Carolyn Moore

Abstract This chapter explores the underlying and invisible mechanisms of digital transformation in the architecture, engineering, and construction (AEC) industry. Technological advancements in the sector have broader impacts than simply productivity improvements, and businesses need to consider other key aspects: business model transformation, sustainability, as well as organizational and cultural reinventions. While most AEC firms look at platform business models with envy, building a portfolio of diverse business models is a long journey that requires new capabilities, and large long-term investments. Not all AEC businesses are approaching digital transformation in the same way, and the range of different approaches taken across the sector is examined. The AEC business model playbook, a tool to explore new business models in relation to the United Nations Sustainability Development Goals, is presented in detail. It is an answer to the need to embed sustainability into corporate strategic initiatives, in order to drive measurable sustainable outcomes. The chapter also analyzes the sector-wide cultural shift crucial to overcome the significant challenges that all AEC businesses face: digitalization, sustainability, innovation, and market differentiation. How organizations need to address both their strategic and cultural transformations in tandem to truly transform their businesses is explicated. Finally, a horizon scan of some of the likely outcomes that these shifts will have is conducted: the impact on traditional value chains, the organizational relationships, and the emergence of new and non-traditional disruptive sector players, and what this means for the future of the AEC sector.

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© The Author(s), under exclusive license to Springer Nature Switzerland AG 2022
S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_15

Keywords Transformation of business models · Technological advancements · Digital revolution · Transformation of organizations · Organizational culture

1 Introduction

As Internet pioneer Douglas Engelbart explains, “The digital revolution is far more significant than the invention of writing or even painting.” A lot of changes are happening around us: Technology is now available at low cost; disruption is everywhere, and digital transformation is more important than ever. In all private industries, and in the public sphere as well, traditional delivery models are challenged by digital. Countless examples show that the risk of commoditization and productization is greater than ever, even for the incumbent players, including the largest ones. To minimize this risk, some companies and organizations decide to progressively let go of the way things are done, to change their mindsets and ordinary perceptions. They start a journey toward total transformation and self-disruption. For them, the adoption of new technologies is not an end, and it is a necessary catalyst for change and survival. The destination is the reinvention of their business.

In the real estate, architecture, engineering, construction, and operations sector, the situation is even more extreme. The value chain, project delivery networks, and ecosystems are still very sequential, fragmented, and transactional. Companies seem to be paralyzed by the same status quo: low productivity, low predictability, low margins, adversarial pricing models, financial fragility, lack of collaboration, lack of investment in R&D and innovation, poor image, and attractiveness. Meanwhile, clients are increasingly concerned that the sector is not keeping pace with the rates of improvement seen in other sectors of the economy. Society at large is increasingly concerned that the sector is not able to meet the imminent challenges posed by climate change, rapid urbanization, changing social expectations, and digitization.

Innovation through technology (the typical way to foster innovation) is not enough anymore. It has become obvious that technology alone will not provide the needed solutions and that new mindsets are imperative. History shows us that true and sustainable innovation does not solely come from technology anymore, it comes from new business models, new cultures, new organizations, and new behaviors. With growing damage to the environment, the construction industry needs to reset its fundamentals. Beliefs and orthodoxies must be challenged to leave room for more radical transformations. This is a necessary step for a long-lasting change to happen.

This chapter discusses future directions that no one can assuredly predict and describes innovations of a new kind. The authors present fundamental mechanisms that are usually invisible to the eyes. With digital technologies, on the surface, things look unchanged. The most essential changes occur in the way the industry is structured and how companies behave, not in the way buildings are constructed. Across the globe, design offices and construction sites look similar compared to ten years ago. But the technology used, the types of companies involved, the types of contacts and transactions between parties, the underlying business models are radically different. This chapter will explore the interplay of three important invisible factors that impact change: business models, organizational design, and organizational culture. The reason the authors have focused on these areas is that they each impact the others, and together they drive transformation across the industry.

What is this invisible revolution made of?

A Firstly, the nature of innovation has changed. The architecture, engineering, construction (AEC) industry is being transformed in the very way it is structured and its services rendered. New ecosystems of companies emerge, and it seems the way the industry is currently organized is outdated.

B Second, the nature of disruption is changing. The pace of transformation is greater than ever, and the speed of transformation has become a key aspect of success. Change is now an organizational and market constant, requiring businesses to keep pace with new developments just to remain competitive. Current corporate cultures, managerial behaviors, and individual beliefs are currently slowing down this process.

C Third, the AEC sector is entering the platform economy. More than software, platforms are eating the world. Companies deliver value, capture value, conquer new markets, or disrupt their competitors by creating their own digital platforms, by orchestrating networks, and by running their new ventures with new business models. This phenomenon has already changed how the telecom, media, retail, transportation, music, and hospitality industries are structured. AEC is no exception. All pioneer AEC firms collect data, build their own digital platforms, and try to offer new services to their ecosystem. This industry is a platform industry already.

D Finally, culture is at the center of this transformation. Construction tends to be a late adopter of change. For the AEC industry, this new wave of transformation is also a cultural one. For existing firms, "the way things are done," traditional behaviors, customs, prevailing orthodoxies, are being disrupted. In this context, an agile culture is a competitive advantage, and it is vital for organizational growth.

First, let us take a quick look at what the future could look like. Manual workers, robots, equipment and machines, raw material, building products will still be necessary to construct, but they will become commodities. Data will be a new raw material. Firms and organizations will buy, sell, and trade data. There will be data miners, data controllers, data brokers, data wholesalers, etc. Later, as shown in Fig. 1, there will be the emergence of new types of players and ecosystems: the originators, the aggregators, the providers, the controllers, and the consumers.

- The originators will be firms gathering land and financial resources. They will create data by defining the built assets.
- The providers will supply the design, the raw material, the building products, the workforce (whether it is humans and robots), the equipment, and, most of all, the data.
- The aggregators will be like the general contractors of today. They will orchestrate the projects and manage the flow of data: They will run, supervise, and monitor.

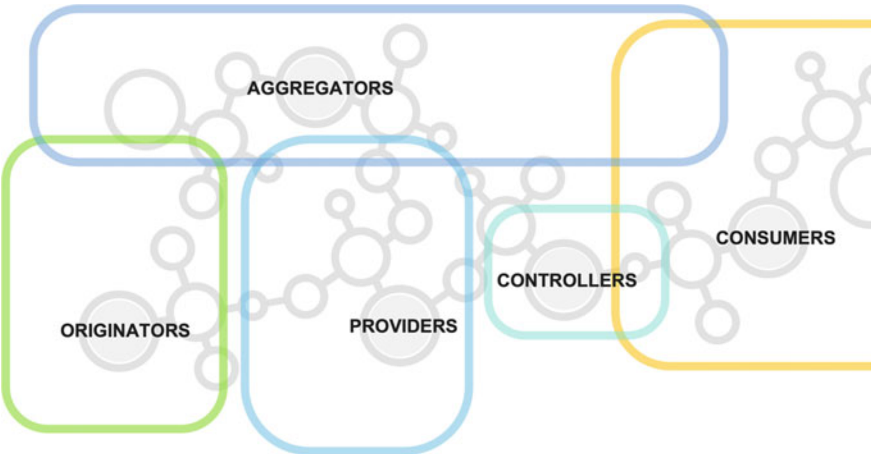


Fig. 1 Hyper-construction: the shape of things to come—originators, aggregators, providers, controllers, consumers (*Source* New Business Models and Digital Platforms in Construction 4.0, Olivier Lepinoy, Autodesk University, November 2020)

- The consumers will be like the facility managers of today, in charge of the maintenance and the operations. They will use the data created by the other players to run the built assets.
- Finally, the controllers will control the finished work (the "as-built"). They will make sure the quality of the data and the processes are enforced.

The most innovative companies have launched their own strategic initiative around platforms and are trying to create new ecosystems around them. They have understood that they are orchestrators of large networks of resources already, but they want more. They want to be the next originators, providers, aggregators, consumers, and controllers. They see the potential benefits across the lifecycle of projects: fewer resources, less waste, greater predictability, better quality, greater traceability, great productivity, better collaboration, better management of the built assets, etc. At a higher level, it implies new contracting mechanisms, a change in skill sets, new processes and standards, and new types of partnerships and alliances.

The ambition of these companies is to make a step change. To do so, they partner with technology companies, build tailor-made solutions, develop new service offerings, and conceive new business models to deliver and capture value. They try to move up the ladder, from asset designers and builders, to service providers, to technology creators and ultimately to network orchestrators. Companies like ACS, Bechtel, Bouygues, Daiwa House, Ferrovial, Kajima, Larsen and Toubro, Lendlease, Royal BAM, Takenaka, and VINCI have all launched strategic initiatives in this direction. Some of these large players already manage several business models. In their case, the challenge is to diversify even more and to build synergies between the old and the new. For other large companies, adjacent to the AEC industry, the pivot of their business and their transformation is already underway. Caterpillar, Hilti, Holcim, ISS, Jones Lang LaSalle, Kone, Saint-Gobain, Schneider Electric, Wienerberger are examples here. Across the globe, mid-size and large engineering and consulting firms (AECOM, Arcadis, Fluor, Jacobs, WSP, etc.) are also attempting to pivot and grow differently. The largest and most innovative design and architectural firms also try to reinvent themselves: offer new services and build new business models to support them.

The platform business model attracts companies because it is considered by all technology and business experts as the most profitable type of business model. But it is still difficult to predict what is going to happen. Business models scale differently, and network orchestrators grow revenues faster, generate higher profit margins, and use assets more efficiently than companies using the other three business models. For incumbent firms, it is a journey. During this long transition, roles and boundaries are changing and becoming blurred. What is certain is that data will fuel a dramatic ecosystem shift. Originators, providers, aggregators, consumers, and controllers: all dominant firms in AEC will create and consume data. Data will really be at the center of everything,

In this unclear future where traditional boundaries have become more ambiguous, a key question will be: Who will become the main information contractor? In an environment dominated by platforms, the players will ask themselves: Who will be the providers of the platforms, who will the producers of the offerings, of the data, of the services, who will the consumers of the services, who will be the owners of these platforms, who will control the intellectual property (IP)?

All companies in the AEC industry need to decide. Do they want to develop technology tools to support productivity and to deliver value to their direct clients? Do they want to become a technology integrator and develop platforms for others to develop their own solutions? Do they want to become a hub to connect, aggregate, and deliver value to the whole ecosystem along the whole lifecycle of built assets?

The AEC industry is going through a revolution. All companies are asking themselves:

- Who are we?
- What is our mission?
- What are we doing now?
- What do we need to do to prepare for the future?
- How do we deliver the projects, products, and the services that we are supposed to deliver?
- How do we increase our margins and capture more value from the market?
- How do we transform?

To address the three integral factors of transformation in the AEC sector (business models, organizational design, and organizational culture), the authors have divided this chapter into two main parts:

1. Transformation of business models
2. Transformation of organizations and cultures.

Before diving into the transformation of the industry, it is worthwhile briefly outlining what the expression “Construction Industry” covers. There is no single universal definition of the construction industry. Most initial perceptions focus on the building of large-scale assets and infrastructure. It is therefore worth noting that when the authors of this chapter refer to the "Construction Industry" or the AEC industry, they are talking about an industry sector that is considerably more complex and involved in the entire lifecycle of a built asset. This includes project planning, approval, design, build, operation and maintenance, and decommissioning of built assets.

The construction industry is comprised of a variety of businesses, manufacturers, consultants, clients, and contractors whose primary concern is the design, building, maintenance, and decommissioning of built assets across all major asset classes ranging from private housing through to airports and large-scale infrastructure. From this definition, several conclusions can also be drawn about the nature of the construction industry and the players within the industry:

- Construction projects are very long term, and they extend from before building has commenced through to the decommissioning of the asset.
- No industry players can provide full-scale end-to-end service provision across all asset classes in the sector.
- The sector is therefore characterized by specialist players that focus on service delivery in a defined phase of the asset lifecycle either in a single asset class, or across asset classes, and multidisciplinary players that provide cross-functional service provision.
- All construction projects include key dependencies where various industry players need to work together collaboratively, even if those collaborations are highly transactional.
- Given the duration and complexity of construction projects, there is a strong need for specialist coordination and project management across all elements of each phase of the asset lifecycle. Many multidisciplinary industry players provide this specialist program and project management in order to connect elements of service provision they also provide, and
- Clients are varied and include both private and public sector clients. In addition, clients will typically focus on a single asset class, or a small group of closely related asset classes.

These complexities make the industry sector unique in respect to the impact, and response to, digital transformation. They will be explored throughout this chapter.

2 Transformation of Business Models

Digital transformation requires data being placed "at the center" of the business and developing a data-centric approach to design, plan, build and deliver projects, products and services. To be truly successful, this approach needs to focus on the bottom line (modernization of operations, cost savings, higher productivity, etc.) as well as the top line: transformation of the business portfolio, intense innovation, and consistent growth. This dual effort cannot be successful if the way firms operate their business is still the same. Inventing alternative business models is not a luxury, it is a condition for success. Currently, as a survival mechanism, most companies launch a strategic initiative by adding services or digital products to their existing "time-and-materials"-driven business model until the initiative becomes financially sustainable. This tweaking is no longer enough, and companies must now look at a widespread overhaul of their business model if they want to create the necessary conditions for change. As Clayton M. Christensen explains in his book The Innovator's Dilemma (1997),"Why is it so difficult for established companies to pull off the new growth that business model innovation can bring? Here is why: they don't understand their current business model well enough to know if it would suit a new opportunity or hinder it, and they don't know how to build a new model when they need it."

Intentional design of new (data-centric) business models is emerging. Soon, the whole real estate, architecture, engineering, construction, and operations industry will turn toward platform business models. Consequently, just like other industries, construction will change dramatically and experience a shift in paradigm: from a sequential/pipeline business model (focused on controlling the clients and the suppliers) to a full platform business model (selling services to the whole ecosystem and with a greater end-user focus) (Harvard Business Review, Van Alstyne et al., 2016).

Purposeful business model transformation is essential for the future of this industry and with so many uncertainties it can be challenging. This section provides observations on business model transformation for firms in the AEC industry. The authors will introduce the *AEC business model playbook* that can assist with business transformation. It connects the invisible world of business models with the *United Nations Sustainability Development Goals* (SDGs), business strategic initiatives, and business capabilities. Furthermore, this playbook supplies insights into business model health, strategic profile, and "best practice" guidance to go from strategic choices in the business model to a first-degree capability roadmap.

The transformation of business models section is divided into the following eight sub-topics:

1. Navigating a vulnerable world while delivering meaningful outcomes.
2. Scanning the future: plan for the unknown, not what you know.
3. Business model diversification and digital transformation.
4. AEC business model cornerstones and health.
5. Strategic profiling: follow a red ocean or blue ocean strategy?
6. Eco-system business models.
7. AEC business model and Industrialized Construction.
8. Support digital transformation with the AEC business model playbook.

2.1 Navigating a Vulnerable World While Delivering Meaningful Outcomes

Nowadays our society is facing enormous social and environmental challenges; climate change, population displacement, wealth inequality, and the demanding need for resources such as food, energy, and water to keep up with the rapidly growing population. The pressure of government regulations, sustainability targets, the speed of the fourth industrial revolution, and the emergence of artificial intelligence will force the AEC industry to rethink and restructure their business. Unlike earlier industrial revolutions which were focused on enhancing our physical capabilities, this one augments our mental ability through connecting and processing mass data while navigating a *volatile, uncertain, complex, and ambiguous* world (VUCA). This abbreviation originated in the military to describe the general threats that are continuously around us. The COVID19 pandemic showed exactly the VUCA we are living in and how it can derail a company strategy. According to McKinsey (The Next Normal Digitizing at speed and scale, August 2020), businesses that once mapped digital strategy in one- to three-year phases must now scale their initiatives in a matter of days or weeks. The waves of the "unpredicted" seem intensive, never-ending, and constantly "scanning for VUCA" is inevitable.

Businesses that have strong leadership and strategies throughout a crisis are best positioned to survive and even grow their business. They were able to quickly adapt their business model(s) to the "VUCA circumstances." The sudden appearance of the COVID-19 pandemic has shown that pure digital network orchestrators, brokers like Uber, Airbnb, and Booking.com were losing tremendous revenue by this unpredicted event. So, would you bet your existence on a "one-muscle" business model? For AEC firms, diversification of business models is an undisputable necessity. In the AEC industry, there have been progressive moves toward commoditization of activities for over a decade: firms with serious plans for their future need to develop new businesses that are more profitable and if these firms want to succeed with new business models, then culture and organizational change are critical. According to business model expert, Strategyzer; to quickly respond and pivot the business you must develop and manage a portfolio with a variety of business models. But what choices and decisions do you need to make? What do you consider as important on the corporate strategic agenda?

A Harvard Business Review study (Roaring Out of Recession, March 2010) revealed that a strictly defensive business model strategy; *cutting costs to survive*, did not do well after a recession. Others chose a strongly aggressive and offensive strategy, *buying companies or building new businesses*, again with poor results. But the firms that selected the right balance between defensive and offensive business models fared the best. Such firms cut costs and improved operational efficiency, but they also developed new markets and invested to enlarge their assets bases. In terms of strategy, AEC businesses need to consider the following.

1. Leadership must articulate the short-, mid-, and long-term goals for the company.
2. Leadership needs to think beyond "just being reactive" and adopt a proactive approach.
3. Leadership must embed future planning and be able to define future VUCA scenarios' and look beyond actual markets, technologies, and macro-trends.
4. Leadership must transcend today's complexity to derive the right priorities.

5. Our society demands that companies not solely focus on financial performance but also on addressing environmental issues, drive social benefits and lead with purpose.
6. Diversification of the business model is the best way to create a successful business and at the same time be resilient.
7. Build and manage a resilience portfolio of "defensive and offensive" business capabilities to be able to quickly respond and pivot the business when necessary.

Leaders must not solely respond to the shifting landscapes, but they must also take their destiny into their own hands: build a portfolio of business models, experiment with new ways of working, develop awareness, and ultimately shape their future landscape. This is the only way they can anticipate the unknown and future proof of their businesses:

1. First, document "VUCA" future scenarios that are driven by uncertainty and impact onto the organization using the PESTLE macro-environmental framework (political, economic, social, technology, legal, and environment).
2. Second, sustainability considerations are becoming increasingly important to business, government, and general society. Businesses therefore need to make direct connections with the United Nations Sustainability Development Goals (SDGs) and test which scenarios are influencing one or more of the SDGs, or vice versa.
3. Third, businesses need to understand their actual strategic profile and the health of their current business model(s). Key considerations are whether the business is operating in an overdeveloped saturated market "red ocean" where there is significant established competition; or whether they develop a "blue ocean strategy" by identifying a new business model and targeting untapped markets with a new value proposition.
4. Once proper business models have been described, business use cases need to be developed as clear demonstrators of business model viability, feasibility, and desirability.
5. Furthermore, this will inform an understanding of the needed business- initiatives and capabilities to layout out a three-horizon implementation roadmap (McKinsey, Enduring Ideas: The three horizons of growth, 2009) **Horizon 1**: What we can evolve today?; **Horizon 2**: What we can produce that will push forward into tomorrow?; **Horizon 3**: How can we disrupt beyond tomorrow?
6. Finally, research the culture ad organization readiness to land new business model transformations.

Figure 2 shows a systematic approach toward documenting our complex world, and how this requires the organization to be responsive taking an outside-in approach. Consider VUCA and the SDGs as the major drivers. Often seen differently one can have an inside-out approach, beginning with exploring a jungle of technologies and mind-blowing gadgets. However, research has proven that often a technology push will become a disappointment because of not correctly addressing its opportunities and business potential. The risk is to pass-by a suitable value proposition, miss-out your clients required outcomes and underlying market potential.

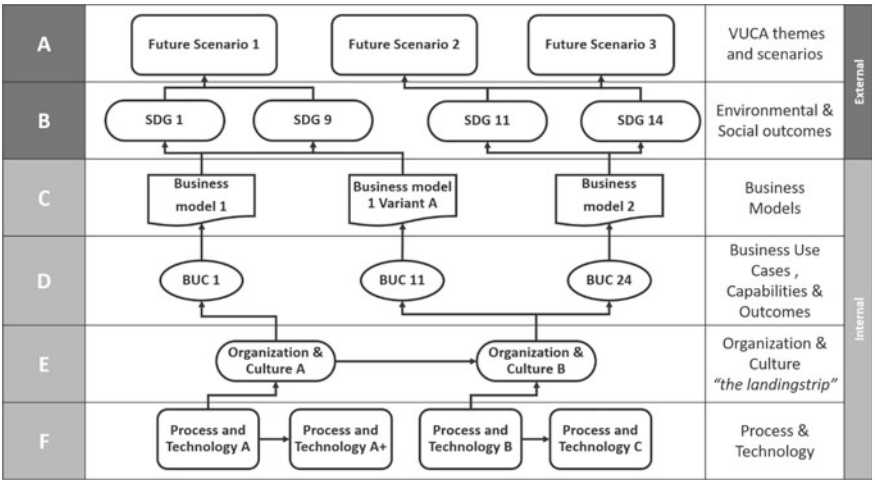


Fig. 2 Business portfolio with diverse business elements across the system levels. Highlighting that technology by itself has no single objective value, the economic value of technology stays latent until it is commercialized in some way via a customer need, market, and business model (*Source* Giso van der Heide)

2.2 Scanning the Future: Plan for the Unknown, not What You Know

Scanning the future is linked to scenario planning and is a technique to "scan the horizon" on environmental and social concerns. The aim is to understand the most uncertain and impactful factors for an organization, called "*driving forces*." These driving forces are categorized using the PESTLE framework that is often used in strategic management. Future scenario planning enables businesses to:

- Explore and design new business models.
- Explore new paradigms or assumptions to design a new vision.
- Validate the existing business models.
- Validation of strategic choices and policies.

As explained by The World Economic Forum (WEF), in "Shaping the Future of Construction Future Scenarios and Implications for the Industry" (March 2018b), "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." For future scenario analysis, businesses need to select a specific set of driving forces, related to their business dynamics (see Fig. 3). A prioritization technique will ultimately result in the two most extraordinary driving forces that will be used to define scenarios and narratives. While scenario planning is important, businesses also need to prepare

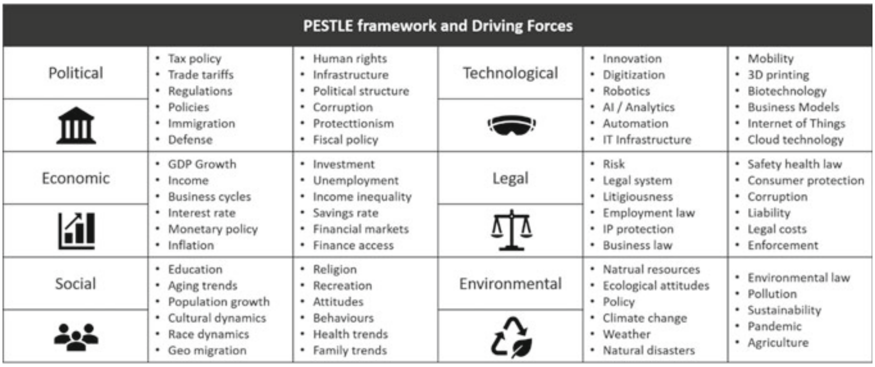


Fig. 3 Detailed overview of the PESTLE framework with the categories and driving forces that can be used for writing future scenarios (*Source* Stratechi.com)

mitigation plans as an integral part of their strategic planning process; moreover, they tend to focus on achieving the ideal future and listing the actions that should be taken to reach that goal. But when the unexpected happens and that planned future suddenly disappears, using the traditional planning process is no longer sufficient and can leave businesses stuck or over-invested in a business model that is no longer valid.

The World Economic Forum published a report in June 2018a entitled "Future Scenarios and Implications for the Industry" describing three major future themes for infrastructure and urban industry. It underpins the following themes and implications for the future of AEC:

- **Building in the virtual world in** an era where people are immersed in virtual reality in all aspects of life, intelligent systems and robots run the construction industry.
- **Factories run the world** with a corporate-dominated society that uses prefabrication and modularization to create cost-efficient structures.
- **A Green reboot** for a world with increasing conflicts over scarce resources and climate change rebuilds using environmentally friendly construction methods and sustainable materials.

In today's scenarios, social and environmental topics cannot be ignored anymore. Therefore, one should deepen further on the global sustainability initiative. On September 25, 2015, all United Nations members signed up for seventeen (17) *Sustainable Development Goals* (SDGs): a set of solutions for the biggest problems the world is facing. Targets are being set for 2030, under a decade from today, one of them is the reduction of global emissions by 50%. Table 1 gives an example of Sustainable Development Goals for AEC.

