Digital concrete: productivity in infrastructure construction

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Productivity in UK construction has flatlined despite the growing adoption of advances in digital technology and increased outsourcing. We examine the evolution of the UK infrastructure construction industry, describing the changing industry structure and the range of digital technologies being adopted. We consider the implications of technological innovation for productivity, both actual and measured, focusing on two possible explanation for this particular piece of the broader productivity puzzle: time lags in technology adoption and potential sources of mismeasurement. While delays in adoption may account for disappointing productivity performance to date, the progressive use of digital technologies both upstream and downstream will exacerbate potential mismeasurement.

Key words: Productivity, digitization, construction, infrastructure

JEL codes L10, L11, L16

1. Introduction

The construction industry accounts for 6-7% of nominal annual GDP in the UK (as in the US), and its measured labour productivity growth has been close to zero for many years (compared to declining productivity in the US). This is consistent with the popular image of construction sites as low-tech environments. Yet Griliches (1994) designated construction as a 'hard-to-measure' sector, and indeed the disappointing aggregate performance is puzzling to industry observers, who note there have been increases in the productivity of specific activities, including a significant increase in the use of digital tools (Goodrum, Haas & Glover 2010). Work by the US Bureau of Labor Statistics to improve deflators for some parts of the sector went some way to resolve the puzzle in U.S. data, involving more detailed deflators for

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different activities (Sveikauskas et al 2016; see also Goolsbee & Syverson, 2022 on residential construction); but did not consider either activity shifts within the sector or the implications for (quality-adjusted) deflators of the ongoing digitization of construction.

In this paper, we explore the ongoing impact of digitization on the structure and productivity of the UK's civil construction sector. Our focus will be major projects and civil engineering rather than residential construction; civil construction has experienced, and likely will continue to see, more digitization, and there are fewer complexities related to land use and land values than is the case with housing construction. In the infrastructure sub-sector there has also been substantial change in market structure since 1980, along with accelerating technical change. Among these changes, designs and materials used have seen innovation, particularly to bring about environmental improvements in construction and use. The use of building information modelling (BIM) tools has steadily commoditized the design stage, leading to considerable outsourcing to countries such as Brazil, India and Poland. On sites, much construction activity is contracted out to specialist sub-contractors. In between, both consultants and major contracting firms seek to capture value through digitally-enabled project and programme management using integrated 3D software models that capture data through time from design through construction to operation (sometimes known as 'digital twins'). For example, sensors embedded in concrete or steel can be monitored in real time allowing reduced maintenance costs or averting structural failures. Thus, operational costs for clients may be reduced over time. In addition, parts of large structures are increasingly built offsite for onsite assembly, a process enabled by BIM, whose major benefit is reduced construction time and improved component standardization and quality. Some major firms are building vertically-integrated offsite factories to produce these parts for their construction projects. Finally, the incorporation of digital sensors is enabling provision of related maintenance services following completion of a project. There is therefore apparently ample potential for productivity improvements.

While all these developments are widely recognized in the industry, these changes are seemingly not yet well reflected in output, price and productivity statistics. We consider whether this could be due either to only gradual implementation of the technologies across the sector, or alternatively to measurement issues such as failure to quality-adjust deflators (although there may well be other reasons for productivity headwinds, such as planning restrictions, not discussed here). The former, often described as a productivity J-curve effect (Brynjolfsson, Rock & Syverson 2021), would imply delay in seeing the productivity benefits of digitzation. Issues with output or input price deflators, which would imply some mismeasurement of productivity, could arise from the absence of relevant quality adjustments (eg enhanced asset lives or performance), or from the failure to capture well some price changes (eg lower-cost outsourced services). There have also been activity shifts across SIC 2007 classifications, which could have led to some mismeasurement of relevant input volumes and deflators.

In this paper, we first set the scene by describing the productivity performance of the infrastructure sector in the UK as captured in official statistics. We describe the evolution of its market structure, touching on sector classification issues. We summarize the digital technologies being implemented across the infrastructure sector, and the way these are shifting value added across the supply chain. Drawing the threads together, we then discuss the challenges for productivity measurement raised by: changing input prices; a shifting pattern of value added and output prices; depreciation and measurement of capital services; productivity impacts in adjacent sectors.