"Only 40% of companies are reporting on SDGs. In terms of understanding the SDGs, companies tend to underperform with a D ranking, in making a business case (where there is one) for SDG actions. Discussing the SDGs in leadership was ranked

Table 1 Example of meaningful SDG outcomes for AEC, 12 out 17 being presented, SDG goals, outcomes and metrics contributing to sustainability performance and indexes

SDG nr	AEC SDG goal	AEC SDG outcome	Metrics
3	A safe, healthy, and transparent work environment	Minimize the Likelihood of Incidents at jobsites	[nr injuries/year]
4	Attract creative talent	Maximize The Nr of new ideas in the pipeline	[nr ideas/breath of ideas]
5	Greater social inclusion	Maximize Diversity of Hires	[% male–female-race-age]
6	Climate-resilient water supply and sanitation services	Maximize the Nr of People that have Access to water and sanitation	[%/region]
7	Affordable urban services	Minimize the Cost of Service (Electricity, Water, Internet, etc.)	[$/unit]
8	Higher productivity	Maximize Productivity output per employee	[units/employee]
9	Accelerate R&D spending	Maximize Corporate Spend on Sustainable Innovation	[$/year]
10	Boost prosperity of local contractors and communities	Maximize the Likelihood for increase of Local incomes	[$/month]
11	Affordable living and commuting	Minimize the Cost for housing and commuting	[$/m2] [$/km]
12	Cutting waste	Minimize amount of Waste for Production + Transportation + Rework	[m3] [Time]
13	Sizing energy and resource efficiency gains	Minimize Construction Energy consumption	[kW/year]
17	Co-Innovation and Co-development for collective IP	Maximize the Likelihood of local Access to IP	[% open IP]

Source Giso van der Heide

as C and is considered relatively low-hanging fruit in terms of improvement effort needed. Companies collectively were ranked A-; in terms of assessing the business's impacts on the SDGs, largely because only positive outcomes are reported, while areas of negative impact garner less (or even no) mention in the report." This is an extract from the KMPG report entitled "How to report on SDGs, what good looks like and why it matters" (February 2018).

This KPMG research reveals that it is strongly recommended that companies seriously start embedding the SDGs within their core strategic business initiatives. This implies that business models, corporate governance, and social responsibility play a significant role in this SDG movement. To make the SDGs more tangible for AEC firms, it is worthwhile translating them into meaningful outcomes and, if possible, have metrics that can be baselined and monitored using specific, measurable, achievable, relevant, and time bound (SMART). Table 1 is an example that lists the twelve (12) most applicable for AEC out of the total seventeen (17) SDGs. The SDGs that are scoped out and least commonly prioritized are: *No poverty (SDG1), Zero Hunger (SDG2), Life Below Water (SDG14), Life on Land (SDG15), and Peace and Justice (SDG16).* Also, notable is that only 10% of companies have set specific and measurable SMART business performance targets related to global sustainability goals.

Measuring sustainability performance is complex. It leads to a lot of confusion among producers and users of sustainability information and makes it difficult to report non-financial information. To resolve this confusion and simplify corporate reporting, several frameworks and standards for sustainability reporting have been developed. The International Integrated Reporting Council (IIRC) and the Sustainability Accounting Standards Board (SASB) announced in 2020 their agreement to merge into a unified organization, the Value Reporting Foundation. This is another step toward a more simplified corporate reporting landscape.

Private and institutional investors are starting to demand for global sustainable investment indexes that are rational, solid, and reliable to allow them to monitor the evolving profitability of their sustainable investments. Therefore, the investment markets launched three major important international sustainability indexes, for the USA, it is Domini 400 social index; in Europe, the two most popular are the Dow Jones Sustainability Indexes and FTSE4Good. These indexes are being evaluated by a group of parameters and their individual scores concerning environmental management, climate change, human rights, labor rights, labor standards in the supply chain, corporate governance, and the fight against corruption.

2.3 Business Model Diversification and Digital Transformation

Whatever value you deliver, a business model sits behind it. As Silicon Valley entrepreneur Steve Blank (the Lean Start-up movement) explains, "A business model describes the rationale of how an organization creates, delivers, and captures value, in economic, social, cultural or other contexts." A business model is invisible, but it is the mechanism that enables an organization to create and capture value, generate profit and to stay relevant. The grocery store, the pizza delivery, all have a business model and are usually part of a bigger network, the value chain. AEC firms are no exception. Their business models are rather conventional, they obey some well-known orthodoxies. Business models act as blueprints for organizations, they guide success or failure, and if you analyze the business model, it will make clear:

- The target market and the opportunity the business capitalizes on.
- The solution the business offers and how it delivers customer value.

- How the business access its customers.
- The operating model that the business follows.
- How the business makes money and what are the costs incurred.

According to BearingPoint and Open Matters research (see Fig. 4), you can classify the business model by the four following types:

Asset Builders make, market, distribute, sell, and lease physical things. In the AEC industry, asset builders design and build physical assets, like buildings, roads, and bridges. Contractors, subcontractors, and product manufacturers belong to this group. Asset builders cover about **64%** of the cross-industry companies today.
Service Providers hire and train skilled employees and sell their services. Architects, real estate agencies, consulting, and engineering companies are typical service providers. About **24%** of cross-industry companies fit in this service providers category.
Technology Creators develop and protect intellectual capital, often intangible products with incredibly low-marginal costs of growth, such as software for example. In this group, there are software vendors, data and construction technology vendors, often the subcontractors (concrete, steel, glazing, MEP, etc.) **11%** of cross-industry companies run this technology creator model.
Network Orchestrators create platforms that participants use to interact or transact with many other members of the network. They may sell or trade products, build relationships, share advice, give reviews, collaborate, and more. Network orchestrators create and maintain networks of people, products, and information, facilitating interactions and transactions between them. Fewer than **1%** of cross-industry companies incorporate this network orchestration model.

Nearly all architecture, engineering, construction (AEC) organizations can be classified into one of four business models. A balanced mixture of the business model types: Asset Builder, Service Provider, Technology Creator and Network Orchestrator gives an average 5-year Compound Annual Growth Rate (CAGR) of 8%- and 2.5-times market capitalization, compared to a “monotype” business model with 5-year CAGR of 4%- and 1.8-times market capitalization. A pure network orchestrator business model drives volume and massive economies of scale. With

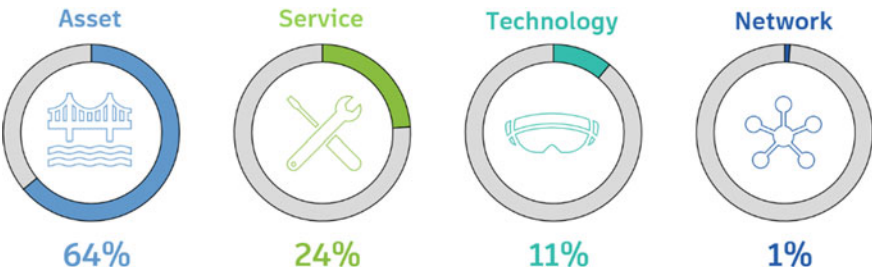


Fig. 4 Percentage spread of business model types across the industry (*Source* BearingPoint)

customer data as a source of insight for innovating new adjacent services but also a source of advertising revenues, within 5 years, CAGR is roughly 20% and average profit margins reach 32%. Network orchestrators are seeing two to four times higher market valuations and market capitalization growth at around 200%.

Pure digital players like Airbnb, Amazon, eBay, Facebook, Google, Netflix, Spotify, Uber, YouTube are already orchestrators of large networks. The growth, the profit, and the scaling advantages of these network orchestrators result in unprecedented market valuations. Their businesses increase not by buying more assets, but by acquiring more users, which is a near-zero cost. Other types of companies, firms like Autodesk, IBM, Microsoft, Oracle, Salesforce, SAP are developing and making available digital technologies. The type of platforms they are offering are IT environments in which software is executed and information is managed. Within these environments, AEC players develop and build their own platforms for Building Information Modeling (BIM), Project Management, Customer Relationship Management (CRM), Human Resource Management, Procurement, etc.

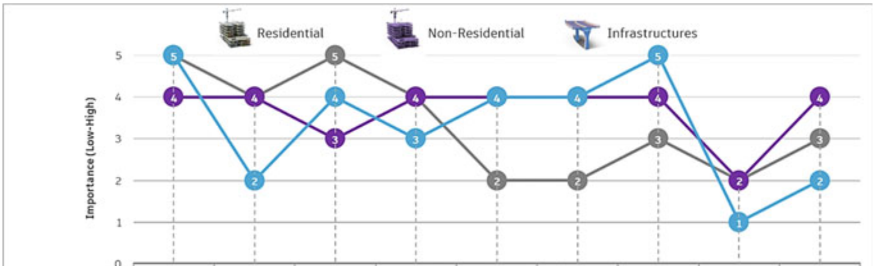
In this context, gradual changes in the mindsets, the behaviors, and the beliefs of the traditional incumbent players can be observed. In yesterday's world, their businesses were run like a pipeline: what mattered was to control resources, to optimize them internally, and the focus was on the value delivered to the client. In tomorrow's world, businesses will be managed like a platform. What will matter will be how you orchestrate resources within a network, what will be important will be external interactions. Architects fear for "democratization" of their business where platform business model is being introduced and intellectual property can become completely passé implicating that everyone can share their designs and creative content. Within these platforms, the technology providers deliver algorithms to generate and automate challenging design problems, faster, better at lower cost. While contractors are adding more digital services to their business portfolio, where historically the major focus was on efficiently running the physical construction site execution by problem-solving and fixing unexpected problems, with of course large implications for the project margins. For contractors, digital services to support risk avoidance are being added to their business operations. Examples of such services are the virtual design and construction services, e.g., *architectural engineering studies* (cannibalization of architects' business), *virtual logistics simulation*, *production model coordination,* and *pre-construction validation* with the goal to significantly eliminate physical site execution problems. Additionally, the contractors are conquering the marketplace for renovation business, knowing that most countries are facing huge asset maintenance backlogs.

In parallel, some manufacturing industries, like automotive, are going through massive changes, and this is the ideal opportunity for contractors to acquire decommissioned production facilities and "plug-in" modular house production concepts. Engineering service providers (ESP) are moving away from drawing delivery, large volume, paid per hour, low-margin business to "upfront" high value engineering services, like *environmental studies* and *virtual twin simulations (serving to owner/operators' space),* supported by increased software technologies and "selling" engineering IP, usually realized through acquisitions. Overall digital transformation is not simply acquiring and injecting technologies into the organization and waiting for magic to happen. Onboarding technology by itself has no single objective value. However, potential new technology may have no obvious business model, and in such cases, one must find a proper business model to be able to capture value from that technology. The following facts then need to be considered (source: Statista, Start-up failure analysis report, February 2018):

- 90% of new start-ups fail (around 20% in their first year and 34% in year two).
- 75% of venture-backed start-ups fail.
- Under 50% of businesses make it to their 5th year.
- 33% of start-ups make it to the 10-year mark.
- Only 40% of start-ups turn a profit.
- 82% of businesses that fail do so because of cashflow problems.
- The highest failure rate is in the information industry (63%), construction (53%), manufacturing (51%), and mining (49%).

BearingPoint research shows that diversifying the business model gives the best results in terms of CAGR, market capitalization, and margins. But what do AEC companies expect from a digital transformation? Figure 5 displays survey results of three major streams in AEC, residential, non-residential, and infrastructure. It plots the scores against nine different business transformation outcomes (horizontal) and low–high importance (vertical). Increased efficiency, cost savings, and competitive positioning (probably in terms of price competition) seem to be the most notable.

Normally, a transformation goes through various stages and maturities. The progress and maturity can be characterized by four "digital maturity plateaus" P1, P2, P3, and P4 (see Fig. 6). Moving up to a higher plateau means more value (CAGR) in return. Oftentimes it begins with the actual business model, focusing on improving



	Increased employee efficiency and productivity	Improved ability to meet customer demands	Cost savings	Improved quality of information available to decision-makers	More effective use of data sharing across functions / geographies	Greater flexibility in technology adoption / transitioning from legacy applications	Heightened competitive positioning	Improvement in research and development (R&D)	Producing greater value for stakeholders / improved return on investment
Residential	5	4	5	4	2	2	3	2	3
Non-Residential	4	4	3	4	4	4	4	2	4
Infra	5	2	4	3	4	4	5	1	2

Fig. 5 Nine business outcomes expected from digital transformation for three major streams in AEC. Notable is that research has low priority, therethrough efficiency, productivity, and cost savings, tight to competitive positing, are key focus areas (*Source* Giso van der Heide)

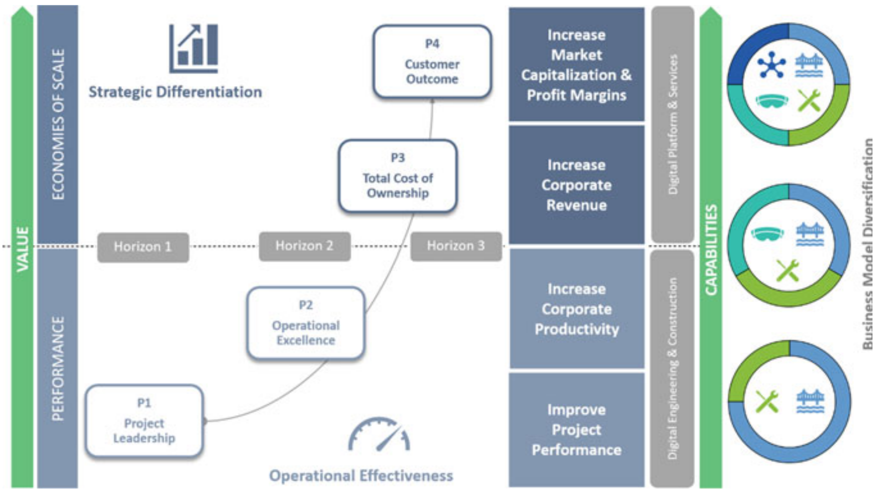


Fig. 6 Business transformation maturity described by four "Digital Maturity Plateaus" (*Source* Giso van der Heide, business model transformation in AEC industry, February 2021)

the project execution and its margins (P1 = project leadership, means standardized, and repetitive). The following step is to achieve better operational results (P2 = operational excellence, means integrated, optimized, and automated processes). Both plateaus are intended to make "financial relevant tweaks" at the existing business model. Thereafter comes an important turning point; plateaus P3 and P4 are intended to drive new and profitable businesses needing a platform approach; outside connected, data-driven, networked, and customer-centric. It will shift the "go-to-market" value proposition, capabilities, cost–revenue model, resources, while at the same time organizational change and culture readiness are crucial to succeed.

2.4 AEC Business Model Cornerstones and Health

According to *Analogy Partners* (Your business model strength comes from 6 cornerstones), the business model can be described by six essential business fundamentals, called **cornerstones** (see Fig. 7). To deliver reliably superior performance than the competition, a company must be better at some or all the all **six cornerstones** of their business model.

1. The **value proposition** is driven by two cornerstones: **Architecture, engineering, and construction services** is to identify which customers you try to serve and holds the collection of products and services (key business activities) the business offers to meet the needs of customers and **revenue–profit** the way you make income from each customer segment (monetization) vs the cost of acquisition (known key resources).

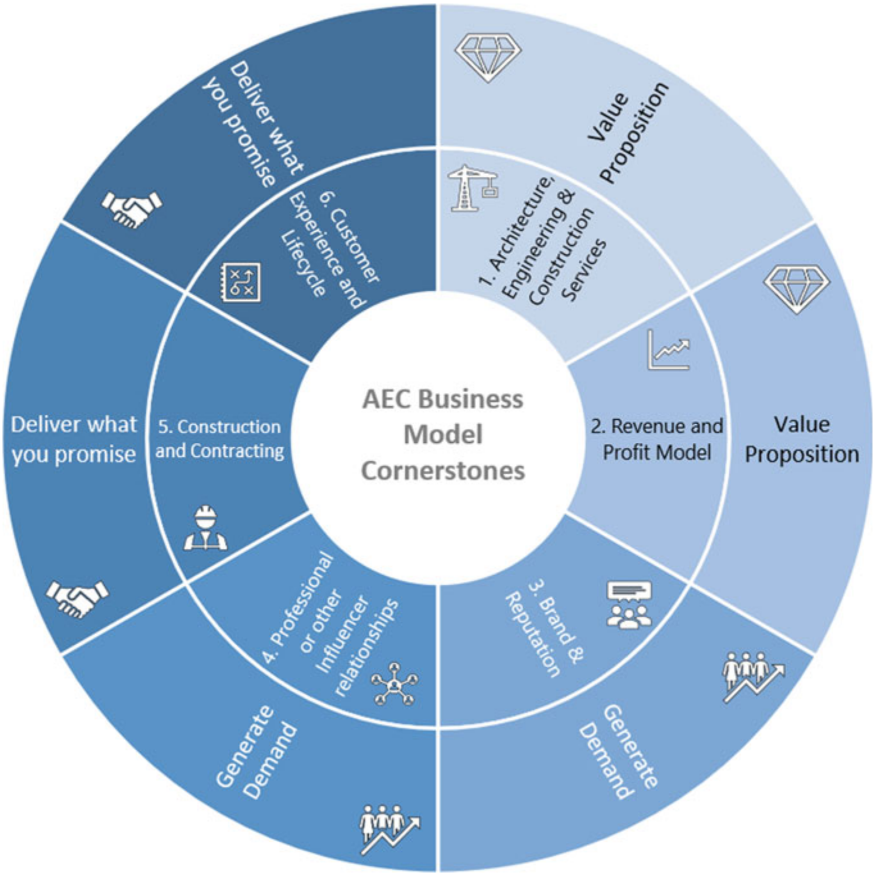


Fig. 7 Six business model cornerstones established for the AEC industry (*Source* Giso van der Heide)

2. The ability to **generate demand** is driven by two cornerstones: **brand-reputation** and **professional–other influencer relationships** to find a scalable way to get new customers. This is how a company keeps its customers using its services and increases its revenue from its existing customers.
3. The ability to make and **deliver what you promise** is driven by two cornerstones: **construction and contracting** cultivate buyer–supplier relationships so businesses can focus on their core activities and deliver through different channels, and the **customer experience and lifecycle** ensures the survival and success of the business. You must identify the type of relationship you want to create with your customer segments.

Businesses must reflect the following six business model cornerstone "viability" questions (one major question for each cornerstone):

1. *Is the business creating significant value for customers by performing and configuring activities in disruptively innovative ways?*
2. *Does the business have a conventional cost structure or disruptive and are margins strong due to low costs and affordable prices?*
3. *Does the business own its key resources that are difficult or impossible to replicate which gives it a significant competitive advantage, and how easy or difficult it is for customers to leave or switch to another provider?*
4. *Is the business large scale and does it have direct access to the end-customer?*
5. *How rapidly and how easily can the business model grow without substantial added resources and activities?*
6. *How large and attractive is the untapped market potential the business is pursuing, and does it require strong revenue streams and pricing mechanisms to monetize the value created for customers?*

The answers to the above questions can be scored using a maturity score on a 1–5 scale, as seen in Table 2, answers range from **1** = *Much worse in all aspects* to **5** = *Much better to an extreme degree.*

Figure 8 shows an example of a business model health score. Attention requires the cornerstones with a level 1 (red) "*much worse at all aspects,*" level 2 (orange); "*much worse at a few aspects than competition,*" or a level 3 (yellow) "*usually match competition.*" Insights into the current health status of the business model can be created by assessing each cornerstone and its performance. These insights can be used to:

- Uncover weak cornerstones in the business model, the root causes and act accordingly with proper initiatives.
- Compare health results of different business models, e.g., diverse business units or compare with "best in class" performer.
- Use it for annual performance reporting, by keeping track of improvement initiatives.

Table 2 Business model health scores

Business Model Corner stones Health scoring	
LEVEL 1	We consistently do **MUCH WORSE** than competition in **ALL ASPECTS**
LEVEL 2	We consistently do **MUCH WORSE** than competition in a **FEW ASPECTS**
LEVEL 3	We usually **MATCH** the competition, there is **NO meaningful DIFFERENCE**
LEVEL 4	We consistently **perform BETTER** than competition
LEVEL 5	We consistently perform **MUCH BETTER** than competition to an **EXTREME DEGREE**

Source Giso van der Heide

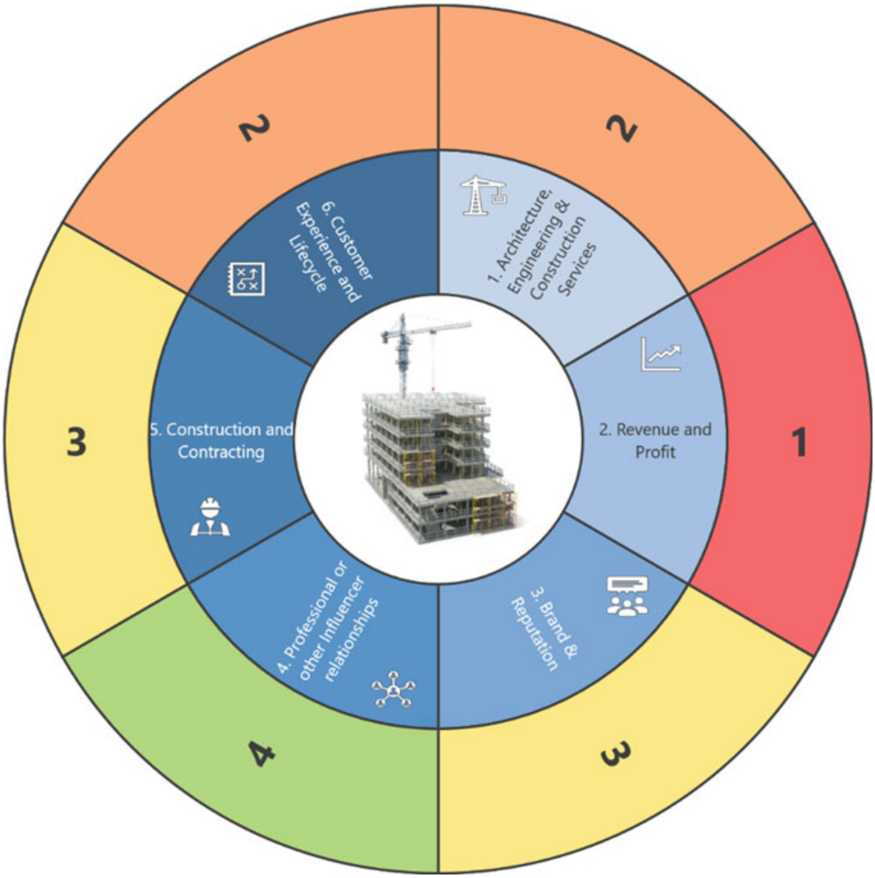


Fig. 8 AEC business model with six cornerstones and individual health scores (*Source* Giso van der Heide)

- Innovate the parts of the business model that are relevant, by using a business model canvas, that gives the right boxes for new and fresh ideas and helps complete the aspects that are still unknown.

AEC business model cornerstones and shift patterns

The firm Strategyzer researched many business models and discovered four major patterns (see Table 3), called business model shifts each owning their unique characterizations. Relevant to mention is the business model competing elements that are related to each business model shift; for example, *Value proposition shifts* has one of the following competing elements, from "**product to service**" which means that you build services that supply predictable and recurring revenues, or you can drive it in another way by adding products to services to increase cross-sell and share of

Table 3 Overview of four business model shifts (patterns) focusing on defensive or offensive strategies helping to support business model innovation

Business model shift types	Value proposition-driven shifts—offensive play	Front stage-driven shifts—offensive play	Profit formula-driven shifts—defensive play	Backstage-driven shifts—defensive play
Business model profiles	Aimed to play offense; typically controlled by **market explorers** and **platformers**	Aimed to play offense; typically controlled by **activity creators** and **gravity creators**	Aimed to play defense; typically controlled by **revenue differentiators** and **margin masters**	Aimed to play defense; typically controlled by **scalers** and **cost differentiators**
Focused business model cornerstones	1. Architecture, engineering, and construction services 2. Revenue–profit 6. Customer experience	2. Revenue–profit 3. Brand and reputation 6. Customer experience	2. Revenue–profit 5.Construction and Contracting 6. Customer experience	2. Revenue–profit 4.Professional–other influencer relationships 5. Construction and Contracting
Business model competing elements	• *Product to service* • *Low Tech to High Tech* • *Sales to platform*	• *Niche market to mass market* • *B2B to B2C* • *High touch to low touch*	• *High cost to low cost* • *Transactional revenue to recurring revenue* • *Conventional to contrarian*	• *Dedicated resources to multi-usage resources* • *Asset heavy to asset light* • *Closed to open IP*

Source Strategyzer

wallet. The twenty-four business model competing elements (twelve and vice versa) will be used to establish a strategic profile.

2.5 *Strategic Profiling: Follow a Red Ocean or Blue Ocean Strategy?*

The goal of blue ocean strategy (How to create uncontested market space and make the competition irrelevant, W. Chan Kim, Renee Mauborgne, Harvard Business Review Press, 2015) for organizations is to find and develop uncontested growing markets "blue oceans" and avoid overdeveloped saturated markets "red oceans." A company will have more success, fewer risks, and increased profits in a blue ocean market.

Figure 9 shows three major streams in the AEC industry: residential, non-residential, and infrastructure. Each is presenting a *strategic profile* along the horizontal axis of the twenty-four different business model competing elements. The vertical axis stands for the importance of that competing element. So, do you want to mimic your peers and be in a red ocean or want to distinguish your business

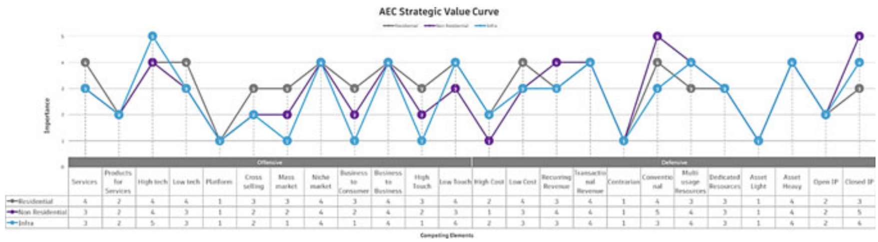


Fig. 9 AEC strategic profile across three major streams, twenty-four (24) business model competing elements have been scored (*Source* Giso van der Heide)

model and move to a blue ocean? Firms that selected the right balance between defensive and offensive moves fared the best. Such firms cut costs and improved operational efficiency, but they also developed new markets and invested to enlarge their asset bases. Most companies in the AEC focus solely on the defensive, red ocean, part and keep trying to battle within "low-margin business," or create new streams out of the existing, turning transactional business into recurring streams. They will never succeed in achieving a flourishing business with high margins and CAGR of 20% or higher. The development of new business models may require coexistence between current and new models. You need to know when shifting resources toward a new model is a delicate balancing act. The organization's culture must find ways to embrace the new business model, while keeping the effectiveness of the current business model until the new one is ready to take over completely.

2.6 Ecosystem Business Models

AEC ecosystems are complex; they have many different stakeholders, interests, value propositions and are mostly broken. How do you want to disrupt a traditional ecosystem? Is it feasible? Or do you only want to improve today's siloed activities? Most AEC companies want to digitize and transform, but with what purpose? Squeezing the average margins with a view percentage will that be beneficial for the company and purposeful for the whole chain? Is that worth the investment in technology and resources? Here are seven ecosystem business model strategies to consider.

- **From profit-focused to purpose-focused**: Citizens have been paying taxes for centuries to governments, and they trust that they will invest in infrastructures and public services for the common good. Crowdfunding is the potential to circumvent the cumbersome decision-making process of how much to tax each person and how to spend it to ensure an even distribution of wealth. The key aspect of it is that it monetizes peoples' beliefs and purposes, which are difficult to ignore if the public are willing to collectively fund a project [1].
- **From risk-averse to risk-embracing**: The use of new business models based on cooperation and the sharing of cost and risk will accelerate (e.g., public–private

partnerships). The ability to think differently and creatively is a critical aspect of business model reinvention.

- **From value chain master to ecosystem orchestrator**: Enabling digital partnering and ecosystem, companies who have a dominant business model, in both B2B and B2C domains experienced revenue growth approx. 27 points higher than their average peers in industry. Complementary offerings make it easier for customers to obtain comprehensive solutions, greater choice, open innovation, etc. Strong partnering capability is key that means exclusive relationships, long-term contracts, and deep integrations [2].
- **From competition to coopetition**: Consortia and joint ventures are usually based upon the design-build-finance-operate (DBFO) model, also called the public–private partnership (PPP) Both are well-established for the construction of economic and social infrastructure and are now used in more than half of the world's countries. It is used for the construction of economic infrastructure such as roads, bridges, and public transport systems but it is also used for social infrastructure such as schools, prisons, and hospitals. A good example is the large overhaul of a Dutch 32 km long sea dike, and it is a joint venture of BAM PPP (46%), Van Oord Aberdeen Infrastructure (46%), Rebel (8%). The duration of the contract is 25 years, and the net present value is 550 million euros.
- **From linear to exponential growth**: Acquisition strategy is aimed to create a merged business, grow revenue, expand market share and reach; e.g., ESPs are acquiring architecture, master planning, facility management, and construction management capabilities (also known as the one-stop shop model). An example is the 16.000 FTE firm, Mott MacDonald.

Sources:

1. Sam Stephens, Crowdfunding—a new model for infrastructure investment? Atkins, October 2015.

2. MIT Sloan, Driving Growth in Digital Ecosystems, Aug 2020.

2.7 AEC Business Model and Industrialized Construction

Modular buildings are attracting attention as an environmentally friendly construction method where environmental regulations are strict from the perspective of short construction periods and reuse of building materials to achieve low carbonization. When thinking about industrialized construction (IC) and running an offsite construction business for modular and panelized production, you need to redesign your business model. You must rethink your value proposition; the way you generate demand and the way you deliver the promise. The "traditional contractor" business model will be disrupted because you must move from B2B to B2C and start serving a mass market against low cost while considering high CAPEX vs OPEX of running a factory. Modern production factories embrace Industry 4.0 that implicates even higher investments due to “configure to order” production flexibility and IT technologies to operate 24/7 around the clock. Moving to IC has a positive impact on multiple SDGs: waste reduction, safety improvement, labor increase, consistent quality, affordable assets, and higher productivity. The diversification of the IC business model is also important. You want to run a “network orchestrator” platform that brings you straight toward the “mass market” and clients? This will require that you add new services and technologies to your existing assets. How will you establish such a platform? Through acquisition, alliances, or new ventures?

The 32-billion-dollar Japanese Daiwa House Company, market leader in modular construction, is entering the European market. The strategy is to extend their business across the globe to address a shortage of housing, lack of craftsmen, and soaring building prices. While the traditional building industry is still an establishment, you might ask yourself if this movement will be disruptive for the coming decade concerning the residential and non-residential markets. Interestingly they acquired a Dutch-based company, Jan Snel, that has 60+ years logistics ability with a network throughout Europe, and it is currently involved in steel frame unit sales and rental business with a focus on products through steel frame modular buildings. Jan Snel is further promoting low carbonization by proactively adopting solar power generation systems in addition to offering short construction periods. At the same time, the company collects the units for which the rental period has expired. It keeps the frames of these in its factory and then refurbishes their interiors to reuse them. This is contributing to the realization of a recycling-oriented economy. Daiwa house is expanding their proven IC business model through:

1. Acquisition of assets; modular units and their capitalization.
2. Acquisition of services by proven rental and lease business.
3. Acquisition of technology by proven, scalable production methods and access to low carbonization execution strategy to serve sustainability goals and legislations.
4. Acquisition of network by proven logistics, distribution centers, and networks.

Many local examples can help understand the rise of these phenomena. In a response to shortage of housing in The Netherlands, and the need for more affordable sustainable apartments, national contractor Dura Vermeer launched a new business called “Block-Up.” With a “Smart Box” at its core, ready-to-use modules can be stacked on the construction site into an apartment complex. This “Smart Box” consists of a structural frame with wooden walls and floors and this smart module holds all the technology needed to provide the apartment with heat, water, and electricity. The apartments can be completely disassembled, so that materials can be reused elsewhere. The smart modules are being prepared in a new assembly facility, which minimizes production costs, reduced material waste, and other construction inconveniences. The apartments can therefore be realized up to 35% faster than with traditional construction. In addition to its durable properties, wood offers a very pleasant indoor climate. The lightweight also limits emissions during transport and the use of large equipment.

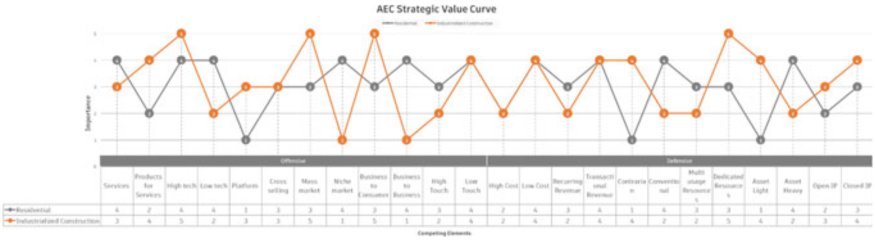


Fig. 10 Strategic profile compares traditional residential construction with industrialized construction (*Source* Giso van der Heide)

Figure 10 shows the different business model choices (competing elements) between traditional residential construction (gray) and industrialized construction (orange). **High tech, low cost**, **B2C**, **mass market,** and **dedicated resources** are the typical strategic differentiators.

2.8 Support Digital Transformation with the AEC Business Model Playbook

What is a playbook? The AEC business model playbook is a "menu card" that has all the "AEC best practice" pieces that make up a how-to navigate and support a digital transformation. Fundamentally it starts with the business model cornerstones, and it adds transformation dimensions (layers) on top of these.

Step 1 Adding the sustainability dimension

How would underperformance of the business model influence the corporate targeted SDGs? Table 4 connects the twelve most relevant SDGs for the AEC industry to the corresponding six business model cornerstones. For AEC firms, connecting business models and sustainability goals is the best way to embed social and environmental performance. It is also a terrific way to build public transparency, legal accountability, and balance investments.

Step 2 Adding the business transformation initiatives dimension

Business transformation initiatives play a strategic role and represent the bridge between the strategic and operational levels. Each business transformation initiative should be a building block for achieving the company goals and should be deconstructed into projects, representing exactly how the goal will be met. Every initiative should be treated just like any other project, with a dedicated project manager in charge of outlining the plan, delegating tasks, and tracking progress. The following thirty AEC business initiatives, in Table 5, are derived from the World Economic Forum report, Shaping the Future of Construction, January 2016.

Table 4 Adding the SDG elements to the business model cornerstones

Business model cornerstones versus sustainability dimension					
1. Architecture, engineering, and construction services	2. Revenue and profit	3. Brand and reputation	4. Professional or other influencer relationships	5. Construction and contracting	6. Customer experience and lifecycle
SDG 9 Accelerate R&D spending	SDG 8 Higher productivity	SDG 5 Greater social inclusion	SDG 4 Attract creative talent	SDG 13 Reduce emissions (incl value chain)	SDG 7 Affordable urban services
Maximize corporate spend on sustainable innovation	Maximize productivity output per employee	Maximize diversity of hires	Maximize the number of new ideas in the pipeline	Minimize CO_2 emissions	Minimize the cost of service (electricity, water, Internet, etc.)
[$/year]	[units/employee]	[% male–female-race-age]	[nr ideas/breath of ideas]	[Tons/year]	[$/unit]
SDG 11 Affordable living and commuting	SDG 12 Cutting diverse waste	SDG 3 A safe, healthy, and transparent work environment	SDG 17 Co-Innovation and Co-development for intellectual capital	SDG 10 Boost prosperity of local contractors and communities	SDG 6 Climate-resilient water supply and sanitation services
Minimize the cost for housing and commuting	Minimize amount of waste for (production + transportation + Rework)	Minimize the likelihood of incidents at jobsites	Maximize the likelihood of local access to IP	Maximize the likelihood for increase of local incomes	Maximize the number of people that have access to water and sanitation
[$/m^2] [$/km]	[m^3] [Time]	[nr injuries/year]	[% open-IP]	[$/month]	[%/region]

Source Giso van der Heide

Step 3 Adding the business transformation capabilities dimension

A business capability is the articulation of the capacity, materials, and expertise an organization needs to perform its core functions. Business capabilities provide an abstraction of business reality in a way that helps to simplify conversations between different stakeholders. Creating a business capability model for the enterprise promotes more of a mutual understanding of the business. In Table 6, a total

Table 5 Adding the business transformation initiatives to the business model cornerstones

Business model cornerstones versus strategic initiatives dimension					
1. Architecture, engineering, and construction services	2. Revenue and profit	3. Brand and reputation	4. Professional or other influencer relationships	5. Construction and contracting	6. Customer experience and lifecycle
Develop advanced building materials	Standardize and digitize way of working	Implement lean and Safe construction management	Open the market to international firms	Standardize and modularize prefabricated components	Develop and explore new business models
Explore new production technologies, e.g., 3D printing	Impose early-stage cost conscious design and project planning	Create an appropriate organization, culture and incentive schemes	Align and agree upon standards across the industry	Explore autonomous construction and survey equipment	Interact effectively with the public sector
Promote R&D, technology and education	Define a common and appropriate framework for project management	Market the company on an industry wide scale	Exchange and share data, benchmarks and best practices	Promote contract models with improved risk sharing	Implement smart and connected enterprise (construction 4.0)
Compose a portfolio of sustainable and digital service offerings	Monitor project performance (cost, time, quality)	Implement transparency and anti-corruption standards	Coordinate consistent communication to civil society	Enhance subcontractor and supplier management	Manage project pipeline with reliable funding
Drive innovations to reach scale	Built a strategic workforce, do smart hiring, and enhance retention	Train continuously and ensure knowledge sharing	Simplify the permit processes	Collaborate along the value chain	Drive cost of ownership minded bidding

Source Giso van der Heide

Table 6 Adding the business transformation capabilities to the business model cornerstones

Business model cornerstones versus business capabilities dimension					
1. Architecture, engineering, and construction services	2. Revenue and profit	3. Brand and reputation	4. Professional or other influencer relationships	5. Construction and contracting	6. Customer experience and lifecycle
Bid and tender intelligence (AI)	Project performance reporting	Education and training management	ISO Certification and project information governance	Digitized site inspections	Customer relations management (CRM)
3D Printing of construction elements	Model driven cost- and quantity estimations	Corporate performance management	Supplier management	Robotized production assistance	Smart maintenance for assets and equipment
Lifecycle- and data management	Enterprise resource planning (ERP)	Environmental impact reporting	Future business scenario planning	Autonomous vehicles for construction assistance	Critical assets and equipment monitoring (IoT)
Design exploration with parametric and generative design	Predictive project risk monitoring	Serious- and realistic gaming for safety Instructions	Competitive insights and analyses	Construction site progress monitoring	Asset- and facility maintenance management
Collaborative design- and production engineering	Reality capture to 3D information model	Construction site intelligence (AI)	Start-up investment- and acquisition planning	Mobile assistance for site workers	Handover and commissioning
Computer-aided simulations (CFD, Structural, etc.)	Drawing production	Site security and safety control	Project portfolio management	Digital work and execution instructions	Requirements management for validation and verification
Construction materials research	Integrated project scheduling	Corporate knowledge management	Sustainable development (United Nations)	Design for manufacturing	Innovation management
Computational engineering	Construction site logistics planning	Change management and communications	Market intelligence and strategy	Integrated design to construction release control	Co-design and co-development
Business application management	Supply chain risk monitoring	Recruitment and retention management	Stakeholder management	Work Packaging for site operations	Customer experience management
New products and services development	3D-driven information modeling	Corporate culture management	Data exchange standards monitoring	Site Work planning and instructions provisioning	New business model innovation

(continued)

Table 6 (continued)

Business model cornerstones versus business capabilities dimension					
1. Architecture, engineering, and construction services	2. Revenue and profit	3. Brand and reputation	4. Professional or other influencer relationships	5. Construction and contracting	6. Customer experience and lifecycle
Concept- and system design studies	Defects and quality management	Employee performance management	Strategic-planning and execution	Design to production coordination	Value driven contracting (DBFO)

Source Giso van der Heide

of sixty-six transformation capabilities are spread across the six business model cornerstones.

Step 4 Adding the stakeholder needs "Jobs to Be Done" (JTBD) dimension.

This dimension targets a change management part that is extremely important for an organization to be able to "land" the transformation program with new initiatives and capabilities at the correct stakeholder levels. The stakeholder needs are expressed by a "job to be done" statement. It comes from a deep understanding of the job the stakeholder is trying to get done. It is the desire to get a job done that causes them to accept and adopt a new way of working (Strategyn, 2020). Table 7 summarizes thirty typical "Jobs to be Done" for the AEC industry.

2.9 Client Case Study Applying the AEC Business Model Playbook

The client case study is related to a national contractor that operates three major businesses: residential, non-residential, and infrastructure. The engagement for this case study was with their infrastructure division unit. Figure 11 shows an overview of the playbook process. It started obviously with the health assessment of the business model. This resulted in four cornerstones of their business model that seems to underperform, scoring 2 and 3. In conjunction with the client, each business model cornerstone was discussed using the "menu card" and checked against their strategic buckets (Living spaces, Safety, Quality of the Organization, Risk Management, Process Improvement, Digitalization and Production Technology) as well the targeted SDGs mentioned in their annual report (respectively, 7,8,9,11, and 12). Checkpoint: all seem to be well aligned with the cornerstones of the business model.

Then after, the client was asked to score their maturity for the complete set of **initiatives** and **capabilities** (appearing on the menu cards), from 1–5, implicating how far an initiative or capability was embedded in the organization. Level 1, *not*

Table 7 Adding the "jobs to be done" to the business model cornerstones

Business model cornerstones versus jobs to be done ("I need to:") dimension					
1. Architecture, engineering, and construction services	2. Revenue and profit	3. Brand and reputation	4. Professional or other influencer relationships	5. Construction and contracting	6. Customer experience and lifecycle
Control the customer specifications and compliance criteria	Transform the physical world into contextual and reusable data	Comply with imposed policies and sustainability agenda	Develop sustainable new business	Contract added value suppliers	Serve our client's comfort and health
Control the design execution and information delivery criteria	Drive efficiency of project execution	Apply financial accounting rules	Maintain the corporate vision, mission and strategy	Report daily project progress vs schedule	Comply with the agreed SLA's
Coordinate multi-disciplinary design activities	Deliver a project within contractual obligations	Contribute to corporate waste and CO2 targets	Develop sustainability innovation agenda	Built- and install equipment according to specifications	Develop compelling offerings
Reuse engineering and construction IP	Understand project delays and implications	Prioritize investments for MUST WIN projects	Communicate company achieved outcomes	Check delivered quality of subcontractors	Making the Voice of customer heard
Win new projects	Anticipate on project cost exceedance	Develop highly engaged and motivated employees	Analyze competitive offerings (white space)	Deliver the correct construction work packaging	Celebrate positive customer experiences

Source Giso van der Heide

existing to level 5, *embedded: enterprise continuous learning and improving*. Considering the targeted SDGs and the weakened business model cornerstones, it led to a filtered set of initiatives and capabilities that are most meaningful for this infra-unit. Thereafter the client was asked to layout the set across the three horizons, considering "feasibility vs importance" This "road mapping" exercise led to a structured digital transformation implementation plan, with prioritizations, dependencies, milestones, and owners.

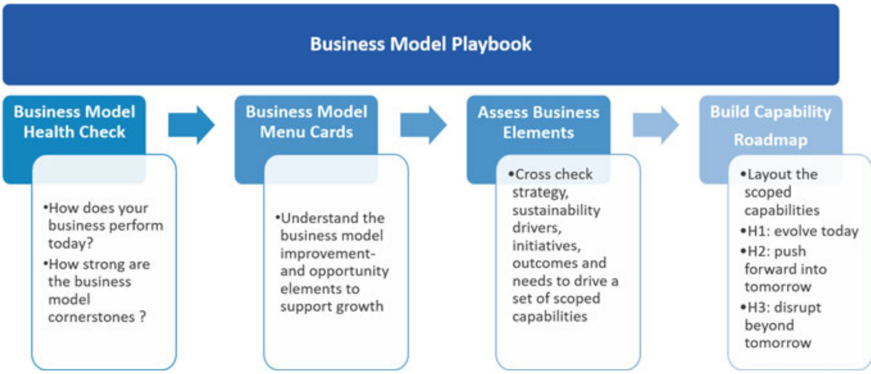


Fig. 11 Steps in the AEC business model playbook, resulting in prioritized capability roadmap (*Source* Giso van der Heide)

2.10 Conclusion

As highlighted earlier in this chapter, the COVID-19 crisis has been a forcing hand in exposing the weaknesses of some businesses, particularly those that fail to diversify their business models. Everyone could see that the risk of commoditization is higher than ever for incumbent and new players, even the largest ones. Running one business model is no longer considered a sustainable approach to business and expert advice is to build a portfolio of multiple business models to build a resilient business. As seen before in the chapter, diversification of the business model itself brings the best value in terms of CAGR and market capitalization.

In every industry, one can witness a shift in business culture, exemplified by the B Corp movement—a movement that has been established to align business interests with those of all stakeholders: employees, consumers, the environment, communities, etc., throughout the value chain. In the future, more AEC firms will strongly consider the impact of their decisions on their workers, customers, suppliers, community, and the environment. As Christopher Marquis writes in his book “Better Business: How the B Corp Movement Is Remaking Capitalism” (Yale University Press, September 2020): “businesses have a key role to play in a capitalist society, they can tip the scales toward the benefit of the few, with toxic side effects for all, or they can guide us toward better, more equitable long-term solutions.” The B Corp movement reflects changing expectations of how businesses should operate in today’s VUCA world: with greater consideration for the impacts that their operating decisions have. Core to this is how traditional businesses need to re-assess their business models, and the way they are being executed. It is not solely about acquiring technologies but finding a scalable way to acquire customers and monetizing them at a significantly higher level than the cost of acquisition. That is the key principle of having a successful business model.

No doubt that sustainability needs to become an integral element in business models within the AEC sector, and decision-makers should consider a common reporting framework for the sector to adopt which also ensures that related activities align to the SMART methodology (specific, measurable, achievable, relevant, and time bound). Earlier in the chapter, corporate strategy has been connected to targeted SDGs and business models. The AEC business model playbook is the mechanism to make it easier to understand business model health, prioritize initiatives, and capabilities that will lead to meaningful business transformations.

Today, most AEC firms provide services to their clients, while construction firms build physical assets. They operate primarily within a time-and-materials basis (otherwise referred to as “brainpower by the hour” or consulting cost structures). With difficulties staying head of the competition, to grow and to maintain their margins, most of the large AEC firms look at platform business models with envy. Yet, the transformation of a business model is a long journey and not all AEC firms are agile enough and have sufficient investment capabilities to pivot toward such business models. In many ways, network orchestrators operate in ways that run counter to what are considered as best practices of other business models. This is why the current transformations are so challenging from a cultural standpoint.

3 Transformation of Organizations and Cultures

Cultural transformation and business model transformation are two sides of the same coin. Business models fundamentally impact upon the shape of the organizational which, in turn, impacts upon the prevailing behavioral norms and organizational culture. In the first part of this chapter, business models were examined and the need for these to diversify has been explained. This shift will pose considerable challenges for the AEC sector, particularly when it comes to operating norms, culture, prevailing behaviors, and orthodoxies. In this second part, the challenges and changes required for the sector to digitize more effectively will be examined.

It is now clear to everyone that implementing a successful digital transformation means transforming your organization and “upgrading” your culture. Data shall now be considered an asset, and analytics a key tool to make better decisions. Leading companies have understood that culture is a pivotal success factor and that they must address deep-rooted behaviors and underlying attitudes, if they are to make the transition to become a data-driven business.

At the industry level, industry experts saw the emergence of new types of players and new ecosystems. This is also true at the company level. An example is the emergence of new roles and departments in firms centered on data and analytics, especially at the C-suite. Positions like Chief Digital Officer, Chief Transformation Officer, Chief Strategic Partnerships Officer, and Chief Data Officer are becoming visible. Even the notion of culture is now more visible with roles such as Head of People and Culture, or Director for Organizational and Cultural Transformation.

These changes aren't just about semantics. Today's environment calls for new activities and roles, and having the right terminology helps shift the way that people think and work. Establishing new roles and terminologies also changes how an organization sees itself, and ultimately shifts its behaviors and actions over the long term. The cultural aspect of digital transformation is undoubtedly one of the missing pieces of the puzzle. A key component, too often underrated, of digital transformation lies in the company culture. A lot of initiatives fail because this domain is underestimated, and there is a singular focus on process over engagement and mindset shift. In today's environment, the way things are done, as well as the behaviors, beliefs, and perceptions within a company, need to be disrupted to unlock the full potential of an organization. If it is agile and innovative, a company's culture is a competitive advantage. Being quick and agile is a must for keeping up in today's rapidly changing environment. As Jeff Bezos explains it, "In today's era of volatility, there is no other way but to reinvent. The only sustainable advantage you can have over others is agility, that's it. Because nothing else is sustainable, everything else you create, somebody else will replicate."

3.1 Challenges of the Construction Industry

The first person to be considered a civil engineer was Imhotep, engineer to the Pharaoh Djoser and widely considered to have designed and overseen the building of Djoser's pyramid at Saqqara. Engineering principles have ancient roots, and the enduring existence and preservation of structures such as the pyramids of Saqqara, the Great Wall of China and the Aqueduct of Sequovia—just to name a few—are a strong testament to the precision that prevails within the culture of the construction industry in general. As American engineer and educator James Kip Finch explains, "The engineer has been, and is, a maker of history." From the need for pinpoint detail and calculations in design, through to building, accuracy of materials use and bills of quantity, through to appropriate construction and maintenance practices, the industry is renowned for enduring orthodoxies in practices which have ensured minimization of construction risk—and literally the maintenance of structures—for millennia. These long-standing and prevailing orthodoxies bind an otherwise highly fragmented and complex industry with an underpinning culture.

Earlier in this chapter, the need for business model innovation and ecosystems development was explored as a macro-response to the need for the AEC sector to digitally transform. In this section, some of the further prevailing sector attributes that impact digital transformation will be examined. Key challenges within the AEC industry are its core culture, its fragmentation, its predominant behaviors, its organizational hierarchies, its principal business models, and its prevailing sector orthodoxies. All these challenges will be addressed throughout the chapter. In the next section, two key challenges that are particularly impactful and unique to the AEC sector will be looked at: the industry and organizational culture, and the fragmentation.