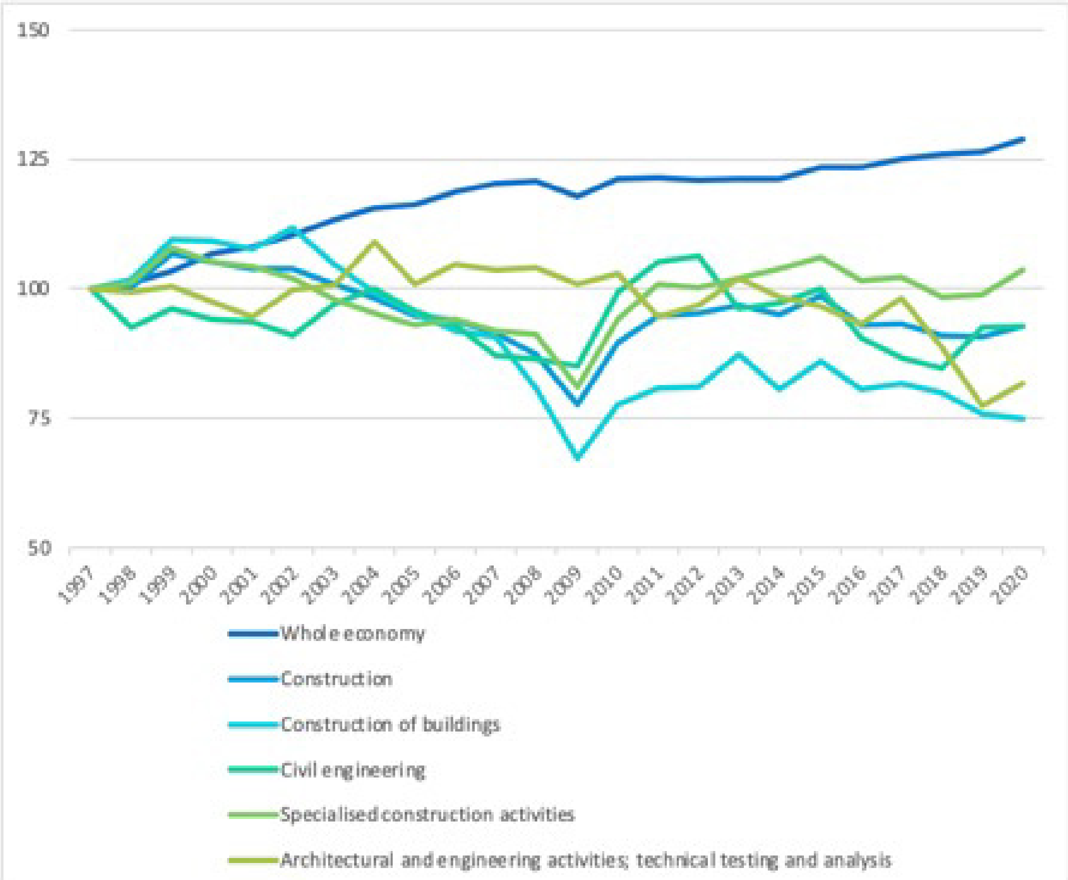
2. Measured productivity performance in UK infrastructure

Flat or negative productivity growth in construction has been experienced in many countries. There has not been much progress across Europe, while labour productivity in the sector in the United States is lower today than it was in 1964 (WEF, 2018). Those countries that have experienced rapid productivity growth, such as China and South Africa, started from a low base level. Blanco et al. (2017) identified several common challenges: regulation, contracting barriers, inefficient design and engineering processes, poor procurement and supply chain management, failure to improve workforce skills, and failure to deploy new digital and materials technologies. This lacklustre performance characterizes many countries despite the substantial differences in funding and governance mechanisms for major projects. In comparison to some other countries, including the US, the flat productivity record of the UK industry is relatively good.

Our focus is on SIC 2007 Section F, Division 42, covering roads, rail, utilities and other civil engineering projects, although as discussed further below, some parts of other sectors (Division 71, Architectural and Engineering Services, and Section C Manufacturing) are closely linked. This division accounts for about 19% of the whole construction sector (at current prices) in recent figures, although with substantial variation at different periods. However, according to the most recent official figures, all sectors of construction saw their productivity grow more slowly than the rest of the economy up to the pandemic (Figure 1), and over a long period its labour productivity has been flat and its total factor productivity (TFP) declining (Figure 2). Infrastructure assets have become relatively more expensive over time (WEF 2018).