3.2 Industry and Organizational Culture

Hofstede defines culture as “the collective programming of the mind that distinguishes one group from another” (Hofstede, 1984). Organizational culture is “defined as shared assumptions, beliefs, and ‘normal behaviors’” observable in an organization or an industry (Ela Oney-Yazıcı, 2007). When the culture of the construction industry is examined, a prevailing set of values and traits emerge that distinguish the industry from others. A clear comparison to draw when it comes to prevailing industry cultures is with large technology organizations that are considered “digital natives.”

There is a growing amount of research focusing on culture in project-based industries such as construction, examining the increasing impact of internationalization and fragmentation of the industry sector (Hillebrant, 2000). As outlined earlier in this chapter, the complexity of the industry, coupled with the project-by-project nature of engagement, the need for technical knowledge relating to specific asset classes, and the need for multidisciplinary expertise, drive a sector that is highly fragmented and has been characterized by predominantly transactional relationships between industry partners. This transactional nature is broadly believed to indicate relatively low levels of trust between industry players, indeed an Autodesk report found “63% of firms do not have a high level of internal trust” (Autodesk and FMI, Trust Matters: The high cost of low trust, 2020). The prevailing culture of the construction industry has been long cited as a critical factor impacting project performance—for instance, in the UK there have been numerous reports over the last 70 years into construction industry performance concluding that many projects fail to meet or exceed expectations (Ankrah, 2007). Culture, and specifically its impact on AEC sector productivity, has therefore become a significant focus of research in construction management in recent years. Table 8 summarizes some of the key cultural elements and their manifestation in the industry.

How does this compare with the prevailing culture of “digital natives?” As one can see in Table 9, there are significant differences in the prevailing cultures of the major players within the AEC sector and digital natives. The established culture within the AEC industry has evolved over a protracted period of time, and now needs to make rapid shifts toward cultural norms that more similarly reflect the digital natives, in order to effective embrace digital transformation. The effort and investment required in order to make these shifts should not be underestimated, as they are significant and, in some aspects, the cultural norms that are required to effectively operate as a digital business are diametrically opposed to the prevailing culture of the industry.

3.3 Fragmentation

Fragmentation is the enemy of digital transformation at both industry and organizational levels. This section explores the nature of fragmentation in the construction

Table 8 Common features of the construction industry culture

Cultural element	Manifestation in the construction industry
Highly rational and data-driven	Engineers, architects, and others in the industry rely largely on scientific methods and mathematical calculations. This drives a highly rational culture where major decision making is focused on the analysis of data
Risk-averse	Construction projects are all categorized by being high-risk; therefore, the methods and precision that drive the industry are focused on risk management and minimization. This drives a prevailing culture that is highly risk-averse
Hierarchy and technical specialization	One of the means by which risk is managed in the industry is through the reinforcement of organizational hierarchies based upon the attainment of technical expertise
Process-driven	The need to coordinate a range of industry players for the delivery of any kind of construction project leads to a heavy reliance on process to ensure conformance and consistency. Some of the criticism that has been leveled against industry performance has been targeted at the predominance of process at the expense of quality of outcomes
Relatively low levels of trust	The process-driven culture also reinforces relatively low levels of trust across the industry. Processes define and reinforce the deliverables of various industry players on a project, further reinforcing silos and reducing opportunities for strategic collaboration. This has been demonstrated to manifest in a high level of adversarial project claims within the industry, as a means of requiring compliance
Controls orientation	Process orientation and low levels of trust in the industry also result in a high level of controls orientation. This manifests on multiple levels: from the operational controls of organizations within the sector (often outlined in highly prescriptive and detailed standard operating procedures) through to project controls that demand high levels of individual adherence. Controls also extend to the timetabling of their periodic review, which also leads to slow and micro-evolutionary changes in procedures
Short-termism	Most industry players manage their organizations on the basis of pitching, securing, delivering, and handing over projects. This project-by-project focus of the sector drives a predominant culture of short-termism. Business development, financial reporting, and even human resource management are all managed with relatively short-term look-ahead views. Human resources, for instance, is managed on the basis of short-term billability and resource allocation

(continued)

Table 8 (continued)

Cultural element	Manifestation in the construction industry
Highly orthodox	"Orthodoxies prescribe a set of relations that are necessary for things to operate smoothly" (Trudeau, 2006). It is therefore no surprise that in a highly complex and multidisciplinary industry sector as construction, that orthodoxies are necessary for the good operation of industry players, and the successful delivery of construction projects that are inherently high-risk to design, build, maintain, and decommission. Orthodoxies, including design principles, have literally existed in the construction sector for millennia, indeed the principles involved in designing a bridge today are largely the same used by the Romans. Such highly orthodox cultures are therefore extremely difficult to transform and change, even when the external environment has shifted significantly

Table 9 A comparison of the key cultural features of the construction sector and digital natives

Cultural features of the construction industry	Cultural features of digital natives and tech giants
Highly rational and data-driven	Decision making at the nexus of data and human centricity
Risk-averse	Entrepreneurial
Hierarchy and technical specialization	Relatively flat organizational structures of enabled teams that combine technical and human-centered expertise
Process-Driven	Outcomes driven underpinned by clear processes
Low levels of trust	High levels of trust
Controls orientation	Freedom within a framework
Short-termism	Medium- to long-term focus
Highly orthodox	Outside-In thinking is encouraged to critically question the status quo

sector, and the impact this is having on the sector's ability to effectively globalize and digitalize.

As construction projects have grown in size and complexity, there has been an increasing focus on engaging multiple sector players, each bringing their own specialist expertise and teams, to deliver discrete parts of each project. This focus on differentiation and specialization within the sector has resulted in two clear areas of industry fragmentation: internal and external (Mohd Nasrun Mohd Nawi, 2014). Mohd Nawi et al. (2014) define these different types as fragmentation as: "internal fragmentation refers to the problem of integration and coordination between different alliance organizations (e.g., client, consultant) while external fragmentation refers to the involvement of non-alliance organization (e.g., local authority) at different stages of the design process." (Mohd Nasrun Mohd Nawi, 2014). While this is evident, sector fragmentation is a cultural feature which is invisible to those within the sector, and a significant issue for all industry players attempting digital transformation. It is broadly considered that this fragmentation drives inefficiencies and performance concerns across the industry.

Beyond the definition of internal and external fragmentation, the fragmentation in the construction industry has been observed in the following different levels:

- **High levels of specialization**: By asset class, deep technical knowledge and expertise.
- **Contractors versus Consultancies**: The differences between those that implement and deliver building; and those that plan, manage, and apply project controls.
- **Projects**: Low levels of mobility of teams across projects. Projects are managed in isolation by all industry players from clients, contractors, consultants, and regulators.
- **Within teams**: Highly prescribed roles of individuals within hierarchical team structures, and a lack of integration of project teams which are frequently comprised of individuals from multiple industry players—particularly on large and complex construction projects.
- **Supply chain complexity**: The full value chain ranges from raw materials, manufacturing through to design, build, management, and decommissioning. Siloing of each part of the supply chain creates a highly transactional culture between each phase of delivery.
- **Cross-cultural challenges**: Localization of projects and teams has made cross-cultural collaborations/internationalization a struggle within the industry.
- **Industry structure**: The complex interplay of industry players from boutique and highly specialized single-service providers, through to large multidisciplinary consultancies, perpetuates continued industry fragmentation.

These features of industry fragmentation led the authors to a working definition of what is meant by "fragmentation" in the construction industry. Construction industry fragmentation exists due to a highly complex and matrixed interplay of diverse industry players required to deliver highly complex construction projects for a range of disparate clients. Specialization of knowledge and expertise, both with respect to the construction phase and the asset class of the project, has created a highly differentiated and siloed industry sector, with a need for clearly defined and highly consistent processes to ensure deliverables and hand-offs are effectively managed both within and across project teams. Fragmentation is evident at all levels in the industry: clients; service providers; regulators; organizationally; and within teams.

What is the impact of this fragmentation when it comes to digital transformation? Construction industry fragmentation, and the cultural features that are evident within the industry outlined above, have created an environment within the sector that is highly challenging to transform, even in the face of increasing digitization within many of the asset classes and changing societal/consumer expectations in areas such as mobility, placemaking, infrastructure, and buildings.

It is therefore no wonder that the McKinsey Global Institute Digitization Index places the construction industry as the second-to-last industry in terms of digitization and digital maturity (the agricultural industry is placed last; however, these sectors interchange). The construction industry has relative low levels of digitization when compared to other highly complex sectors, such as pharmaceuticals, health care and medical equipment, automotive and financial services.

The implications for this on a sector level mean that successful digital transformation requires a whole-of-sector shift, as each industry player is inter-dependent on the others. Additionally, each industry player needs to focus specifically on building an organizational culture that reflects more of the cultural features of digital natives and technology organizations.

Digital transformation in construction therefore needs to focus on building the industry environment that can enable the industry players to more effectively collaborate, underpinned by mutuality and trust that is reflective of digital ecosystems, as outlined earlier in this chapter. In addition to cultivating the industry environment that enables digital transformation, each industry player needs to focus on their own digital transformation by building an organizational culture that is entrepreneurial, innovative, embeds human-centered design principles, and is technologically enabled.

Successful digital businesses have the following features in common:

1. **People led, technologically enabled**: A paradox of digital transformation is that as businesses become increasingly digital; they need to simultaneously become more human in capability. Successful digital businesses recognize this paradox and invest in key elements that improve human centricity by investing in soft skills, embedding design-thinking techniques into their organizational DNA, and viewing the interplay of technology and people through the lens of augmentation, as opposed to displacement.
2. **Common language**: Most digital transformations fail because businesses take the approach of "bolting on" their digital capabilities to an established legacy business, rather than establishing a baseline of understanding underpinned by a common language of digital, strategy, sustainability, and technology. Without establishing a common language across the full business, organizations create a significant business risk that the dominant business model will not enable the growth of the digital components—and it certainly will not result in the creation of a platform business.
3. **Freedom in a framework**: Another paradox of successful digital businesses is the existence of high levels of organizational accountability, and low levels of organizational rigidity and bureaucracy. Change is therefore often driven from the top through the establishment of a clear framework of deliverables and expectations that are clearly understood throughout the organization. Within this framework, employees have relative freedom to experiment and innovate. The AEC sector, by comparison is often characterized as having high levels of

organizational bureaucracy and rigidity, which stifles innovation and limits the capability for new ideas to become new organizational norms.

4. **Defragged**: Strong operational and accountability frameworks—reinforced by regular performance feedback loops, discussions, and aligned performance objectives through approaches such as Objectives and Key Result Areas (OKRs)—effectively reduce internal siloing in successful digital organizations. Successful digital businesses avoid matrixed structures and focus on clear lines of operational alignment from the top-down, underpinned by devolved decision-making structures that enable rapid deployment at the project level. This contrasts significantly with many of the larger corporate organizations in the ACE sector that are highly matrixed, with complex operational and bureaucratic decision-making structures. This has the dual outcome of ensuring the business is effectively defragged with high levels of operational alignment, as well as change being able to be driven from the top through the accountability framework which enables new ideas and approaches to be rapidly deployed into the organizational structure.
5. **Data-driven and evidenced-based**: MIT Principle Research Scientist, Jeanne Ross, has found that businesses that successfully narrow focus on a clear data set and structure their decision making and operational structures around that data, are more successful in driving digital transformation. For instance, businesses can choose to focus on their client data to inform how they understand their clients' preferences, decision making and operations, in order to best serve them. This information then informs the organizational, operational, and decision-making structures of the digital business. The ACE sector produces and processes a significant amount of data; however, given that the digital maturity of the sector is still evolving, businesses in the sector are still not effectively structured to be truly data-driven and evidence-based in their operations and decision making as Ross has identified for truly digital businesses. Indeed, most businesses in the sector continue to be traditionally focused on financials, rather than customer or operational data, as a means of managing business decision making. This therefore leads to a short-term focus on operations, rather than a longer-term strategic outlook incorporating digital investment, which is a cultural characteristic of the digital natives.
6. **Succeed slowly**: Contrary to popular belief, most digital businesses are not overnight successes or "digital unicorns." Digital businesses succeed slowly, and largely by actively addressing the important need for "stability management" in an increasingly accelerated environment of transformation. Stability management is necessary for businesses to take the longer-term view for business decision-making and strategic investment, while incorporating agile internal organization that enables the business to make decisions and pivot in response to market demands. Another feature that characterizes successful digital businesses—and why they tend to actually succeed slowly—is that they are most often portfolio businesses which incorporate multiple business models and underpinned by a platform of digital components. This means that digital businesses often have one or multiple "cash cow" offerings that are profitable and

fund the investment in new digital offerings. New digital offerings either fit into the category of "big bets" which are potential high yield investments, or scale-up offerings that are already proven with a client and require further investment to scale. This diversification of the business portfolio ensures greater business resilience for digital businesses, against the implications of technology S-curves.

7. **Don't Fail Fast**: The concept of "failing fast, failing forward" is a buzzword and a misnomer in the field of digital transformation. It is a mantra spoken by those who really don't understand the intersection of business models, operational effectiveness, organizational design, and culture. The reality is that many digital businesses fail because they don't kill off their failing components and continue to invest in failing products and service offerings. Even large digital organizations have fallen into the trap of continued investment into a product or service offering well beyond the point where it is apparent that it will not succeed in the market: Amazon's Fire Phone, the Microsoft Kin (which was discontinued just 6 weeks after its release), and, most notably for the AEC sector: Google's Sidewalk Labs. These large digital corporates could effectively afford to write off these over-investments because of their cash-cow businesses; however, there are also plenty of examples of digital failures of businesses that were not as established or diversified. The underlying key to managing big bets in a digital portfolio business is having a clear limit on the level of investment and being prepared the cease the investment and stop the product or service when it is clear that it won't succeed. In this sense, successful digital businesses create a culture of experimentation: hypothesis-led activity to explore new ground that is also supported by a clear investment case. This is not about failing or continuing investment well beyond the point of no-return.

Given the culture and characteristics of digital businesses, there are some clear implications for the AEC sector when it comes to digitization. These implications can be categorized into the following key themes:

- **Prevailing culture**: As alluded to earlier in this chapter, there is a prevailing culture in the AEC sector which is characterized by high levels of procedural bureaucracy, risk aversion, precision, and low levels of trust between sector players. This culture needs a radical shift to enable the sector to digitize effectively, operate in a more agile way, be responsive to evolving client expectations and market demands, take riskier investments that enable disruption, and build strategic partnerships within a sector ecosystem that is fundamentally founded on trust.
- **Prevailing sector orthodoxies**: As explored earlier in this chapter, the AEC sector is founded on approaches that are largely "tried and true" of literally millennia of building and construction works. Prevailing sector orthodoxies don't lend themselves to radical experimentation that drives innovation and disruption. Another sector orthodoxy is the focus on short-term financial management of businesses, driven through the fragmented project-by-project operational focus of most sector players, which stifles long-term strategic investment decisions into innovative "big bets."

- **Organizational structure**: Given the nature of the sector and the cultural points outlined above, organizational structures in the AEC sector tend toward high levels of hierarchy and are highly matrixed. There is also a delineation between "technical" roles and "managerial" roles, with different career streams established for each. Technical role career streams are focused on increasing specialization and technical expertise as the fundamental of development. Managerial roles are focused on "soft skills" and functional capabilities management. This differs from many digital businesses that focus on building T-shaped capabilities within their middle and senior management by ensuring both technical expertise and management capabilities are developed in parallel.
- **Operating model and ways of working**: Matrixed structures, coupled with hierarchy of decision making, drive decision making to the highest point of responsibility in the organization, rather than the lowest point as seen in more agile digital businesses. The prevailing operating model is one where matters are escalated through layers of hierarchy for decision and approval, rather than the "freedom in a framework" model of enablement seen in many successful digital businesses, which devolves decision making to the point closest to the work. There is a reason why the term "over-engineered" exists, and it represents the opposite of agile working.
- **Business model**: Much of the ACE sector operates under the "time-and-materials" business model. This business model manifests in two ways: "brainpower by the hour" where clients are billed an hourly rate for the provision of services; or project-based billing which is effectively a total amount billed to the client based upon the cost of time and materials to get the work done. This business model impacts upon digitization in the sector in three significant ways:

    - o **Undermines Trust**: Or more precisely, it does nothing to build trust across the sector as each engagement is dependent upon scope definitions for service delivery. A whole sub-industry to manage contractual disputation and conflicts has therefore emerged as a result of the need to interpret contracts supporting the time-and-materials business model.
    - o **Reinforces Sector Fragmentation**: Contractual structures that support the current approach to the time-and-materials business model in the ACE sector drive sector fragmentation, rather than an ecosystem approach based upon mutually beneficial strategic partnerships, as explored in more detail earlier in this chapter.
    - o **Stifles Long-Term View and Innovation**: Time-and-materials is ostensibly a short-term approach that places the operational focus on billability of resources. This narrows operational focus within the ACE sector onto maximizing billability of current resources and inhibits the longer-term strategic focus required for innovation. In this way, the time-and-materials business model acts as a strong immune system against alternative business models and approaches taking hold.

In this section, the fragmentation of the ACE sector has been explained. This fragmentation has long been identified as a key inhibitor of productivity and performance. There are broader cultural implications of this fragmentation which are now translating into challenges for digitization of the sector. In the next section, the organizational design challenges will be explored further, and how these need to change across the sector to enable digital transformation.

3.4 Transforming Organizational Design (Structural and Organizational Changes)

Structural, cultural, and organizational challenges need to be addressed across the AEC sector to better enable new business models and drive digital transformation. In this section, the focus will be put on the elements of organizational design within key industry players within the AEC sector, and how these require structural transformation to enable sector digitization.

Organizational design in any business looks at the interplay of people (including the capabilities they bring), with process (including ways of working) and technology to build value propositions for a business. In a digital business, the focus is therefore on how these three key components interplay and are enabled to innovate **new digital value propositions**.

As shown in Fig. 12, organizational design relies upon the interplay of people, process, and technology to create digital capabilities for a business. It is the effective use of these digital capabilities that create new digital value propositions and enable new digital business models to emerge within a portfolio business.

1. **People**: By people, the authors are not referring to individuals, but more roles, capabilities, accountability framework, and reporting structures.

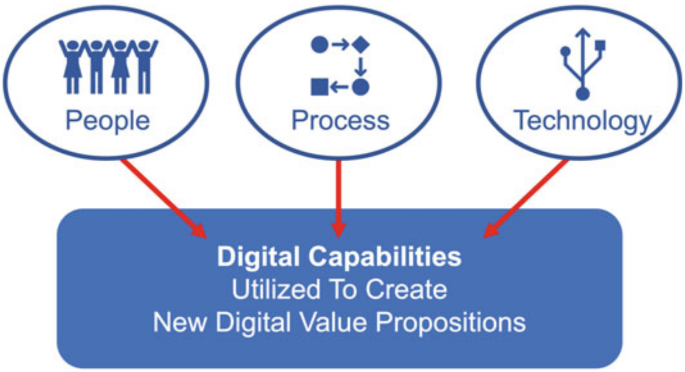


Fig. 12 Fundamentals of organizational design principles (*Source* Carolyn Moore)

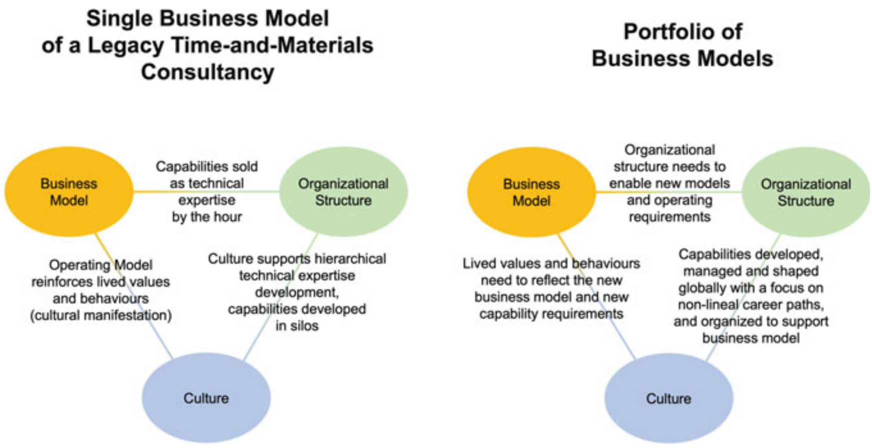


Fig. 13 Interplay of business models, culture and organizational structure as businesses transform from a single business model to a portfolio business (*Source* Carolyn Moore)

2. **Process**: Are defined as ways of working including routines and workflows, and operating procedures.
3. **Technology**: By technology, one is referring to both the technology infrastructure that enables the business (e.g., enterprise systems), and applications.

The interplay between these organizational design principles is represented by, and drives, the organizational culture. Each plays an important role in driving both the digital transformation of the business (digitalization) and driving the development of a digital business (digitization).

The organizational design features, and how these interact with organizational culture, have been outlined. A third element needs to be considered: how they interact with the business model. The interplay of organizational design, business model, and organizational culture is also a critical element in driving digital transformation within businesses. As explored earlier, changes to the business model both impact and require, a fundamental shift in culture and organizational structure, to be successful. These three elements are the key to the invisible revolution that is occurring to drive digital transformation across the sector. This interplay is illustrated in Fig. 13.

3.5 How to Prepare the Business for a Culture Ready for the Future (Transforming a Legacy Business)

The first step in preparing any business or organizational culture for digital transformation is to acknowledge that change is now a business constant. As John Kotter explains, "Perhaps the greatest challenge business leaders face today is how to stay competitive amidst constant turbulence and disruption." Driven by the accelerated

Table 10 Change management practices categorization

Order of change	Description	Application
First-order change	Self-imposed lineal change	Making a personal change from a known constant state to a new known constant state
Second-order change	Top-down imposed lineal change	Directing change (such as a software implementation) which moves behavior from a known constant state to a new known constant state
Third-order change	Constant and non-lineal change	Transformation: the process of ongoing, non-lineal change which cycles through periods of evolution, disruption, and stability

pace of data creation and digitization in the business environment, businesses now find themselves with the reality of needing to embrace constant change and evolution to survive and thrive in the digital world. Digital disruption also means that businesses need to accept that traditional change management practices are no longer sufficient to ensure ongoing business resilience in the face of constant volatile and disruptive change. Change management practices are listed in Table 10.

Even John Kotter, the global authority on change management, has acknowledged that traditional change management practices that managed change in a lineal shift from one constant to another, require a rethink in this new volatile and uncertain digital environment (Kotter, 2012). Traditional change management approaches reflect second-order change management practices: with a clear current state, defined future state, and a transition state that is lineal with a known roadmap. The key concern with applying this type of approach in a business environment that is characterized by constant change, disruption, and volatility is that it creates change exhaustion within the business. Employing traditional change management, administered through highly procedural project management practices, is one of the most significant mistakes businesses make when they embark on a digital transformation. It frequently leads to an incapacity to pivot effectively when faced with disruption, leading businesses to "stay the course" of their over-planned approach, even when that is no longer suitable because the business environment has changed significantly in a short space of time.

So, how do businesses best prepare themselves for transformation in a volatile change environment?

1. **Digital Leadership Capabilities**: Leadership capabilities that are necessary for digital businesses differ significantly from traditional management practices. To prepare a business for transformation, businesses need to invest in building digital leadership capabilities both by developing their current leadership, and by bringing into the business capabilities external to the organization. The injection of "outside-in" thinking into a traditional organization is key to building a culture

where innovative thinking, and ideas that challenge established orthodoxies, can be embedded and accepted by a critical mass of employees.

2. **High-Engagement Transformation Approaches**: Innovation cultures can only be created in environments where a critical mass of employees adopts this mindset. As with any adoption curve, there will be early adopters and laggards in every organization. Transformation needs to engage a critical mass of employees, by building on the enthusiasm of early adopting employees and developing them into cultural architects, supported by first following organizational champions who can aid with embedding new ideas across the business. Therefore, it is an imperative for businesses to take a high-engagement approach to transformation by establishing a common language of digital for the organization and establishing a baseline of organizational awareness around the digital strategy. This should then be supported by organizational frameworks that drive employee-led innovation and continuous development. By doing so, businesses can identify those employees who are early adopters, and best placed to engage others on the digital transformation journey.
3. **Planning… Iteratively**: Business strategy approaches also need to shift from being lineal and definitive, with highly detailed implementation roadmaps to a more iterative approach. Such an iterative approach requires organizations to set a longer-term strategic direction—an inspiring north star for the business—with medium- and shorter-term goals that can be iterated, pivoted, or even killed-off entirely in response to market and environmental change. This strategic planning process leads itself to the development of digital businesses as portfolio business as explored elsewhere in this chapter. Strategy therefore needs to account for a diversified portfolio of businesses, unified by the overall north star aspirations of the business. In this sense, strategy implementation requires an approach that embeds it into the organizational DNA by being part of the rhythmic cycle of business. Particularly savvy companies are replacing their monthly and quarterly financial reviews, with more holistic business reviews that focus on digital and innovation through the three lenses of viability, feasibility, and desirability.
4. **Stability Management**: As outlined above, traditional change management practices that have a clear beginning, middle and defined endpoint are not suitable in an environment of continuous change, and lead to change exhaustion within businesses. To build organizational resilience where constant change is the norm, equal focus needs to be given to enforcing periods of organizational and operational stability, as much as there needs to be a focus on transformation. Stability management in this context becomes an important factor in embedding change within a business undergoing digital transformation. It enables new practices, ways of working and the innovative mindset to be reinforced within the business context.

3.6 Cultural Architects and Organizational Champions

The value delivered by technology doesn't just lie on technology alone. It is about how companies evolve as they adopt these technologies. The biggest challenge firms have is the cultural transformation they have to go through. It seems that all the technological conditions for a revolution are united, but it appears that the ecosystem is not culturally ready. Which words people use to describe Construction? Delays, over budget, last minute changes, fragmented industry, no integration of the supply chain, poor risk management, poor information handover, no investment in IT and R&D, low margins, limited collaboration between stakeholders, lack of visibility in work progress, no knowledge management, no maturity in digital, too much improvisation, low productivity, lots of rework, poor use of data, heterogeneous tools and systems, no anticipation, unclear business processes, archaic project management, etc. What is wrong, what needs to change from a cultural standpoint? How can the Construction industry make a step change?

As seen earlier in this chapter, embedding technology into a business is insufficient to drive a digital transformation. To enable innovation and diversification of business models—particularly in a sector with strong prevailing orthodoxies like the AEC sector—cultural shifts are paramount. Many organizations take a process-led approach to cultural transformation, erroneously believing that following a lineal from–to roadmap will create lasting cultural change. It does not. And it certainly won't have an enduring impact in an environment of continued and accelerated change. This is why the need for ongoing organizational engagement is essential to drive cultural and mindset shifts.

Transformation—whether within a single business or across an industry sector—will only ever get traction once a critical mass of players become aware of the need to change, and start to plan and implement tangible actions toward addressing the environmental factors that are creating the need to change. In this sense, the power of peers is important in building momentum toward change. Within any peer group (once again, whether individual or business peers), there will be some players who "set a tone" within the group—these are the cultural architects—and others look to them to learn from their approaches and emulate their successes. Within an industry sector, a cultural architect is most often an established player that starts to drive transformation and is viewed by others in the industry as leading edge. They need to have sufficient clout within the industry to be respected, and they are seen to be highly responsive to environmental shifts, emerging players, and new ways of working. Their responses will be analyzed by others within the industry who will follow, or choose to hold off. In this sense, industry cultural architects are "first among peers" to be seen to engaging with transformative efforts. In Europe, Arcadis, Bouygues, Ferrovial, Holcim, Royal BAM, Saint-Gobain, Schneider Electric, VINCI, can be considered cultural architects. Even if they are also competitors, cultural architects informally act as the eyes and ears of the whole industry, leading by examples and showing how the hardest challenges can be overcome. Cultural architects communicate between each other, in various informal ways. They also observe and inspire each other. One of the biggest difficulties for these firms is they are the first movers; they cannot benchmark against anyone else.

Industry and organizational engagement in digital transformation is needed to drive the changes necessary to defrag the sector and businesses, embed new ways of working and to adopt new ways of working that challenge traditional orthodoxies. To create this engagement, cultural architects are required at the both industry and organizational levels that have the vision necessary to inspire others to engage with digital, and consider new approaches. At the industry level, these cultural architects would be organizations that are operating differently: the increate of new players and start-ups in the sector indicates the sector is ripe for this form of cultural disruption. Traditional industry players are also attempting to act as cultural architects by engaging with emerging players through accelerators and incubators; however, the impacts of these approaches are necessarily having the impact on the operations of the main areas of those businesses.

Within organizations, champions willing to drive for transformation are essential. These organizational champions fulfill an important function of being the "first followers" of cultural architects, by normalizing and operationalizing the behaviors and operational norms necessary for cultural shifts to occur. As new practices become the norm both within organizations, and across industries, organizational champions play an important role of reinforcing and embedding the changes that are necessary to continuously drive transformation. In this sense, organizational champions "normalize" the transformation efforts that are established by the cultural architects. Both play a crucial and symbiotic role in driving transformation efforts across industries.

3.7 Embedding the Innovation Culture

The most fertile circumstances for step changes to happen in the construction industry are when innovation is driven well, when business ecosystems are orchestrated to deliver projects, and when the workforce is well-managed. Unfortunately, in today's construction industry, with limited collaboration between the parties in the supply chain, innovation is limited to technical developments in individual products and services. Step changes do not happen, one needs to go beyond individual heroics. As identified above, the industry needs a cultural shift toward greater levels of trust and collaboration, it requires industry players to act as cultural architects and accept some of the risks necessary to take a longer-term view of sector sustainability and drive scalable digital solutions, build interlocking digital components, and build a successful and sustainable ecosystem.

Significant and accelerated change is impacting the AEC sector. Businesses that embrace this change and accept both the level of ambiguity and risk that comes with it, are positioning themselves for greater long-term business resilience. The key underlying principle is to embed a culture of change resilience and innovation within a business. In this section, the authors will examine how businesses can effectively embed these new cultural norms into their business—especially as they navigate constant change and disruption.

Our observations of businesses in the AEC sector have demonstrated several major approaches to embedding innovation within their businesses, each with varying levels of success. Key observed approaches include:

1. **Acquisitions**: There is evidence of several key industry players making acquisitions of digital businesses, and even creative consultancies, in order to inject digital capabilities into the core business, such as the Aurecon acquisition of Studio Magnified in 2018.
2. **Joint ventures and partnerships**: There are several instances where industry players have created a strategic partnership or joint venture to combine digital capabilities with asset knowledge. These are most-frequently done on a project-by-project basis.
3. **Digital studios or laboratories**: Several key industry players have established their own innovation funds, design studios or laboratories, which operate separately to their core business in order to drive innovation outside of the legacy business environment and the time-and-materials immune system. Arup's launch of the Pegasus Lab and Makers Lab in their Toronto Office are great examples of this approach.
4. **Start-up incubators and accelerator programs**: A few industry players have sought to engage with emerging start-ups in the industry either directly or through partnership programs, such as the Arcadis-Techstars City of 2030 Accelerator.
5. **Agile teams**: Some industry players have created agile teams that are then given the opportunity to use new ways of working and methodologies such as Kanban use, as opposed to waterfall-based planning, on projects. In most references to "agile" across the industry, however, it is used interchangeably with "flexible" rather than to denote the scaled-agile methodology of working, leading us to conclude that the uptake of agile practices is in reality lower across the industry than appears.
6. **Holistic transformation management**: Many industry players have transformation teams that are attempting to drive digital transformation in their legacy businesses; however, the majority of these teams continue to adopt second-order practices, and traditional process-driven approaches to change. Very few industry players are taking a truly holistic transformative approach to transformation management, which engages a critical mass of employees. The one notable exception to this is the Expedition DNA program adopted at Arcadis.

In Table 11, the efficacy of each of these approaches in respect to driving and embedding cultural transformation is examined.

As indicated above, there is no single approach that will enable a legacy business in the AEC sector to digitally transform. To successfully adopt digital practices and embed an innovation mindset across the organization, legacy businesses need to engage multiple practices, underpinned by suitable holistic transformation management.

Table 11 An analysis of the impact of approaches taken in the AEC sector on cultural transformation

Cultural Transformation Indicator	Acquisition	Joint Venture/ Partnership	Digital Studios & Labs	Start-Up Incubators & Accelerators	Agile Teams	Holistic Transformation Management
North Star Strategic Direction	✗	✗	–	–	–	✓
Builds Digital Leadership Capability	✗	–	–	✗	–	✓
Establishes a Baseline of Awareness and Understanding	✗	✗	✗	✗	–	✓
Builds Critical Mass Engagement	✗	✗	✗	✗	–	✓
Develops Cultural Architects and Organizational Champions to drive and reinforce change	✗	–	–	✗	–	✓
Creates organizational frameworks and systems that reinforce cultural change	✗	✗	–	✗	✓	–
Celebrates bight - spot demonstrations of changed culture for positive reinforcement	✓	✓	✓	✓	✓	✓

✓ A key intervention for driving cultural change and innovation mindset development in a legacy business

– Has some impact on cultural change, usually in reinforcement mechanisms and establishing norms in operations, within a legacy business where the pre-requisite criteria for cultural transformation are already established

✗ Unlikely to impact the culture of a legacy business, but useful in applying changed behaviors and new digital capabilities

It is also important to emphasize here that digital transformation of the AEC sector cannot happen separate to the complexities and nature of the sector. As seen earlier in this chapter, the sector itself is characterized by certain prevailing orthodoxies and cultural norms. Critical to any digital transformation within AEC businesses is the combination of digitization and asset knowledge. Alphabet's Sidewalk Labs has become the cautionary tale to sector entrants that fail to recognize the impacts of fragmentation and operational orthodoxies, when attempting to delivery construction practices in new innovative ways and using approaches that are not common to the sector. Sector regulation (such as zoning and planning processes), design standards that rightfully ensure the safety of construction projects, design principles, and orthodoxies exist and are very difficult to break down. The balance still needs to be struck where innovation is enabled, within the framework of processes that exist to assure construction project outcomes.

Key to this will be encouraging established industry players to invest further into research and development, innovation, and experimentation. This is a key tenant that needs to be embraced by the cultural architects within the sector and embedded by the organizational champions. The only way the AEC sector will successfully transform, innovate, and build new business models, and become effectively digitized is through embracing a culture of experimentation, allocating time and resources to research and development efforts, and investing in the capabilities that will enable these to thrive within their new culture.

3.8 Conclusion

The resilience and sustainability of the construction industry are at stake. This is not an over-dramatization. While Alphabet's Sidewalk Labs may have mothballed their ground-breaking digital construction project in Toronto, it represents only the "bleeding edge" of sector digitization—new entrants engaging more agile practices, experimentation, and with the risk-appetite to invest in new processes will emerge in the sector. The construction sector is being digitized now and has been on the path of digitization for over a decade. This will now accelerate as new entrants take hold, as new ways of working emerge and influence clients, and as stakeholder expectations influence further how the industry operates within the market. The construction industry needs to embrace—rather than resist—these changes by engaging in holistic business strategies that have cultural transformation as a central tenant and that ultimately leads to defragmentation of the sector.

Cultural change needs to occur at the both industry level and within each organization driven by visionary cultural architects and embedded by organizational champions who are enabled to operationalize the changes necessary to digitize the sector. AEC businesses need to engage practices and strategies that are both holistic and engaging in order to create real impactful change to the culture and organizational design. This is necessary for new business models to emerge and thrive, and for current players to evolve into resilient portfolio businesses.

As Peter Thiel writes in the first sentence in the preface of his book Zero to One (2014), "Every moment in business happens only once." The authors strongly believe that, for the AEC industry, this defining moment is now. Even before the COVID crisis occurred, signs were showing cracks in the entire industry. The tipping point had been achieved: reverting to "business as usual" is no longer an option. To become more resilient and sustainable, organizations in the AEC sector need to take action to adopt new business models, adapt to new ways of working, and build new cultural norms. If they do so, they will be able to continuously navigate and succeed in this state of "business as unusual" that digital disruption presents. As venture capitalist Marc Andreessen explains in his essay It's Time to Build (2020), "Part of the problem is clearly foresight, a failure of imagination. But the other part of the problem is what we didn't *do* in advance, and what we are failing to do now."

Data is transforming our world and fostering innovation through technology alone is not enough. Processes that were previously disconnected are converging, enabling new forms of collaboration, and opening new ways to create value. This convergence will change how things are made, it will shift traditional value chains, and it will continue to blur boundaries between players and even industry sectors. Leaders do not simply respond to the shifting landscape, they take their destiny into their own hands: build new portfolio of businesses, experiment new ways of working, and ultimately shape their future landscape. This is how they try to anticipate the unknown.

Independent of technology, the authors harbor no illusions about the status quo in the built environment. To a considerable extent, the pursuit of digital transformation in the AEC industry today has already collided with the limitations of existing procurement models, standards, and insurance models. Hybrid players are gaining importance, but they keep struggling with the same obstacles. AEC firms willing to embrace circular economy struggle with these challenges every day. Innovation must clearly happen in the contractual space as well.

For now, what will be the greater catalyst to digital transformation? As seen in Fig. 14, at the level of an organization, what matters most is to build a resilient model.

- Build the right platform, because a platform is the modern way to run a business.
- Expand the portfolio of business models, because a digital platform cannot be run like a traditional business.

Fig. 14 Four key elements to build a resilient business (*Source* New Business Models and Digital Platforms in Construction 4.0, Olivier Lepinoy, Autodesk University, November 2020)

- Build the right ecosystem, because what matters in the digital economy is the readiness and maturity of an organization's ecosystem.
- Nurture the right culture, because corporate culture, as much as technology, is a competitive advantage.

Some building blocks for a large transformation in the industry are emerging. International process standards, building and component standardization, offsite manufacturing techniques, alternative models of procurement, new forms of contracts and insurances, and increasingly globalized corporations are potentially game-changing. But as the AEC sector shifts toward more data-driven approaches, it will need to overhaul outdated processes founded on information exchange. Some foundations are already in place: cloud computing, reality capture, building information modeling (BIM), and blockchain. However, meeting the future digital needs of owners, operators, occupants, and users, while also achieving wider societal goals will require new principles on how data is created, shared, owned, managed, stored, accessed, used, analyzed, and traded. To achieve that, roles and responsibilities of the incumbent players will have to change.

As Alan Mossman said in his essay Construction is broken (Lean Construction Blog, 2020), maybe "Construction is broken." Can the AEC industry take the risk of becoming a commodity? The quality of constructed assets has progressively become uniform across the producers. Across the whole industry, it is hard to differentiate one product from another, one player from another. The economic value of the assets built is now hard to distinguish in the eyes of the clients and the end-users. Decision-makers, all along the value chain, tend to buy the cheapest. Consequently, almost all companies fight for price only and the added value they bring is always hard to recognize. As illustrated in Fig. 15, firms with serious plans for their future need to

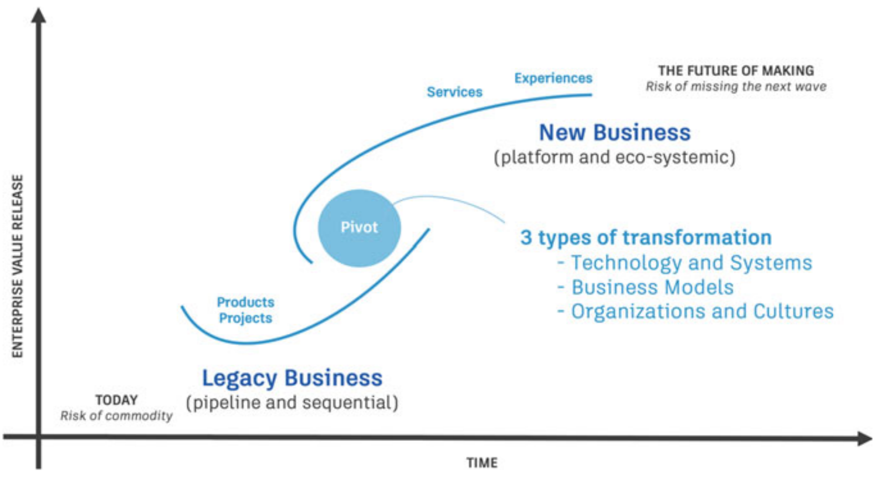


Fig. 15 Future of making in AEC and what pivot means (*Source* Olivier Lepinoy)

make a step change: implement the relevant technologies, operate changes in their business models, develop new organizations, and reinvent their culture.

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Chapter 16
The Next Engineers—Equipping Industry for the Future of Construction

Dan Bergsagel and Phil Isaac

Abstract The construction industry is often classified as the world's largest ecosystem. Like other ecosystems, it must adapt to changes, such as the climate emergency and Industry 4.0. To ensure the industry can adjust dynamically to these drivers of change, we need to make sure that the next engineers are equipped with the necessary skills to manage the challenge. First, we need to understand which future skills these engineers will need. This chapter presents the key skills that we believe will be needed to respond to the coming changes of Industry 4.0 and the climate emergency. Second, we need to understand whether these skills are taught currently, and if not, how to introduce these skills into the next engineers' training. This chapter presents a review of contemporary and recent engineering curricula in the UK, the skills and content recently added to curricula and proposals for future additions on the longer-term scale. Finally, as the training provided to engineers changes, the workforce will begin to divide into an older cohort which received 'traditional' training and a younger cohort which received 'future-thinking' training. This dichotomy presents both intergenerational training opportunities and management challenges in organising a workforce with a non-uniform core skill set. This chapter proposes methods to navigate the changes within the industry to improve knowledge sharing, as well as opportunities to reframe engineering in the public mind set to expand and diversify the engineering workforce beyond its existing limited size and demographics.

Keywords Next engineers · Future of construction · Industry 4.0 · Skills · Teaching and education · Workforce

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_16

1 Introduction

An ecosystem is a community of organisms that interact with their physical environment to form an integrated system, encompassing material flows and energy transfers. Ecosystems reach temporary states of equilibrium, but are controlled by internal and external factors and must respond reactively to these changes; whether short-term destabilising events—drought, hurricanes, wildfires, disease—or longer-term structural events, such as rising sea levels and climatic shifts.

The complex network of relationships that an ecosystem describes can be in our natural world, or the human-controlled world. The global construction industry is perhaps the world's largest ecosystem (Ribinheiro, 2020). As compared to natural ecosystems, our man-made construction ecosystem operates on material flows, energy transfers and information. This information is parsed by engineers, and engineers act based on this information. In this sense, engineers are the primary regulatory mechanism of the construction ecosystem; who they are, what they know, and how they respond to this flow of information is crucial to the success of the construction ecosystem.

Just as with a natural ecosystem, the construction industry ecosystem must adapt to short-term factors—recessions, government policy—and longer-term changes, such as the climate emergency and Industry 4.0. To ensure the industry can adjust dynamically to these drivers of change, we need to make sure that the next engineers who are part of the construction ecosystem—the future operators who will navigate the change—are equipped with the necessary skills to manage the challenge.

Society has seen significant change since the First Industrial Revolution, which brought about widespread economic and social reorganisation (Kuznets, 1955), as well as the birth of modern construction materials and practices (Taussig, 1900) and the founding of learned societies to formalise the design and construction process of the revolution's necessary infrastructure endeavours (The Times, 1890). During the subsequent three centuries, society has continued to be reformed, yet whilst our contemporary lives are fundamentally shaped by the electronics and digitization of the Third Industrial Revolution which began in the 1960s (Robinson et al, 1997), civil engineering practice has changed comparatively little since the Second Industrial Revolution.

The core work of a civil engineer was established in the early 1800s and modernised rapidly between 1870 and 1920 (Bonshek, 1988); however the project types, construction materials, design processes and construction methods of the 1920s largely endure in our work in 2020. Figure 1 graphically approximates when key changes in engineering occurred, and the general trend of development and change. The graphic is split into construction materials, project types and design and construction processes. Clusters of significant change have been circled. Three occurred during the Second Industrial Revolution and are interconnected: the industrialization of reliable and mass-producible construction materials, the refinement of engineering theory and associated change in scale and ambition of project types. These

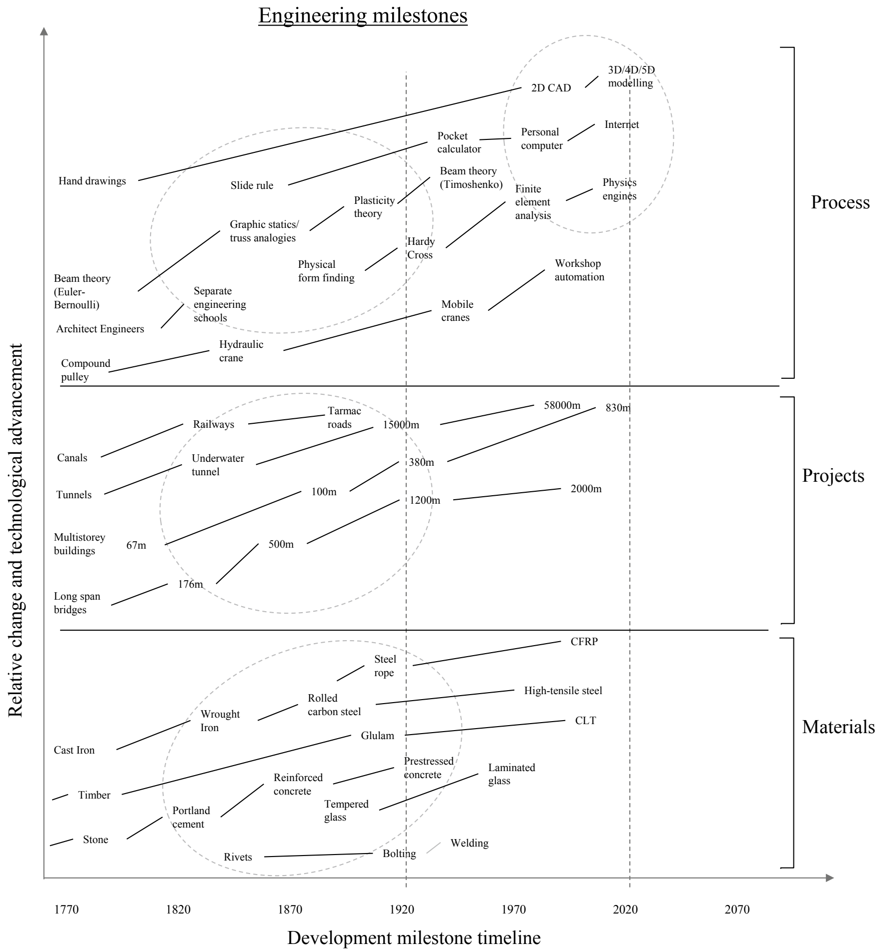

Fig. 1 Consistency and change during 250 years of civil engineering (Authors' Original)

moments of radical change were largely complete by 1920. The subsequent incremental development in engineering practice over the last century has been matched by a similarly consistent curriculum of skills and knowledge in which engineers are trained. University and construction-site skills have not needed to adapt significantly over this time.

However, the Third Industrial Revolution has had a significant impact on engineering practice in the field of design processes: particularly the development of personal computers, spreadsheet software and finite element analysis (the 4th and most recent cluster in Fig. 1). The significance of this change in engineering design is exemplified by the Sydney Opera House project completed by Ove Arup and partners and the change over the seven year project lifespan from physical modelling and hand calculations to computer processing (Trafas White, 2016). However, beyond a reactive recent emphasis on teaching computer coding skills and proficiency in 3D drawing and modelling—and parallel movements to ensure that qualitative analytical skills are not lost during these changes (Brohn & Cowan, 1977)—defining the required skills of the next generation of engineers has not been seen as an existential question. Today, we are facing two paradigm shifts in civil engineering—the climate emergency and the advent of Industry 4.0—and we must urgently update and redefine the necessary skills required to equip the next engineers to continue to work for the future benefit of society in this brave new world.

Whilst the civil engineering of the past 100 years may be comfortingly familiar, we expect the civil engineering of the next 30 years to be uncomfortably unfamiliar. To paraphrase L.P Hartley: the future is an unknown country; they will do things differently there.

The objectives of this chapter are to explore how the engineering community can prepare for this change. This chapter presents the key skills that we believe will be needed to respond to the coming changes of Industry 4.0 and the climate emergency. It then presents a review of contemporary and recent engineering curricula in the UK, the skills and content recently added to curricula and proposals for future additions on the longer-term scale. Finally, it proposes methods to navigate the changes within the industry to improve knowledge sharing, as well as opportunities to reframe engineering in the public mind set to expand and diversify the engineering workforce beyond its existing limited size and demographics.

2 Industry 4.0 and the Climate Emergency

The impact of Industry 4.0 is the continuation and expansion of the 4th cluster of change in Figure 1 related to digitization of the design process. Based on previous progress in the last 30 years, our dependency on technology is only going to increase in the next 30 years. However, this trend is predicted to broaden and lead to significant changes to the functioning of the industry (Ribineirho et al., 2020). Graduates will be entering a workplace demanding skills in areas such as digital design, coding and digital-based communication. Following the experiences gained during the Covid-19 pandemic, shifts in workplace practice and digital collaboration are already commonplace. However, to fully understand the skills required of the engineers of the future workforce—the next engineers—we must first understand the major changes that the engineering industry will face: demands for improved productivity and reduced risk, addressed by the many components which make up Industry 4.0; and the climate emergency, whose decarbonising impetus will affect every aspect of our work in the construction industry, and an engineer's place in the wider economy.

The construction industry has a reputation as a technological Luddite, lagging behind most other industries in adopting new methods of working (Hastie, 2019). Productivity growth in construction has remained at a third of that of the wider global economy (Barbosa, 2017). The overall slow rate of change in construction is in contrast to individual aspects of engineering which have adapted almost unrecognisably, such as the dependency of today's engineers on computational modelling, digital drawing packages and BIM. Construction is important: the construction sector is estimated to contribute 11% to global GDP, a figure that is only expected to grow (Roumeliotis, 2011). In the UK, construction is estimated to be worth 6.5% of the UKs GDP and to provide 6.3% of UK jobs (Infrastructure and Projects Authority, 2016). To counter this lack of progress, successive governments have sought to reform the industry through reviews and high-level policy statements. Of particular relevance is the farmer report 'Modernise or die' (Farmer, 2016) which focussed on the labour model for the construction industry whilst also touching on low growth in productivity in the sector, and the industrial strategy report 'Construction 2025' (HM Government, 2013).