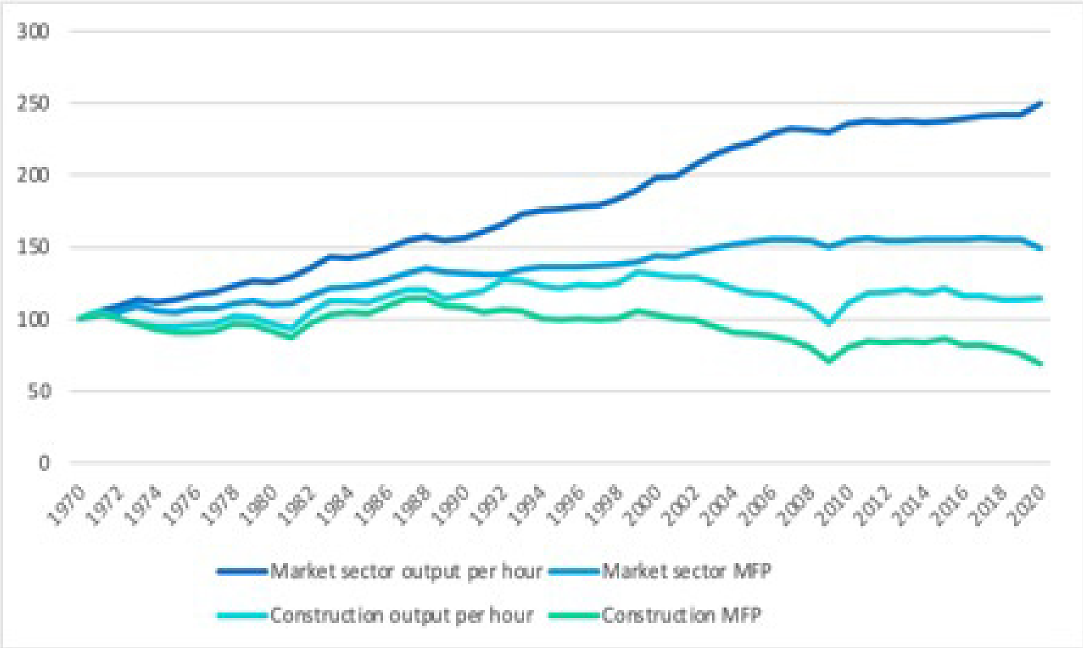
The intermediate expenditures used to calculate nominal value added in infrastructure construction have shifted over time from materials to services (mainly architectural, engineering and technical services). Office for National Statistics (ONS) figures show that in 2018, compared with 1997, the share of the sector's intermediate spending on computer services had risen by 1.3 percentage points and on architectural, engineering, technical and testing services by 2.7 percentage points, while the shares of other categories in total intermediates expenditure declined (by 4 percentage points in the case of mining and quarrying products) (all figures ONS 2021, Table 7). The shift can be summarized as more intangibles and less material being used, in this most material of industries. This is reflective of the progression of digitization and the way this is changing the structure of the industry, as we detail below.

Figure 1: UK Productivity (GVA per hour worked), whole economy and construction, 1997-2020, 1997 = 100



Source: ONS (2021)

Figure 2: Total factor productivity, 1997-2020, Index 1997=100



Source: ONS (2021)[4]

Real value added in construction as a whole and the infrastructure sector in particular has increased more slowly than for the whole economy; for infrastructure the volume terms index has trended upward since the late 1990s, with a dip in the post-financial crisis period, but more slowly than constant price GDP. The output price index for this segment of construction has increased faster than the GDP deflator: if this output price had risen by the same as the GDP deflator, the counterfactual real volume index would have increased by over 11% more between 1997 and 2021 than its recorded growth. Output prices for the infrastructure sector are also more volatile than for construction as a whole while following the same profile. The published index has shown an acceleration recently, although less so than for all output prices (Figure 3).