Both reports reached the same core conclusion: that the construction industry needed to embrace digital technologies if it is to be able to meet the needs of society in the coming years. 'Construction 2025' set the following specific targets for the construction industry: 33% lower costs, 50% faster delivery, 50% improvement in exports and 50% lower emissions. The farmer report (Farmer, 2016) made numerous recommendations covering the wider labour market and economic model of the construction industry, drawing particular attention to: on-site factories and pre-assembly, industry wide adoption of design for manufacture and assembly (DfMA) principles and pre-manufacturing capabilities and BIM-enabled collaboration.

The top-down call to embrace the tools and methods of work of Industry 4.0 was clear and to some extent successful. BIM has been mandated and implemented to varying degrees of success (HM Government, 2015), and some on-site factories have been piloted, such as the six-storey 'jump factory' developed by Mace—a moving canopy and gantry crane that provides the benefits of an indoor construction site at the top of a tower under construction (Byrd, 2020). However, the action has been less dramatic than might be expected. This is partially related to the lack of the bottom-up ability to do so, as the workforce of the next engineers is largely receiving training within a framework established with limited training to implement the industrial shift.

Both these industry reports must now be considered in the more recent context of the climate emergency and the building sector's outsized contribution of 38% of global carbon emissions (UN Environment Programme, 2020). As well as a moral imperative, there are new regulatory criteria to meet such as the UK's declaration of a climate change emergency and the related legislation that requires the UK to be net zero carbon by 2050 (Priestley, 2019) with a further target introduced in 2021 of a 78% reduction in CO_2 emissions from 1990 levels by 2035 (Committee on Climate Change, 2020). This has been met by a robust response from the construction industry, with architects (UK Architects Declare, 2019), engineers (Engineers Declare, 2019) and learned institutions all prioritising the demands of the climate emergency for the industry (IStructE, 2021; Thorniley-Walker, 2020). These are not only UK specific actions—globally legislation to bring countries to net zero by 2040 and 2050 is being adopted, and COP26 in Glasgow in 2021 is a further opportunity for the international community to affirm this.

Together Industry 4.0 and the climate emergency are external challenges to the status quo of engineering. They will have significant knock-on effects on the industry and the skills that will be needed. This relationship is summarised in Figure 2. These two shifts will lead to a range of new industry goals in response, such as reducing the embodied carbon of new construction or automating construction sites. These challenges and goals are shown in the first columns of Figure 2. To meet these goals, the next engineers must be versed in a range of new skills which are not currently core parts of a civil engineer's training. These skills are proposed for each industry goal and categorised into four groups: physics and mathematical skills, technological skills, communication skills and critical thinking and design skills. The skills in response to each goal are outlined in the body of Figure 2. The overarching theme is the expected broadening of skills and knowledge. This could lead to two types of engineers emerging: those with a broad overview of the varied and multi-disciplinary

Skills for the next engineers

External challenge	Industry goals in response	Physics and mathematical skills	Technological skills	Communication skills	Critical thinking and design skills
Climate Emergency	Build less	Core design skills for refurbishment, adaptive reuse and deconstruction Historic construction practices and methods	Assessment of existing structures geometry, history, integrity	Presentation of appropriate design interventions to decision making partners and organisations	Designing with complicated existing design constraints Initial approximate analysis and evaluation at stages where design decisions are most impactful
	Reduce embodied carbon	Knowledge on low carbon materials (timber, reusable system) Quantity surveying and carbon counting	DfMA and designing for zero waste. Optimisation routines to reduce embodied carbon	Presentation of technical embodied carbon information and data information to non-technical partners and organisations	Understanding of appropriate design lifespans and the impermanence of structures
	Reduce operational carbon	Understanding embodied carbon associated with production, fabrication, erection and deconstruction			Design problem setup for multiple weighted constraints
	More extreme weather	Knowledge of building physics and interaction between operational and embodied carbon	Statistical analysis to understand weather models for future changing loads (temperature, snow, wind, rain)	Summary of statistical long-term prediction information to non-technical audiences	
	More adaptable building codes	Requirements of incremental maintenance and structural upgrades			Divergent thinking to enable future redesign for changing requirements
Reduce risk	Vertical integration of supply chain	Understanding of the theoretical basis of fabrication methods and their impact on design and execution		Methods of communicating with multiple other parties	Methods of creative thinking and collaboration with multiple other parties
	Automated construction sites			Cross-cultural communication for international supply chains	Designing for specific fabrication methods, and DfMA
	Offsite manufacture	Developed understanding of new material properties	Use of 3D design and modelling software	Producing construction information in formats directly interpretable by machines/fabricators	Designing for novel erection processes
Improve productivity	Digital manufacturing	Developed understanding of structural system behaviour of calculation models/FE analysis and coding	Linking 3D design to manufacturing		Designing for specific new and diverse materials
	Automated/ A.I design routines		Fluency in computer sciences, machine learning and coding algorithm setup Site data collection and reprocessing	Open source data sharing Digital communication methods - on screen sketching, 3D modelling, AR/VR/XR	Categorising problems into repetitive tasks and bespoke tasks
	Quantitative analysis of performance	Greater levels of statistical knowledge and data processing	Post occupancy data collection and reintegration of real life data into design	Statistical data analysis and presentation skills	

Fig. 2 Predicted required skills for the next engineers (Authors' Original)

aspects of the engineering profession, similar to the integrator role in the ICE's Project 13 framework (ICE, 2021) and specialists with a strong expertise in a smaller subset of the identified areas. It may also be that more T-shaped engineers emerge with a broad knowledge across the wider professional skills but with a deep knowledge of one particular area (Johnston, 1978; Neeley & Steffensen, 2018).

The broadening of skills is of interest in the historical context. If we take mathematical skills as an example, students graduating 30–40 years ago would have been entering a profession where much of the analysis was done by hand using advanced mathematics. The changes since the 1970s have reduced this hand calculation and replaced it with a greater reliance on technology and finite element analysis methods, such that these are now widely accepted as the primary analysis tool for all but the most simple of situations (Open University, 2016). With this rise in computational solutions, a continuing emphasis has also been placed on ensuring proper questioning and a qualitative understanding of the computational results (Brohn & Cowan, 1977). It is anticipated that this will further shift with a much greater emphasis placed on understanding and knowledge in coding, which will be required as processes become more automated, supply chains shorten, and there is greater integration of software. For many larger consultancies, this transition is already underway with in-house computational teams developing scripts and software to integrate various elements of processes which drives efficiencies in the design process.

Whilst the ubiquity of personal computers in society has carried through to an engineer's design processes, other recent societal shifts have been less well incorporated, such as the prevalence of big data as a tool: for design, informing design with large data sets; for evaluation, collecting data to verify the success of work and inform future work and for motivation, presenting results and information in a concise and comprehensible way to explain the logic for certain decisions. Engineers are not currently equipped with the skills to process large data sets—or pass judgement on the reliability of the collection method and contents of these data sets—whether it is meaningful statistical analysis or the presentation of data-based conclusions.

Technological skills are also expected to combine with a range of other skills such as management, leadership and communication as the engineering profession continues to adjust its role within the construction ecosystem. Management and leadership skills have always been required to found, grow and manage independent engineering companies; however, the scope of these skills may need to extend into other industries and fields as engineers work within more complex projects and provide technical leadership to ensure safe and efficient adoption of novel and unfamiliar technologies in design and on construction sites. As the industry changes, engineers will be required to communicate those changes clearly to other parties and partners, explaining without technical jargon why things are changing and how they will change.

Another key expected combination of technological and communication skills is in the closer link between design and manufacturing, harnessing the concepts of Design for Manufacture and Assembly (DfMA) or additive manufacturing (Ribineirho, 2020). At present, many engineers lack the skills and knowledge to fully embrace the fabrication and manufacturing aspects of DfMA, given that their education would typically focus on the design side. This will require engineers of the future to be trained in these skills, or workers with this experience will need to be recruited from professions where DfMA is more widely adopted, such as the automotive, aerospace or naval industry and product designers.

Industry 4.0 presents opportunities to improve productivity and execute design and construction in a more holistic and controlled fashion. The potential for change is significant; however, it is change that is largely motivated by the industry responding to competitive market pressures to reduce time, risks and costs and to improve quality of design, fabrication and erection. The climate emergency is an existential external challenge to the construction industry and civil engineering's primary occupation of building new structures. To meet society's net zero targets, we must build less, and what we do build must contain less embodied carbon. These twin requirements bring to the forefront a change in mathematical, physics and materials science knowledge and a significant focus on critical thinking and design. These skills will focus on analysis of existing structures, refurbishment and adaptation as we deal with more challenging, variable and unknown design constraints. New structures will need to utilise renewable and low carbon materials, and engineers will need to understand whole life cycle carbon assessment and the implications of circular economy principles on designs to allow for assembly, deconstruction and material reuse.

More broadly, there will be a demand for new innovative solutions. The industry has traditionally followed a route of incremental cautious development instead of entrepreneurial start-up change. In this regard, the industry must work harder to increase diversity in the profession and allow new ideas and innovations to flood into the industry and greater opportunities for knowledge sharing, collaboration and the potential for recombinant innovations. An example from a different sector would be the combination of photography and location mapping to create Google Street View, which revolutionised how we interact with unknown environments and route planning (Campanella, 2017). Achieving this will require companies to be less protective of their data, working methods and in-house knowledge and instead more open for sharing, collaboration and learning from those outside their traditional zone. Achieving innovation will also require flexibility and longer-term thinking from clients in their procurement. To facilitate innovation may require upfront resource investment for future benefits, instead of short-term minimal capital expenditure and always awarding contracts to lowest-cost providers without considering other benefits and parameters.

To confront the challenges, we face will also require a greater focus on solving larger and more complex problems which will require engineers to think creatively whilst working in larger and even more multi-disciplinary teams. This will require greater emphasis to be placed on communication skills where engineers will be required to interface with both the design team and the manufacturing team. Virtual and augmented reality have been trialled as ways of aiding team working, and the use of these technologies can only be expected to grow. The use of these technologies will require engineers to be proficient in 3D modelling techniques—either creating models as designers or viewing, tagging and editing models as constructors—potentially linked with parametric design, such that they can maximise the benefit of these working methods.

3 Teaching and Education

The engineering industry relies on two primary routes to train the next engineers: university and apprenticeship. Together, these paths provide students with the core knowledge and skills they need to perform design, construction and management tasks.

What is taught to the next engineers is partially decided by individual institutions, but largely regulated by national regulating bodies. If we take the UK as an example, the core requirements of accredited Bachelor's and Master's degree programmes are controlled by three documents and the groups which draft them: The UK Standard for Professional Engineering Competence (UK-SPEC), the Accreditation of Higher Education Programmes (AHEP) and the Joint Board of Moderators (JBM) additional guidelines. UK engineering apprenticeships are controlled by UK-SPEC and the Approval and Accreditation of Qualifications and Apprenticeships (AAQA). Together, these groups outline what knowledge and skills are required to be taught at university to become a Chartered or Incorporated Engineer (CEng, IEng) registered with the Engineering Council and define the core skill set of the profession. The Engineering Council represents the UK in organisations that facilitate mobility of engineering professionals internationally, such as the International Engineering Alliance (IEA) and the European Federation of National Engineering Associations (FEANI) (Engineering Council, 2021a, 2021b, 2021c).

Aside from variation amongst the forest of acronyms, this method of defining the training of the next engineers is globally accepted. Similar approaches are applied across the world, such as the National Council of Examiners for Engineering and Surveying (NCEES) in the United States of America. In summary, a group of regulatory institutions define the knowledge and skills content of an education to become an engineer, and rely on different institutions to implement that skill set. The goal is 'to meet the engineering and technological needs of today, whilst also catering for the needs of future generations'. (Engineering Council, 2021a, 2021b, 2021c). The remainder of this section will focus on the framework for training engineers through the university route; however, we would like to emphasise that the apprenticeship route is of equal importance to the industry, and many of the conclusions drawn from review of the university route are also applicable to apprenticeships. We expect a diversity of people working together to be a crucial aspect of the role of the next engineers.

The university accreditation guidance, by design, avoids being over prescriptive to provide leeway for educators to teach with different focusses and different teaching methods. The UK-SPEC and AHEP learning outcomes approach utilises a broad framework for general engineering with sufficient scope for interpretation structured around: knowledge and understanding; design and development of processes, systems, services and products; responsibility, management or leadership; communication and interpersonal skills; and professional commitment.

This approach also allows for innovation and diversity in how the teaching is provided, whether learning through physical experimentation and analysis such as at the University of Cambridge, through design exercises and industrial placements such as at the University of Bath, or through problem-solving learning approaches such as at University College London (Graham, 2018). Within this flexible framework, the approach functions well for already established and existing core learning topics that meet the needs of today, such as analysis and design of concrete and steel structures to existing codes of practice. This accreditation approach functions less effectively when discussing what new and developing content is needed to meet the needs of future generations of engineers, such as automated fabrication or a focus on adapting and upgrading existing infrastructure. The authors believe this lack of over-prescription in accreditation is a net positive—it allows educator's flexibility and independence—yet challenges with predicting and preparing for an unknown future tend to encourage universities to provide education overly based on the requirements of the past, and additional support could be provided in this field.

Out of the suite of guiding documents for engineering training at university, the JBM guidelines for developing degree programmes provide the most targeted guidance for civil engineering degrees, and the latest version of the guidelines (JBM, 2021) is applauded for its forward-thinking encouragement of knowledge and skills, in particular with regard to the climate emergency—exemplified by the introductory statement to place the 'Climate Emergency as a very necessary central cultural feature in the education of civil engineering students' and the accompanying guidance on the low carbon agenda. However, do these guidelines anticipate and prepare training for all the skills we believe the next engineers will need? And if not, what other skills should we add to close this skills gap?

Engineering education extends significantly beyond the UK and the JBM's purview: not all engineers complete degrees, and most of the world's engineers study outside the UK. However, if we use the existing UK University engineering education framework of the JBM guidance, we can highlight: which skills required for the next engineers are currently being taught, which skills required for the next engineers should be added to curricula, and at what stage and method of education these skills should be taught.

In Figure 3, we categorise the anticipated necessary new skills highlighted in Section 2 onto two axes: the first is the learning stage the skills could be introduced (from high school to early career), and the second is a timeline for when the skills are to be introduced in the training of the next engineers. The skills have been formatted based on which annex of the JBM's guidelines they are outlined in and placed on the timeline according to typical adoption in UK university engineering curricula. The resulting new skills are collected into six groupings, which broadly divide the new skills into categories related to either the skill type (column headings from Fig. 2,

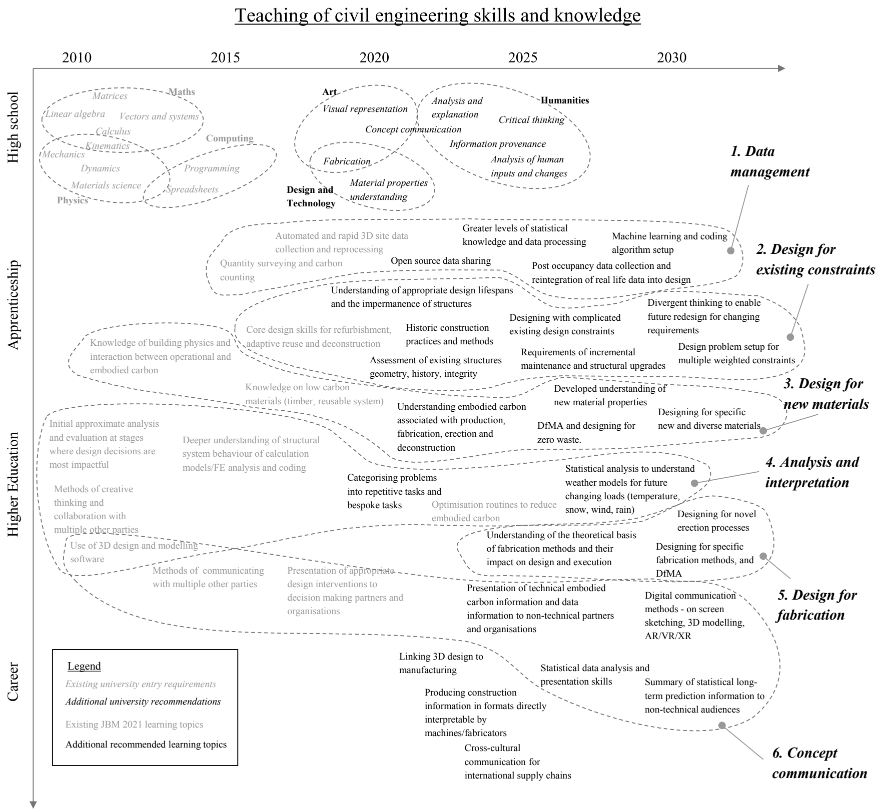

Fig. 3 Skills for the next engineers—current and future curriculum changes (Authors' original)

i.e. Technological skills) or the industry goal (row headings from Fig. 2, i.e. build less or with less embodied carbon).

Of the core skills, we anticipate will be important in the developing engineering industry; a number have already been emphasised in an engineer's training recently. The last decade has seen the continuing importance of an understanding of concepts of system behaviour, interpretation and understanding of calculation models, initial approximate calculations to facilitate design decision making (Ibell, 2019) and an emphasis on communicating in teams and creative thinking in collaboration with others (Reiter-Palmon & Leone, 2019), both in person and increasingly virtually, particularly post 2020. These skills are part of a general understanding in the engineering profession that the added value of engineers is shifting from situations where rigorous calculations are completed manually, and towards a scenario where engineers establish problem boundaries, seed different potential solutions and interpret and evaluate their outcomes (ASCE, 2013). This 'Analysis and interpretation' grouping (group 4, Fig. 3) must continue to develop, enabling the next engineers to decide on appropriate calculations, establish the key design parameters and interpret the results.

Of the skills that are being newly promoted in the training of the next engineers, many skills relate to the climate emergency. This includes the ability to evaluate embodied carbon and global warming potential of projects, the future importance of reuse, recycling and the possibilities of retrofit and the understanding of using new suitable materials. We believe these groupings of ‘Design for existing constraints’ and ‘Design for new materials’ (groups 2 and 3, Fig. 3) are crucial skills for the next engineers, and require significant priority and elaboration in training plans. An understanding of low carbon materials has been proposed as an important step for the education of engineers; we propose that this should be augmented to lead to more training in the design for renewable materials like timber, but also an understanding of the production and fabrication process of different materials and material systems to enable further reductions in embodied carbon and the integration of circular economy principles. Whilst there is some discussion of retrofit and reuse, we believe there is a need to have a better understanding of historic construction practices and how to work with existing structures for future development, as well as the associated critical, divergent thinking and creative problem solving that successful interventions on existing structures require. In a future world, where we must build less (Hurst, 2019), having a deep understanding of our existing structures is vital. We expect this to be a paradigm shift in the work of the next engineers (UN Environment Programme, 2020).

There are nascent proposals to better align the skills of the next engineers with changes related to Industry 4.0. The next engineers will require development in ‘Data management’ (group 1, Fig. 3) for collecting and processing large amounts of source data, whether that is through evaluating and sharing information about their own designs (carbon counting and benchmarking) or through evaluating data collected from construction sites or buildings in use to inform their future design processes (site surveying, algorithmic and statistical processing). A key aspect which is not a focus of current training proposals is a better understanding of new fabrication and erection methods related to offsite manufacture, digital and additive manufacturing, ‘Design for fabrication’ (group 5, Fig. 3). The fabrication process itself has a significant impact on material properties and what can be achieved in terms of design and erection, and we believe better theoretical understanding of the mechanics of these processes will be important, as well as opportunities to understand from real-life experience what can be altered.

The last grouping of necessary skills for the next engineer is ‘Concept communication’ (group 6, Fig. 3). This is a route which has been understood as a core skill for engineers for some time, related to an engineer’s role as a manager and member of larger design teams. As the role of an engineer develops within a design and construction team, and as engineers gain more prominence in key early decision-making related to the climate emergency, the next engineers will need to be proficient in communicating their concepts to a wider audience. Future communication methods should develop skills such as presenting technical information to non-technical audiences, being equipped to use new visualisation techniques such as augmented reality, as well as explaining the results of large data sets in statistically meaningful ways.

Many of these skills are well-suited to being taught in an academic environment in higher education institutions. However, there are two constraints which limit how this can be done: the limited duration of a training programme—whether that is a degree or apprenticeship—and the available skills and experience of the instructors of the training—whether academic at the exclusion of applied skills, or applied skills at the exclusion of academic. One approach would be to spread the acquisition of the skills of the next engineers over a broader time-period, starting in high school and continuing into early career stages. At the high school level, this would encourage engineers to have a broader educational background, encompassing design and technology, arts and humanities (Isaac & Bergsagel, 2020). This would provide the next engineers with the key skills in communicating and representing information, as well as an understanding of practical construction methods. This would have a direct impact on the 'Data management' and 'Concept communication' skill groupings. The early stages of an engineering career are an excellent opportunity to continue to develop skills in the 'Concept communication' grouping based on real examples of team and client interaction, with the support of engineers with some practise in this field. An earlier focus on computer programming skills at high school could liberate time for teaching other things at university. By spreading the teaching of some of these more general skills over a broader time-period, universities can still commit time to specialisation in technical content streams.

The limited duration of training opportunities also leads to demands of prioritisation of study. The impression is that the standard engineering curriculum is always full, and to allow for teaching, new skills would require removing important topics. Whilst a solution to this is challenging, we would suggest that change is coming. In some instances, re-prioritisation is straightforward, and a focus on new and natural materials could be at the expense of a partial reduction in focus on traditional materials like steel and concrete. The promotion of embodied carbon assessment can be as an alternative to a focus exclusively on weight reduction or simplicity in construction. A shift to using new digital representation techniques can be at the expense of traditional draughting training. Another approach could be to consider the training of the next engineers as a longer process which links across these three learning stages—high school, further education, career—and continues in a structured format into the early stages of a career, not dissimilar to an architectural part II. There is also the opportunity to specialise in a subcategory of engineering earlier, or to extend the academic training stage to be longer than the current 3 + 1 Master of Engineering (MEng) qualification.

4 Existing Workforce

Thus far, we have highlighted the coming changes to the industry and their novelty in the context of the last century of civil engineering practice; we have discussed the range of skills that the next engineers will need to deal with these changes, and we have reviewed which of these changes are already being introduced in the UK, and which can be further promoted in the UK and abroad. However, it is clear that if these new skills are only being introduced into an engineer's training now, the existing engineering workforce which has not received this training will not possess these skills sufficiently and broadly. This will lead to a stratified workforce and will present both challenges that the industry must mitigate, but also real opportunities that the industry can exploit.

The primary challenge of a stratified workforce is the lack of shared experiences between the next engineers trained in these new skills, and the teams and managers that they will join in industry. The existing workforce may not understand how best to take advantage of the new skills set (Wallace & Creelman, 2015); managers may be disheartened when noticing that some previously taught skills and knowledge are no longer covered in an engineer's training. If teams and team leaders are not aware of the value of new skills that embrace Industry 4.0 and address the climate emergency, then the skills will not be effectively applied to help solving engineering team problems.

In addition to a stratified workforce, if training in these new skills is only provided to the next engineers starting today, then there will be a delay of 20–30 years before these engineers are in positions to make informed industry decisions. This generational cycle of knowledge can lead to delays in the industry responding robustly to the external challenges, and slower adaptation could bring long-term degradation to an engineer's position in the design and construction process. Without contemporary leadership, understanding the industry changes and potential application of new skills in response, engineering as we know it could see reduced investment, a loss of influence and job flight into adjacent construction industries, in a manner similar to the collapse of the New England Whaling Industry in the 1860s when faced with international competition, technological development and increased competitor productivity and the advent of petroleum products (Thompson, 2012).

Some reports indicate that the engineering industry is already in decline, with skills shortages and skills mismatches in STEM subjects a recurring challenge in the UK (National Audit Office, 2018). Many business leaders already rank their ability to recruit skilled staff as their number one concern when growing their business (Cappelli, 2019). Ensuring that the next engineers feel welcomed and valuable in an industry which may be out of step with their skills may be crucial.

The mix of young engineers with new skills and older engineers with more traditional skills and knowledge presents a significant opportunity for cross-education. If an atmosphere of mutual learning is fostered, then young engineers can continue their education during their early careers through project interactions with their team members on real design challenges, and older engineers can realise efficiencies and maintain a breast with newly developed technologies and processes (Bersin & Chamorro-Premuzic, 2019). Indeed, with so much technology at their disposal, the next engineers will need assistance and perspective in assessing the appropriateness of the information, systems and technologies at their disposal—whether through the reliability of raw data or the suitability of computational outputs. This will require a deep understanding of engineering principles which can be provided by mentorship with members of the existing workforce.

To avoid workforce stratification and instead achieve workforce stability, a concerted industry effort should be made to ensure that an atmosphere of openness and continuous mutual learning is provided. This can be done in a number of ways:

4.1 Internal Company Training

Large organisations have the resources and facilities to invest in retraining staff, to both understand the impact of the changes in the next engineer's skill set, as well as to promote some of these skills. This can be done through structured learning between new career entrants and existing team and group leaders or through hiring external trainers to facilitate sessions. Companies have incentives to do this to maintain market position and to demonstrate a willingness to adopt new work methods to their new recruits. Indeed, many large consultancies are already beginning to embed aspects of Industry 4.0 in their workflow (Cousins, 2021; Mann, 2018; Rolvink et al., 2010).

However, as much as 80% of the registered engineering enterprises in the UK have four or fewer employees (Engineering UK, 2017). These small businesses do not have research development and continuing development budgets to tackle further retraining, and changes to working methods may be unaffordable or incompatible with the existing staff skill set. Reaching these companies and individuals is therefore essential if the industry is to fully witness the benefits of Industry 4.0.

4.2 New Targeted Continuing Professional Development (CPD)

Smaller enterprises may not be able to organise their own internal training; however, they can take advantage of available CPD to ensure lifelong learning. Learned institutions such as the ICE and IStructE can emphasise these new skills in their training development and promotion to ensure that all practicing engineers understand the importance of these changing skills, even if they are not proficient in them. This emphasis has begun to emerge recently with regards the climate emergency, with the IStructE's commitment to provide freely available technical resources, and the ICE's 157th President Rachel Skinner's focus on Net Zero (Skinner, 2020). In this regard, more can be done to promote Industry 4.0, and we expect to see further development in training packages offered to practicing engineers that provide introductions to key developments in technology and fabrication techniques to allow engineers to stay abreast of new opportunities in design and construction.

4.3 Knowledge Sharing Facilitation

For small and medium enterprises (SMEs) who are unable to provide in-house retraining to their staff, institutions could facilitate sharing of knowledge within the industry by developing platforms and local training forums that are beyond those organised by themselves. This could be in the form of greater incentives for knowledge and skill sharing through grants and awards or through enabling pooling and sharing of resources that allow SMEs to reduce their exposure to risk when investing in new technologies or working procedures. The onus to share knowledge related to tackling the climate emergency should already be familiar to signatories of UK Engineers declare as one of the key commitments of the manifesto.

4.4 A Return to the Classroom

A more structured approach that would allow for the partial retraining and learning of new skills instead of the high-level awareness of them could be provided by longer-term training courses. This could be realised through government funding for intermittent training in a classroom, technical school or university environment. This would allow for a more coordinated adult-learning curriculum to be developed in these new schools and might also provide opportunities to develop closer ties between industry and academia.

Courses which are completed entirely through evening study—such as at Birkbeck, University of London—provide a long-term successful template for managing part-time training (Birkbeck, 2021). The Open University has successfully led the field in distance learning for over 50 years (Open University, 1969); however, previous barriers to online learning have been overcome, and acceptance of online learning has been widely gained by students and society during the COVID-19 pandemic (Lockee, 2021). Training providers that are not directly linked with academic institutions—massive open online courses (MOOCs) such as Coursera or LinkedIn Learning—have seen significant growth in use over the last year as working patterns shifted online (Shah, 2020). Remote learning courses of both academic and MOOC types are expected to expand in number rapidly and may be able to address key topics related to Industry 4.0 and the climate emergency in more depth in the near future.

4.5 Public Acknowledgement

Organisations that respond to the changes of Industry 4.0 and the climate emergency are expected to be rewarded through growth and development in their competitive market. However, in addition to these organic rewards, additional acknowledgement can be provided to engineers that retrain and apply these new skills at a holistic level to new projects through industry awards and accolades. Annual company rankings such as the NCE 100 can prioritise specific technological innovation in design and construction methods and embodied carbon and refurbishment. This process has begun with the new Structural Award categories for Zero Carbon and Minimal Structural Intervention (IStructE, 2021).

If this environment of continuous mutual learning is provided, there are opportunities for more serendipitous effects to come about. When changing the skills of the next engineers and retraining the existing workforce, there will exist more opportunities to retrain engineers from other adjacent industries. New engineers from a diverse range of other industries can reinvigorate engineering through cross-pollination and actively develop the adoption of change. This retraining approach could learn from other industries such as journalism, who bring in staff with specialist skills and knowledge in a certain industry and retrain them to perform journalistic analysis of that industry.

Broadening the potential core training of the next engineers at high school to incorporate arts and humanities may lead to a more diverse range of people becoming the next engineers. This will lead to better representation within the industry and consequently more equal and just decision-making by the industry. As with the infiltration of new skills into the existing workforce with the arrival of the next engineers, this process may take decades. The opportunity to retrain new engineers into the workforce at a later stage in life can provide a shortcut to reforming the workforce to be more representative in the shorter term and to serve as valuable role models for future students considering entering in the industry.

5 Conclusion

Engineering faces two paradigm shifts in civil engineering—the climate emergency and the advent of Industry 4.0—and what we teach future engineers will determine whether the industry is able to adapt to the changing world that we anticipate. The next engineers will be the future operators of the construction ecosystem, but only if they are prepared. If we do not prepare, then we are at risk of being repositioned within the construction ecosystem; as with all ecosystems, organisms that adapt will survive, and those that do not will perish.

This summary of the skills requirements of the next engineers can be considered a broad outline for potential changes to training and curricula that could be adopted throughout the world engineering community and beyond the scope of higher education. These conclusions can be seen as a guide checklist for industry input on engineering education.

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Chapter 17
The New Generation of Construction Skills: Transition from Onsite to Offsite

Srinath Perera, Buddhini Ginigaddara, Yingbin Feng, and Payam Rahnamayiezekavat

Abstract Offsite construction (OSC) is gaining popularity against traditional onsite construction, owing to digitalised, productive, safe, sustainable, and cost and time-efficient construction project delivery. OSC embraces manufacturing and construction tasks. This integrated approach is changing the skills required to assure project success. As such, a range of traditional construction skills are being substituted, eliminated, or marginalised. The transition of onsite skills to serve offsite activities is the focus of this chapter. The comparison is based on an analysis of onsite and offsite construction skills that are implemented for distinct types of predominantly industrialised construction projects. Five cases were studied to review the skills associated with five OSC types, namely components, panels, pods, modules, and complete buildings. Research findings reveal that non-volumetric OSC types (components and panels) require a higher quantity of onsite assembly skills, compared to volumetric OSC types (pods, modules, and complete buildings). Onsite skills in volumetric projects are limited to a smaller crew to form the substructure and fix building elements or the building. Design and drafting skills using Building Information Modelling (BIM) and Design for Manufacturing and Assembly (DfMA) techniques are exemplar OSC skills that need to be developed to reduce the skills shortage in OSC projects. Moreover, new skills are recognised that need to be generated to match the increasing OSC demand. They are integrated designers, logistics managers, and OSC project managers. Educational institutions and the government, along with industry practitioners have a leading role to play in developing these OSC skills to cater for industry requirements.

Keywords Construction skills · Transition · Onsite to offsite · Skill shortage · Offsite construction

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_17

1 Introduction

Industry 4.0 is rapidly transforming the manufacturing industry, causing greater levels of smart and automated manufacturing (Schwab, 2016; Woodhead et al., 2018). This among other factors is forcing the construction industry to become more efficient and productive through the adoption of industrialised processes. The innovations in areas of artificial intelligence (AI), robots, co-bots, Internet of things (IoT), sensor technologies, big data analytics, cloud computing, 3D printing, additive manufacturing, and cyber-physical integration are driving this process of transformation (Ginigaddara et al., 2019a; Goulding & Rahimian, 2020; Newman et al., 2020; Schwab, 2016; Woodhead et al., 2018). Practically, in the construction industry, this transpires as offsite construction (OSC) (Marks et al., 2020), which is the production of buildings or building elements in a factory to be transported to the site for assembly. The construction industry is renowned for its unwillingness to embrace industrialisation, digitalisation, and innovation (Perera et al., 2017). As a result, construction has become the second-least digitalised industry next to agriculture and hunting (Agrawal et al., 2016). One may argue that a reason for such lag in technology uptake is the lack of skills (Dallasega et al., 2018), among other reasons such as cost, technology acceptance, insufficient support, poor planning ahead, and integration to existing processes (Newman et al., 2020; Perera et al., 2017).

Skill shortage has been a perpetual factor affecting the construction industry, resulting in 66% of the surveyed markets to be facing continuous skill shortfalls (Turner & Townsend, 2019). Similarly, in a social context, the unattractiveness of the industry to younger generations continuously creates skills shortage and skill gaps (Goulding & Rahimian, 2020). The post COVID-19 new normal with social distancing practices further exacerbates the issue of skill shortages (Biörck et al., 2020). The move to greater industrialisation is resulting in the creation of new skills in areas such as design automation (Design for Manufacturing and Assembly—DfMA), robotics and automation, data analysts, manufacturing and assembly, innovation, and integration (Marks et al., 2020). Despite the need for identifying and developing technology-driven offsite skills, how this demand will be addressed is yet to be recognised (Ginigaddara et al., 2019a).

Filling the skill gaps and creating paths to develop new skills call for a united forefront comprised of employers, training providers (academia), and the government (Daniel et al., 2020). The UK government has implemented such skill development initiatives by establishing institutions to work collaboratively with education providers (Brennan & Vokes, 2017). Similarly, the New South Wales government of Australia conduct collaborative research with education institutions to improve the construction industry (Perera et al., 2021). The emergence of manufacturing industry-based practitioners in OSC implies the transformational range of skills causing the displacement of traditional construction skills (Woodhead et al., 2018). As such, the universities and vocational training providers have a critical role to play in matching the contemporary trends and technologies in the industry to enhance employability through work-integrated learning, and off-campus training opportunities (Ruge &

McCormack, 2017). The Offsite-Hub in Scotland (Hairstans & Smith, 2018) and the Prefab Innovation Hub in Australia (Advanced Manufacturing Growth Centre, 2020; Penrith City Council, 2021) are such initiatives where academic–industry collaboration is evidenced.

This chapter aims to analyse both onsite and offsite construction skills that are typically required for various types of predominantly industrialised construction projects. In order to achieve this, case study methodology is adopted where five case studies are evaluated to identify the onsite and offsite skills utilised. The case studies are selected to map to a predefined typology of OSC projects. The chapter starts with a literature review of construction skills in both onsite and offsite construction. A discourse of OSC typology follows the case study review which enables the researchers to understand how construction skills evolve under the OSC approach. The contribution of educational institutions, industry practitioners, professional institutes, and government to the evolution of construction skills is reviewed correspondingly. Finally, conclusions are derived by evaluating the new generation of construction skills in an industrialised construction context.

2 Literature Review

2.1 Evolution of Construction Skills

Skill is a person's ability to perform a specific task. Generally, the meaning of the English word "skill" in the UK, the USA, and Australia is attached to predefined tasks in jobs and occupations (Clarke & Winch, 2006). Accordingly, this chapter uses the term skills to refer to job roles or occupations under both professional and vocational work categories. General construction skills can be recognised through the Australian Bureau of Statistics (2021), while an OSC-specific skillset has been differentiated through a separate classification (Ginigaddara et al., 2021b). Construction skills have extensively evolved from the beginning of time to the current use of robots as a substitution for human skills (Woodhead et al., 2018). Similarly, the evolution of construction skills is particularly evidenced through OSC, due to its potential for higher precision (Smith & Quale, 2017), efficiency (Blismas et al., 2009; Hou et al., 2020), inclusion of advanced technologies and related skills (Ginigaddara et al., 2019a; Nadim & Goulding, 2010), and optimum use of skills within shorter construction cycles (Sutrisna & Goulding, 2019). This section captures how construction skills were transformed over time, owing to the factory-based manufacturing of buildings that eclipsed traditional construction.

The transition from agricultural to industrial setting during the first industrial revolution in the eighteenth century (Schwab, 2016) engendered the "craft system" of skills in factories, which was also shared with construction and mining (Winch, 2003). However, the unique characteristics of construction projects and the mismatch between mass production and construction expectations led to a return to traditional

Table 1 Traditional construction skills

Trade profile	Skills
Woodwork	Carpenter, joiner, wood-machinist
Wet trades	Bricklayer, plasterer, mason, tiler
Roofing	Slater/tiler, roofer, mastic asphalt applier
Painting and decorating	Painter, decorator
Prefab component fitting	Partitioner/dry liner, ceiling/floor system installer, cladder
General construction/plant	Concreter, paver, ground-worker, civil engineering operative, plant operator, plant mechanic, demolition worker
Accessing operations	Scaffolder, façade worker, lightning conductor engineer, steeplejack
Building services	Electrician, plumber, heating and ventilating engineer

Source Clarke and Wall (1998)

construction with specialised skills (Nam & Tatum, 1988; Winch, 2003). Clarke and Wall (1998) proposed several trade-based construction skills (Table 1) to the UK construction industry training system by comparing the construction training programmes available in Germany and the Netherlands.

Table 1 provides a snapshot of trade-based traditional construction skills, which were most common before, and during the twentieth century. Interestingly, it recognised several OSC skills under the trade, prefab component fitting, which are comparable to onsite assembly skills in a typical OSC project. Also, construction heavily relies on Temporary Multi Organisations (TMO) with many stakeholders joining together for a short period, which is distinct to the long-term partnership arrangements in manufacturing (Kagioglou et al., 2000). TMO incorporates multi-disciplinary skills to brief, design, construct, and manage construction projects (Lizarralde et al., 2011). However, researchers anticipated a transformation of construction skills to meet the technological adaptations of the twenty-first century (Dainty et al., 2004; Gann & Senker, 1998). Although the construction industry has been dominated by the traditional setting for centuries, current industry practices witness an uptake of Modern Methods of Construction (MMC) and subsequent skill changes (Farmer, 2016). The influence of the fourth Industrial Revolution is visible in MMC such as pre-manufacturing, additive manufacturing, advanced robotics, Internet of things (IoT), and OSC (MMC Working Group, 2019; Schwab, 2016; Woodhead et al., 2018; World Economic Forum, 2016). MMC demonstrates the shift of construction skills from onsite to offsite (Brennan & Vokes, 2017).

Offsite skills portray "plug and play" actions in a factory environment (Farmer, 2016), which requires an extensive amount of digital modelling with accurate design, measurements, and testing (Gruszka, 2017) while scaling down the labour-intensiveness of construction tasks (Hou et al., 2020). Similarly, robotics acts as a convenient solution for OSC, which has the potential to substitute repetitive tasks such as material handling, welding, assembly (drilling, fastening, fitting, riveting), processing (gluing, painting, polishing, routing), packaging, and inspection (Keay, 2018). Moreover, production planning, scheduling, digital design, and logistics management skills are essential for OSC projects (Brennan & Vokes, 2017; Ginigaddara et al., 2021a). Also, product managers, robotics and automation specialists have become emerging construction skills (Marks et al., 2020; World Economic Forum, 2018). At the same time, assembly and factory workers, civil engineers, general and operational managers are set to decline (World Economic Forum, 2018). Although there seems to be a rationale for reduction of factory workers and operational managers in the long term due to advanced manufacturing and robotics, in the short term, as construction moves from predominantly onsite to predominantly offsite, these skills may still increase in demand significantly. Further, skills in civil engineering are unlikely to reduce in the short to medium term due to the trajectory of forecasted infrastructure development in the next decade (World Economic Forum, 2016).

Vokes et al. (2013) categorised OSC skills under primary (design and project delivery), secondary (contribute to project delivery—assembly of components), and tertiary (supportive functions—office administration) job roles. Furthermore, OSC skills were later recognised under six functions: digital design, estimating/commercial, logistics, offsite manufacture, onsite assembly and placement, and site management and integration (Brennan & Vokes, 2017). It highlights the need to develop a skill profile classification to recognise the OSC skills that are different from traditional construction skills (Ginigaddara et al., 2021b).

The "Construction 2020" roadmap recognised OSC as a vital future direction for the Australian construction industry, which enables the reduction of onsite labour usage with incremented factory-based manufacturing (Hampson & Brandon, 2004). The succeeding roadmap to 2030 recognises OSC as an emerging area, along with education as a key requirement in promoting OSC research in the Australian construction sector (Bok et al., 2012). With reference to OSC in the UK, Nadim and Goulding (2011) indicated the oblivious nature of construction education to industry needs, despite the huge amount of training and education provided. Likewise, it is recorded how the prevailing OSC education and related research in the USA are not aligned to reach a common goal between the industry and the academia (Smith & Quale, 2017). As a way of integrating technology into construction education, Taylor (2020) suggests including computer science, mechatronics, and manufacturing principles in construction education, which enables OSC skills development.

2.2 Onsite and Offsite Skills: A Quandary

The broad definition of OSC is the manufacturing of buildings or functional elements of buildings within a factory to be transported and erected onsite (Arif & Egbu, 2010; Goulding & Rahimian, 2020). Thus, the offsite portion includes design, manufacturing, and transportation skills, whilst the onsite portion is limited to onsite assembly skills, demonstrating the heavy reliance on design and manufacturing skills at the front-end of an OSC project (Sutrisna & Goulding, 2019). A major difference between onsite and offsite skills is the specialisation of repetitive offsite tasks, opposed to onsite assembly skills that need a higher degree of situational awareness (Vokes et al., 2013). Moreover, OSC inclines to attract more women for factory-based manufacturing, owing to the enhanced working conditions (Smith & Quale, 2017). It is proven that offsite labour costs are lesser compared to traditional construction (Sutrisna et al., 2019), which can be due to the opportunities of multi-skilling in a factory (Nasirian et al., 2019). Evaluation of manufacturing costs using multi-skilled workers, opposed to fixed-skilled workers, has proven the overall cost savings in hiring multi-skilled workers (Barkokebas et al., 2020). However, the possibilities of multi-skilling in OSC are not considered under trade-based skills development introduced by Brennan and Vokes (2017). Similarly, the current research findings elucidate the fact that OSC skills can be differentiated based on the location of processes; onsite or offsite, where offsite skills have embedded features of repetitive tasks, multi-skilling, better working conditions, and safer work environments.

2.3 Typology of Offsite Construction

Types of OSC have unique features and expected outcomes. Gibb (2001) introduced component manufacture and sub-assembly (door, furniture), non-volumetric pre-assembly (panels, pipework), volumetric pre-assembly (toilet pods, plant rooms), and modular buildings as the initial evidence of different types of OSC. This classification was later exploited, subjected to industry practices, and usage of various terminologies (Ginigaddara et al., 2019b). This chapter considers types of OSC under non-volumetric (components, panels) and volumetric (pods, modules, complete buildings) categories to evaluate how the OSC skill composition affects different OSC types. Components (doors, windows, light fittings) are the items that will never be considered to be constructed onsite, while panels (floor, wall, and ceiling panels) do not create usable space in a non-volumetric stance (Gibb, 2001). Pods (bathrooms, prisons) are repetitive items with a high level of finishing (Goh & Loosemore, 2016), compared to the modules (apartments, school buildings) which are a part of a whole building (Gibb, 2001). Several modules together create a complete building (site sheds, disaster recovery buildings). As such, the OSC skills are evaluated in a qualitative basis by considering case studies under the five OSC types.

3 Research Methodology

The case study methodology was adopted by selecting five case studies in five types of OSC: components, panels, pods, modules, and complete buildings. A purposive, non-random sample of completed OSC projects dispersed in the UK, the USA, and Australia was used for the case study review representing the prevailing industry practices of OSC. Data collection was conducted via a thorough literature review to capture case study information based on secondary data available in reports, project stakeholders' websites, and other publications. Table 2 mentions the descriptive details of each selected case study. It is followed by a structured analysis of factors to determine how each of the selected case studies demonstrates the significant shift of skills from onsite to offsite in varying degrees under each OSC type. Factors that were taken into consideration in this structured analysis are the total cost and area of the building, smart and modern technology-driven OSC techniques used, and the OSC skills usage which provides insights on how OSC has been used in the project.

Table 2 Summary of case studies

Case factor	New South Glasgow hospitals, Scotland, UK	111, East Grand, Iowa, USA	Journal, Uni Place, Melbourne, Australia	Lynch Hill Enterprise Academy, Slough, UK	AUSCO Modular, Australia
Relevant OSC type	Components	Panels	Pods	Modules	Complete Buildings
Completion year	2015	2019	2018	2017	2021
Total cost	£ 575 M (USD 806 M)	USD 18.5 M	AUD 90 M (USD 71 M)	£ 20 M (USD 28 M)	Products for sale
Building dimensions	25,000 m^2 over 14 storeys	6200 m^2 over four storeys	21,000 m^2 over 16 storeys	8759 m^2 over 3 storeys	Available in 5–36m^2 areas
Building type	Hospital building	Office building	Student accommodation	School building	Construction site sheds
Project scope	1109 bedded adult hospital and 256 bedded children's hospital	A retail facility on the first floor, commercial office space on other floors	718 apartments with 782-bathroom pods	Structural modules	Structural complete building
Scale of OSC	Bridge connecting buildings, prefab services risers, glass curtain wall, unitised structural cladding system, pre-cast concrete columns, beams, stairways, and panels	Dowel Laminated Timber panels in the superstructure with pre-cast concrete wall panels in the building core and Glulam beams in the substructure. 1180 m^3 of timber volume	782-bathroom pods featured in four designs, out of which 760 delivered with curved walls	146 steel-framed modules including internal walls, doors, windows, ironmongery, services, and cladding	A single complete building including all services and fixtures

(continued)

Table 2 (continued)

Case factor	New South Glasgow hospitals, Scotland, UK	111, East Grand, Iowa, USA	Journal, Uni Place, Melbourne, Australia	Lynch Hill Enterprise Academy, Slough, UK	AUSCO Modular, Australia
Onsite/Offsite Skills usage	1,800 workers employed by the contractor during the construction period of 5 years	Six carpenters for the onsite assembly of panels which was completed within 7 weeks	Seven carpenters were involved in the production over four months	Only 35% of the project work was done onsite, while the rest was completed offsite	Not Available

Source ADP Consulting (2018), AUSCO Modular (2021), Icon (2018), Interpod (2021), Mcavoy (2021b), Multiplex (2017), NHS Greater Glasgow and Clyde (2015), Neumann Monson Architects (2021), StructureCraft (2021), The Irish News (2018), Urbandsm (2019), Zero Waste Scotland (2015)

4 Case Study Review

The case study review includes a detailed discussion of the selected projects under the five types of OSC: components, panels, pods, modules, and complete buildings.

4.1 Components—New South Glasgow Hospitals (NSGH), Scotland, UK

NSGH project incorporated many offsite constructed components along with the onsite building construction processes, leading to the delivery of the project five weeks ahead of the original schedule (Multiplex, 2017). The extent of offsite constructed components in NSGH (Table 2) highlights how major building elements such as columns, beams, slabs, stairways, service risers, cladding, curtain wall, and bridge connecting buildings were manufactured offsite, rather than constructing onsite. Especially, the use of pre-cast concrete elements in spite of in situ concrete structural components reduced the onsite labour usage drastically, as the onsite work related to structural concrete elements was limited to lifting and fixing the delivered components into the right position (Zero Waste Scotland, 2015). Similarly, the unitised structural cladding system eliminated the need for contractors to work with material onsite, while the installation of mechanical and electrical services simply became an action of plug and play (Zero Waste Scotland, 2015). Overall, the contractor employed 1,800 workers, signifying the complex, traditionally built nature of the project which comes under the components OSC type (Multiplex, 2017).

4.2 Panels—111, East Grand, Iowa, USA

The project is an award-winning mass timber structure, which was the first North American construction project to use Dowel Laminated Timber (DLT) panels (StructureCraft, 2021). Due to the extensive use of OSC techniques, onsite installation of the structure was completed within seven weeks and required only a smaller site crew of six carpenters (Architect, 2021; Neumann Monson Architects, 2021; StructureCraft, 2021). Integrated project delivery is an important feature of this case study, where Virtual Construction Design (VCD) meetings were held among all the project stakeholders to resolve conflicts and finalise the integrated design (StructureCraft, 2021). Also, the fabrication of both DLT panels and Glulam components in the 111, East Grand project was inclusive of pre-assembling connections within the factory to deliver a finished element to the site (StructureCraft, 2021). The project symbolises how the shift of major tasks to factories reduces the onsite labour component.

4.3 Pods—Journal, Uni Place, Melbourne, Australia

The project comprises 718 apartments for student accommodation, and the entire project includes 782-bathroom pods in four unique designs (Interpod, 2021). This indicates that approximately 195-bathroom pods were repeatedly manufactured in a single unique design. The frequency of bathroom pod delivery by the manufacturer was eight finished bathrooms a day (Interpod, 2021). Therefore, the pods manufacturing of the project involved extensive repetition similar to a production facility with an assembly line. As such, a team of seven carpenters was involved in the entire production process, loading, sequencing, and manufacturing, and the process was completed within four months (Coombes et al., 2019). In the same vein, it can be recognised that repetitive pods manufacturing involves extremely mundane tasks. This finding confirms that OSC incorporates more repetitive activities (Goh & Loosemore, 2016), which can be easily substituted by machines over humans (Ginigaddara et al., 2021b; Keay, 2018).

4.4 Modules—Lynch Hill Enterprise Academy, Slough, UK

The school building was constructed by assembling 15.6 m long 146 steel-framed modules together, which were pre-clad offsite, including internal walls, doors, windows, ironmongery, and services resulting in 65% of project work being offsite (Mcavoy, 2021b; The Irish News, 2018). It implies the significance of offsite activities in modularised OSC projects, which subsequently result in more offsite skills rather than onsite skills. Moreover, the project was delivered 17 weeks ahead of the programme, while school operations were continued with minimal disruptions from onsite construction works (Mcavoy, 2021b).

4.5 Complete Buildings—AUSCO Modular

The range of complete building solutions provided by AUSCO Modular (2021) varies among project offices, site sheds, commercial offices, lunchrooms, kitchens, diners, toilets, laundries accommodation buildings, and COVID-19 temporary emergency spaces. Although the skills used in the manufacturing, transportation, and onsite fixing of these buildings are not available, completion of all construction works within the factory signifies how the skill usage becomes minimal onsite, which can be a matter of few hours depending on the formation of the substructure.

5 Discussion of Findings

Findings related to the case studies are explained in detail under smart and modern technology-driven OSC techniques used. It indicates the shift of skills from onsite to offsite, along with the extensive adaptability of OSC skills to technological advancements. 4D BIM modelling technique was used for the design of the NSGH building, under the OSC type, components. Designers of the project characterised the inclusion of 4D BIM in the project as "lonely/partial BIM" usage, as it was only incorporated for the design of architectural, structural, mechanical, and electrical models for internal production and management purposes, rather than a collaborative BIM output (Shah, 2013). One reason for this could be the complex, traditionally built nature of the project coming under component OSC type. Furthermore, the project was delivered before the mandatory BIM usage in the UK construction industry, which might have led to partial BIM incorporation in the project. Lynch Hill school building related to modules, was also designed using BIM, to ensure uninterrupted construction by reducing additional onsite work (Mcavoy, 2021b).

While the selected case studies portray varying levels of BIM incorporation, it is driven by the standards, regulations, and industry practices of different countries. For example, despite being a developed nation, the Australian construction sector is still reluctant to use BIM due to lack of legislative pressure and perceived short-term costs (Perera et al., 2021). Although the use of BIM cannot be perceived as an OSC-specific requirement, it is anticipated that BIM incorporation can be easier for OSC projects due to the nature of integrated project delivery in OSC. Although DfMA is considered a suitable design development and procurement strategy for OSC, its practice was not highlighted in any of the case studies. This is somewhat concerning. However, there is significant active encouragement towards the use of DfMA (NSW Government, 2020).

The award-winning project, 111, East Grand on panels OSC type was acclaimed for its' close collaborations among the design team (architect, civil engineer, structural engineer), mass timber engineering team (manufacturer), and the project delivery team (general contractor) (Architect, 2021). A key aspect of integrated project delivery was how the initial BIM model developed by the architect and engineer was shared with the mass timber manufacturer to prepare shop drawings, which were then used by the general contractor during the structure erection phase (Neumann Monson Architects, 2021). This is an interesting finding against the fragmented nature of traditional construction projects, as OSC is heavily dependent on integrated processes from the point of project design to onsite assembly. Therefore, OSC skills also need to possess a sound comprehension of integrated project delivery (Bertram et al., 2019), rather than working in silos in their specialised areas. Educational institutions need to consider incorporation of integrated project delivery in their curricular relevant to procurement methods. Although there is evidence of this happening, there is much work to be carried out to achieve required levels of proliferation.

The case studies indicate that there is a greater need for different professionals to collaborate in design development from early stages to manufacturing. This could be inculcated by developing a culture of collaboration and mutual understanding through multi-disciplinary group projects in construction. One way to achieve this could be to create opportunities to interact with professionals and workers from different disciplines other than the relevant field. For example, quantity surveying students can be given opportunities to learn from engineers and architects who have been involved with OSC projects to understand their perspectives and experiences of integrated project delivery. Such learning opportunities will ensure that the students are aware of the specifics of OSC project delivery as it is different to working with the same cohort of professionals in traditional construction.

Delivery of bathroom pods with curved walls was done through intensive innovations to assemble curved, designer panels to the pods within the factory and then transport, lift, and fix the finished pod on site with a "Quick Lift" system (Interpod, 2021). The onsite hoisting system was specially developed for the selected case study. This presents innovative methods of onsite assembly arising through OSC. This finding indicates the differences of OSC tasks and their related skills to traditional onsite construction. In order to achieve successful project delivery, the onsite assembly process requires OSC-specific project management. The advantages of using manufactured building elements can only be achieved if their sequential assembly and fixing were well-planned in addition to the offsite tasks of manufacturing, storage, and transportation. Therefore, although the onsite skill quantities can be of limited usage, they are also a vital requirement to achieve successful project delivery. Furthermore, lean procurement process should be used to ensure that offsite manufactured components are bought to the site following a just-in-time procurement method.

The main contractor of the Lynch Hill school project under modules claims how the company employs graduates of architectural technology and manufacturing management to provide offsite solutions (Mcavoy, 2021a). Hiring skills specifically related to manufacturing management signifies the nature of OSC skills that are relatively different from typical construction-related skills. Unsurprisingly, modular built projects can shift 80% of labour activities to factories, while repetitive tasks of fixing services can be done by manufacturing workers at a lower cost (Bertram et al., 2019). Although the shift of specialised construction skills (plumbing, electrical, and mechanical services) to manufacturing workers is not evidenced through the analysed case studies, it could be a future possibility to solve the construction skill shortage.

6 Current Skill Shortage and the Challenges to Overcome

The chapter reveals that there are critical OSC skills that need to be urgently developed to match the uptake of OSC. It also exhibits how different types of OSC projects require varying levels of OSC skills under both onsite and offsite aspects. Although the maturity of OSC markets in the UK, the USA, and Australia is not evident within the case study review, other researchers have identified the high maturity level of OSC adoptions in the European construction sectors (Steinhardt et al., 2019). As such, the subsequent research and initiatives on OSC skills development are also matured in Europe (Brennan & Vokes, 2017; Vokes et al., 2013).

Researchers reviewed the global initiatives in OSC skills development from four perspectives: industry, academic, professional institutes, and government. Industry-based learning, or "on-the-job training" is considered as an experiential learning process to improve OSC skills (Goulding et al., 2012). Nadim and Goulding (2010) recognised the causal relationship between industry and academia in developing OSC skills, related to on-the-job training. Therefore, the synergy between academic learning and in-house training can be a more convenient mode of OSC skills development, especially in immature OSC industries. Although the skill shortage is not widely apparent in the selected case studies, upskilling of prevailing skills to suit OSC needs is an essential requirement (Ginigaddara et al., 2021a). Such upskilling processes could be government initiatives, by creating training opportunities to relevant industry practitioners and improving the educational curriculum through mandated regulations (World Economic Forum, 2016).

In terms of government initiatives, the policymakers have to define, measure, and then develop OSC skills (Nadim & Goulding, 2010) to cater to the demand of OSC in respective countries. The critical need for understanding and defining OSC skills is evidenced within the Australian construction sector (Ginigaddara et al., 2021b). However, owing to the maturity of OSC markets, the identification and development of OSC skills in Europe are at a considerably appreciative state.

It is anticipated that OSC skills can be recruited based on the digital savviness in handling and assembly skills in manufacturing plants (Brennan & Vokes, 2017). Moreover, production-related skills can be easily substituted by robots or co-bots which implies the need to generate skills to meet the next levels of OSC manufacturing (Ginigaddara et al., 2019a; Woodhead et al., 2018). Therefore, the industry needs to be prepared for the next generation of robotics where the skills usage will be limited to machine operators who can work besides robots (Keay, 2018). Furthermore, Woodhead et al. (2018) suggested how professional institutes can include digital skills as part of the accreditation processes which can result in indirect skills development.

Finally, onsite assembly of OSC projects is yet to be improved with proper planning and management of processes where builders can handle inevitable onsite construction works such as surveying, demolition, and substructure along with the onsite assembly of building elements. While the onsite skills usage seems to be extremely limited in volumetric OSC types, full advantages of OSC can only be enjoyed with offsite-specific project management skills (Ginigaddara et al., 2021b). As such, the construction managers, who are excelled in handling traditional construction projects, need to be upskilled to match the offsite composition of OSC projects with more knowledge and an overall idea of the entire process (Brennan & Vokes, 2017).

Skills creation is directly connected with the demand for OSC in the market and the supply of services based on the number of OSC service providers. In that context, it is essential to increase OSC availability by promoting its benefits compared to traditional onsite construction. OSC has an embedded set of drivers led by sustainable construction (Blismas et al., 2009; Goulding & Rahimian, 2020). In contrast, one of the greatest barriers for OSC is the excessive cost of production, which can be reduced by increasing the market demand and providing government support to bear the heavy initial fixed capital of developing a manufacturing plant. Once the challenge between low demand and high supply cost is solved, OSC uptake will be higher, resulting in more sustainable, safe, and less-risky construction.

7 Conclusion

This research analysed both onsite and offsite construction skills that are typically required for various types of predominantly industrialised construction projects. The research focussed on completed OSC projects falling under the five OSC types: components, panels, pods, modules, and complete buildings.

The non-volumetric type of OSC components require a considerable amount of onsite skills, compared to other types of OSC. The majority of OSC projects based on volumetric types have the luxury of simply installing the complete building or building elements onsite rather than the assembly of numerous panelised elements onsite. This necessitates changes in skill requirements for the categories of non-volumetric and volumetric OSC types. Moreover, there is a heavy possibility of a robot and co-bot engagement for routine manufacturing processes resulting in the reduction of the number of workers in factories. As such, the variations of OSC skills in both onsite and offsite aspects are evident in different types of OSC.

The construction sector has to be well-equipped with the necessary skills to embrace the transition from onsite to offsite, which encourages the adoption of new skills that are different from traditional construction. Many skills can be influenced by the adoption of smart and modern technology-driven OSC techniques, and hence, the skills development has to be in line with these techniques. BIM integrated 5D modelling, innovative manufacturing techniques, and unique onsite assembly processes are some of the techniques that will result in subsequent skill changes in OSC. Therefore, skills development can be focussed on different technologies and their impact on the OSC skills under design, manufacturing, and onsite assembly aspects.

The educational institutions along with government involvement have a strong role to play in creating skills that are directly connected with prominent OSC tasks rather than evolving from traditional construction tasks. It is not recommended to assume that traditional construction skills can be directly transformed to OSC skills as many emerging OSC skills can be easily substituted from other industries such as manufacturing and information technology. Proper education on OSC will result in improved learning curves to be specialised in OSC, as the current skills are simply created based on industry practices and on-the-job training. Therefore, the OSC skills development has to be initiated from educational institutions for skills generation and the government for standards and regulations implementation. Furthermore, government-initiated training programmes in collaboration with education providers and OSC practitioners in the industry can accommodate apprenticeships. Such programmes may attach school-leavers to join vocational training on OSC while undergraduates can gain industrial training on OSC as a part of their educational qualification. There are many independent studies that support these concepts of modern construction skill development (Advanced Manufacturing Growth Centre, 2020; Hairstans & Smith, 2018).

Some of the selected case studies are from the Australian construction industry, which does not possess a mature OSC market. Hence, it is recommended to evaluate the onsite and offsite skills composition in more mature OSC industries in, Europe, North America, and parts of Asia based on primary data. Furthermore, the unit of analysis of the case studies can be changed to OSC organisations rather than OSC projects, to understand the nature of OSC skills from a different perspective. Finally, a detailed evaluation of job roles in the identified OSC skills will be a further research area to map the possibilities of multi-skilling and substitution of OSC skills from other industries.

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Concluding Remarks

Seyed Hamidreza Ghaffar and Paul Mullett

Abstract Transformations brought about through the implementation of innovative technologies for the construction industry have been discussed in this book, and this chapter highlights the main concluding remarks along with future perspectives on innovation in construction. The positive impacts of breakthrough technologies in terms of sustainability, productivity, health and safety, economic as well as workforce upskilling are discussed in depth; however, many practical bottlenecks are still unresolved including business models, commercial and contractual reform and a need for attitude change related to innovation in the sector.

Keywords Construction industry • Innovation in construction • Transformation • Breakthrough technologies

Introduction

Delivering a worldwide transition to a digitised and sustainable approach towards construction, operation and renovation requires the engagement of local value chains and decision-makers in all regions of the world, reflecting a diversity of cultural, economic, regulatory and climatic environment.

According to the World Economic Forum, the construction industry currently accounts for about 6% of the world GDP (Future Scenarios and Implications for the Industry, 2018) and is expected to reach around 15% in 2030 (Global_Construction,

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S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8

2015) in which the construction sector will play a vital role in any country's economy. The construction industry, however, is one of the least digitised and automated sectors that resulted in stagnating productivity, a lack of performance optimisation in products, and a general loss of attractiveness of the sector as a place of work. A global trend to develop digitalisation in the construction sector has emerged. As reported by the Industry Digitization Index of the McKinsey Global Institute (2017), in the USA, construction is one of the least digitised sectors, placed penultimate, only ahead of agriculture, and occupies the last position in Europe. Between 2013 and early 2018, £14 billion were invested in construction technology (Blanco et al., 2019) and in the UK, from 2017 to 2018, the number of construction companies adopting BIM increased by 12% (Waterhouse & Philp, 2016).

The construction sector is regarded as one of the most hazardous, wasteful, carbon-intensive sectors, sustained by gender imbalance, skills gap in digital competencies and a limited workforce. A recent survey by McKinsey found that 90% of executives interviewed strongly believe that the construction sector needs to be rapidly transformed, and 80% also believe that the construction industry will look radically different 20 years from today.

Generally, construction companies, research institutions and clients of the construction projects are already benefiting from the implementation of Construction 4.0 principles and breakthrough technologies. For instance, the use of 4D BIM for controlling and planning transportation activities at construction sites, drones surveying the sites and other breakthrough technologies elaborated in this book. It is clear that, in order for the construction industry to remain the engine of prosperity, it must lead the way to digital and green transitions. Industrial transitions are different periods in time with significant jumps in technology that have happened due to discoveries or radical innovations beyond what was or could be imagined prior to their occurrence. The vision for the construction industry should be set beyond productivity and efficiency as its main objectives, rather, strengthening its role and contribution to society. It should place the well-being of the workers at the centre and utilise breakthrough technology to provide prosperity beyond jobs and developments while complying with the sustainable use of energy and resources.

The construction industry's transition requires breakthrough technologies such as data analytics, sensors, augmented reality systems, high-performance computing, additive manufacturing, advanced materials, autonomous robots and simulation systems to be adapted for construction applications. This transition could bring benefits by automating traditionally manual, laborious, repetitive and unsafe tasks for human workers construction activities. However, construction has been slow to adopt new technologies and has not yet undergone a major disruptive transformation (Gerbert et al., 2016). This slow implementation pace is mainly due to the barriers including: (1) the incompatibility of the new technologies with existing construction practices that forces workers to prefer the former and proven solution instead of innovative technologies; (2) the fragmented and risk-averse nature of the construction industry that inhibits the adoption of new technologies; (3) the high sophistication of digital technologies that prohibit their acceptance from less technological familiar construction workers; (4) the fit-for-purpose automation solutions that address unique construction activities bring high investment costs and hinders their accessibility from all but the largest of enterprises.

Highlights of the Construction Transformation

Fundamental elements that are related to construction industry's transformation should be centred on a human-centric approach for digital technologies including artificial intelligence and upskilling or reskilling of the work force, particularly digital skills. This could also lead to modern, resource-efficient and sustainable industry and transition to a circular economy. Clearly speeding up investment in research and innovation is paramount for the construction industry's transformation. However, an upsurge of innovation and change in industry will have more complications that reach far beyond the technological change in practice and on-site. A transformed construction industry will have a transformative impact on construction industry's workforce, who may see their role changed or even threatened. Changing roles and increased reliance on complex advanced technologies will undoubtedly require new skills. Will the ageing workforce be attracted to work in a new high-tech environments? Or can this lead to younger workforce being attracted to the construction sector? Imagine the use of robots designed for interior building finishing, brick laying, masonry and the development of robot-based prefabrication of facade delivery (Asadi et al., 2018). These concepts have not reached the market for construction automation since the proposed technologies still struggle to operate in a live construction environment do not meet essential safety requirements, and there are no trained operators to perform and monitor these tasks.

The basis for highly automated construction sites lies in the availability of high-performance robotic and autonomous systems that can execute a wide variety of construction tasks. Currently, only a few automated construction robotic systems exist on the market. They are tailored to fulfil only one construction task at a time and, therefore, only a very limited number of construction tasks can be automated on an actual construction sites. Moreover, the available construction systems are developed by different companies, which implies a time-consuming and cost-intensive production of such robots. The specificity of the automated construction robots and the development overhead results in systems that are not flexible enough and are expensive for the end-users. To achieve the goal of a highly automated construction site, the development of tailored robots must be accelerated and systematically distributed among many stakeholders: vendors of automation and construction equipment, construction and prefabrication companies, software developers, scientists.

The construction industry could learn from the productivity gains seen in the manufacturing sector. To support a circular economy, built assets must now be seen as material banks, where components can be used in various configurations, then later disassembled and reused elsewhere. Once moved to a controlled manufacturing environment, the design for manufacture assembly and disassembly (DfMAD) process can be improved for resource efficiency. This will lead to increased recycling and recovery of waste. To reduce construction waste and increase the reuse of construction materials at their highest value designing buildings for adaptability and deconstruction, increased reuse of components, use of materials that can be reused and recycled, and improved demolition systems are the fundamental requirements. For the construction industry to respect the planet's limitations and be sustainable, the stakeholders, including the governments, need to develop circular processes that reuse, repurpose and recycle natural resources, recover secondary raw materials from waste and reduce waste and environmental impact (Ghaffar et al., 2020).

Breakthrough technologies such as AI and additive manufacturing can play a significant role in improving sustainability credentials, by optimising resource-efficiency, materials recovery and minimising waste. Some materials fit quite easily into the circularity concept for recovery of secondary raw materials, for instance, concrete, timber and plastic, while others, such as composite materials, fibre-reinforced plastics, and metallurgical wastes, present a much harder challenge and require further research.

Circular construction complies with the 12th UN's sustainable development goal, i.e. sustainable consumption and production, which can generate fast and lasting economic benefits. Circular construction leads to a clear innovation challenge, through which stakeholders should seize the opportunities in terms of redesigning the current practices of liner construction where huge quantities of waste are produced and sent to landfill. The optimisation of existing solutions is surely not enough. The construction industry has to pursue innovative radical solutions, put them into practice and understand the implications of reworking its business models. Often when sustainable construction is discussed, more emphasis is given to energy and emissions (Hazarika & Zhang, 2019). Being too focussed only on emissions might lead to innovative efforts ignoring the potential for systematically reducing energy demand over a period of time through breakthrough technologies.

Leveraging Innovation Through Business Models

History has shown that innovation in the broadest terms requires the creation of value through novelty, oftentimes (but not always) through the implementation of technology. Successful innovations often feature several of seven common threads, namely developing the why, setting big goals, planning resources, promoting diversity, creating proximity, giving permission and driving adoption.

The unique factors that shape and define the construction industry also provide the context for managing and implementing innovation successfully. These factors can be viewed through the lens of the product, the art and science, and the system itself. Consideration of the latter is of primary importance in realising innovation and understanding the systemic changes needed to drive a paradigm shift in the industry; however, difficulties exist in terms of industrial lock-in, fragmentation and value ownership, regulation, life-safety and risk aversion, and drivers for change.

The issue of industrial lock-in presents an ever-present headache for much-needed change, flowing from some of the specific challenges relating to permanence, scale and materials and methods. It is represented in two forms: asset legacy and process legacy. The first requires the industry to deal with existing physical infrastructure, and the second requires the industry to design and deliver in a way which is compatible and mutually understood.

It is therefore acknowledged that, whilst incremental innovation may be achievable in isolated parts of the supply chain, or in specific areas, transformational innovation will require a fundamental change in business models built around digitised platforms, collaborative frameworks and enterprise agreements.

The issue of fragmentation and value ownership is broad and relates to both project and supply chain discontinuities that prevent knowledge sharing and investment in innovation, and also drive risk aversion and adversarial commercial arrangements.

Initiatives, such as the introduction of enterprise-based procurement arrangements, for example, Project 13, suggest that the industry is responding; however, it represents slow progress when we consider that the Latham Report (1994) was published in 1994, nearly 30 years ago. However, the demand for change is increasingly being driven by the potential opportunities offered by digital technologies, opening up wider possibilities relating to vertical integration, off-site construction and increasing sustainability drivers. The acceleration of digital technology provides unique opportunities for data-transfer throughout the supply chain which, when applied to standardised and componentised systems and empowered with AI-based tools, can be used to boost efficiencies throughout the whole construction process and de-risk activities. This opportunity is maximised where digital platform business models are adopted, rethinking traditional models of delivery and creating new, diversified ways of creating value. Unfortunately, this is a difficult step for many AEC businesses to visualise, requiring a proactive approach to partnering and knowledge sharing that is unnatural to a traditional industry. Nevertheless, the increasing importance of sustainability and the rise of circular construction will make this a step that many businesses will not be able to afford to miss.

Shaping the Future Engineers with the Right Skills

Keeping pace with the technological development is a complex issue for organisations of all sizes. While innovative technologies generate significant business opportunities, they also create skills gaps, particularly in the construction industry, where the demand for skilled workers is extremely high. Engineering is the ultimate people focussed profession, working to formulate the solutions to numerous current global challenges such as mitigating the effects of climate change. Education of the engineers of our future is the foundation on which the economic success and future security depends on. The fast pace of technological development and its impacts on society, intensifies the need to ensure that all young people improve the broad range of technical, communication, creativity and problem-solving skills.

It is also extremely important to make engineering more inclusive. There are still nowhere near enough females up taking an engineering profession. The construction industry's transformation is gaining momentum, and therefore, it is important to ensure the education and skills system are future proof by preparing the workforce for the upcoming innovation-driven digital transformation. Additionally, much greater attention is needed for the existing engineering workforce so that their knowledge and skills capacity is enhanced to engage with the innovative technological breakthroughs. Notably, the majority of the engineers and technicians of 2030 have already left the education system. The construction industry and governments need a significant change in their commitment to supporting lifelong learning and professional development to ensure the workforce continues to progress with new skills in an increasingly technology-driven industry. Moreover, to maximise productivity gains, the construction industry's workforce must be fully capable of exploiting technological advances. To this end, higher education institutions should be responsible for workforce development and upskilling, where they must reconfigure their engineering programmes and change the old-fashioned theory-based teaching philosophy with innovative hands-on experience, in addition to covering the topics of research on breakthrough technologies at the curricula for undergraduate level. Higher education continues to be an important pathway to professional engineering careers. Development of learning resources for the current and future generations of employees is, therefore, paramount. It is worth noting that upskilling is a smaller investment than hiring and training a new worker (ITA Group, n.d.). Organisations investing in reskilling their employees create a better-rounded, cross-trained workforce, and increase team's effectiveness. Moreover, the retention will be improved along with new talents being attracted to the organisation. It also boosts morale, where employees who have training and development opportunities are satisfied in their roles and have a positive outlook on their future with the organisation.

Conclusions and Future Perspective

Innovation in the construction industry can comprise new or improved ways to reach higher functionalities or greater efficiencies with lesser resources, effective implementation of technological breakthroughs, and overall systematic changes in the processes of construction, maintenance and renovation. The technological innovation process in construction must start with investments in organisations R&D, and then the knowledge capital will be converted into technological innovation output, where they are transferred back to the market and ultimately increase productivity, sustainability and overall performance of the organisations. Governments have a critical role to play and should consider financial supports for technological innovation of construction companies. Moreover, large construction companies should increase the resource investments towards innovation, improve knowledge management and include knowledge from external sources such as research institutes and universities. It is also imperative for construction companies to reinforce the transfer of knowledge.

A paradigm shift in the construction industry would have an overall positive impact on sustainable development and its three main pillars of society, environment and economy. The increased digitisation, automation and modularisation are all key parts of the construction industry's transformation. However, the construction sector has been less keen on these developments compared to the aerospace and automotive industries. This is due to several factors stemming from the difficulty and complexity of building design, project delivery and technological risk aversion, which do not support innovation. As a consequence, the sector in many countries continues to suffer from low productivity, workforce shortages, safety and logistics issues along with time and cost overruns. Some radical changes are, therefore, paramount for this transformation. Specially, when the construction industry has been criticised for being inefficient, generating huge quantities of waste, emitting significant amounts of greenhouse gases and consuming a lot more energy compared to other industries (Abanda et al., 2017). Research and development for transformation of the construction industry are taking place in many directions including advancements in individual breakthrough technologies such as BIM, adaptive building systems, robotics in construction, large-scale additive manufacturing and many more. Furthermore, there is an increasing awareness of the potential benefits of technologies such as artificial intelligence and big data analytics, embedded sensing technologies, VR/AR, mobile/cloud computing as well as blockchain arising from the successful application and dissemination of such technologies outside the construction territory.

The COVID-19 catastrophe has emphasised the need to re-evaluate working methods and practical approaches. It has exposed the vulnerabilities of the construction industry, such as fragile strategic value chains, and boosted the necessity to find flexible yet robust innovations to tackle these vulnerabilities. This is a decisive moment, in which some of the previous practices (old normal) will be obsolete and a new normal will arise. This transition could be a window of opportunity for the construction industry to shape its future drive for a sustainable, productive and innovative sector. This will require a proactive and ambitious approach, considering the paradigms shift necessary for the society, economy and environment as pillars of transformation in construction using the impact and added value of innovative technologies in the sector.

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