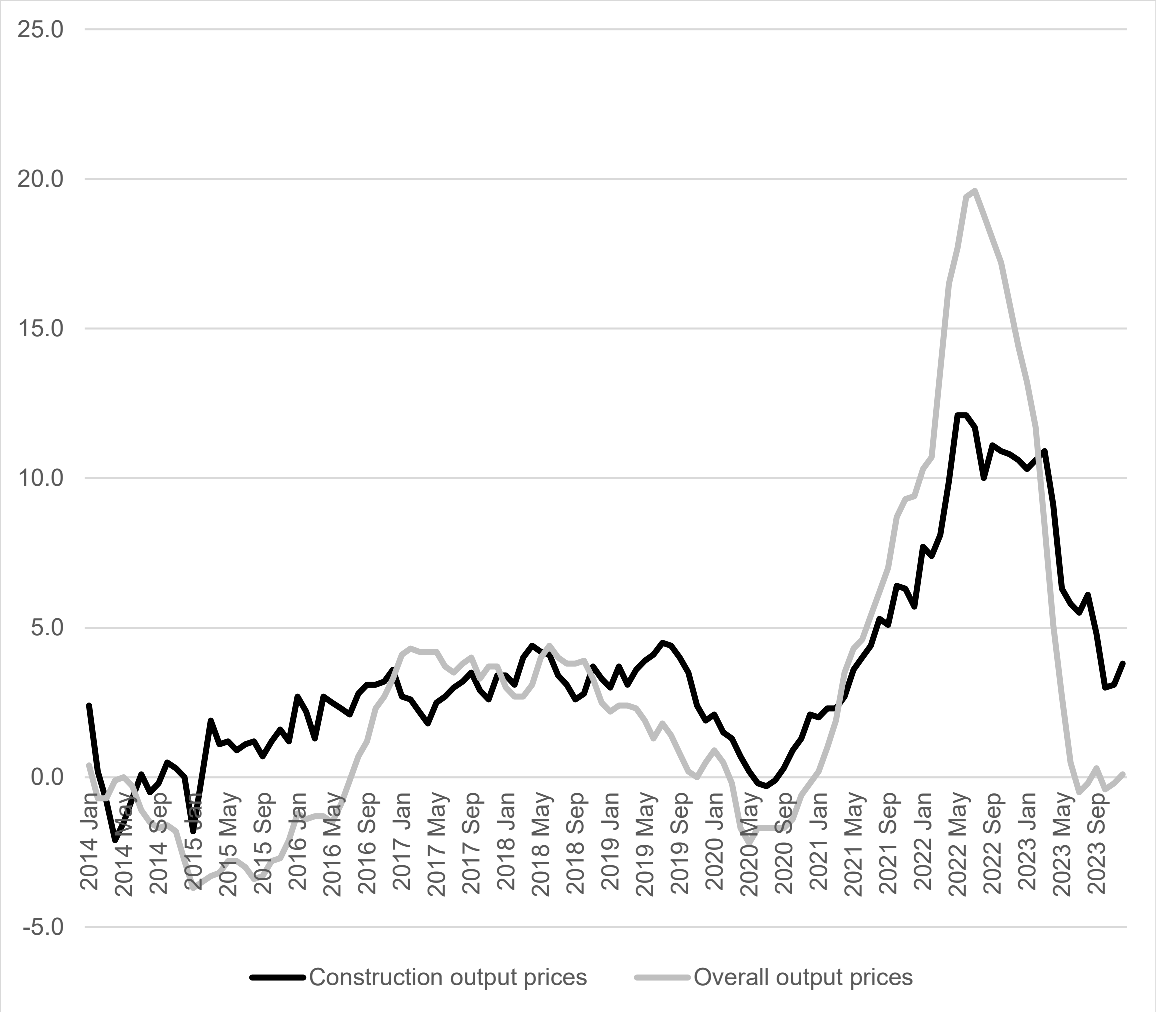
There are additional questions about input prices. The index used may not fully reflect the price of the services taking a growing share of purchases of intermediates, as compared to materials inputs, so as noted above there may be an increasing 'mismeasurement' challenge in double deflating sector value added. We return to this below. Data for the volume of labour and capital services used are also required to calculate TFP. ONS (2021) figures show that there has been a gradual upskilling in the construction labour force (although around two fifths have no qualifications or GCSE only), so hours worked can be quality adjusted to reflect the higher average qualification level; the share of hours worked by the most highly educated

[4] MFP, multifactor productivity, is used by ONS as the term for TFP

has increased over two decades (from 1% to 4.7%), albeit remaining lower than the share of this group in whole economy hours worked. This upskilling could be linked to the increasing technological sophistication of the sector but we do not consider it further here. Capital stock measures include the usual tangible assets, software and R&D but not data or other intangibles; capital services used have grown quickly over time. The proportion of the sector's capital stock in the form of IT hardware and recorded intangibles has increased significantly from 6% in 1997 to 14% in 2020 (ONS 2021). There has been a sharp increase in capital services used in the sector over that period.

While civil engineering has not been the worst performing part of the sector in terms of productivity performance, it is nevertheless surprising that its productivity record has been flat for decades, given the downward pressures on costs through the bidding process and the technological changes the industry has already experienced (for example in areas such as tunnelling or engineering design) as well as the digital transformation that is now under way. While productivity stagnation might be attributed to the extreme fragmentation and decentralized project organization that still categorizes the broader architecture, engineering and construction industry today (Hall 2018), there are several areas where it is worth exploring reasons for delayed productivity effects or measurement challenges. These areas include the changing structure of the industry, as well as the shift in intermediates purchased, due in large part to implementation of digital technologies.

Figure 3 Output prices, 12 m % change, infrastructure construction and overalll PPI



Source: ONS

https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/datasets/interimconstructionoutputpriceindices and https://www.ons.gov.uk/economy/inflationandpriceindices/datasets/growthratesofoutputandinputproducerpriceinflation

3. A brief history of the UK infrastructure sector[5]

The origins and market structure of the industry today can be traced back to the Industrial Revolution, and the building of canals in the second half of the 18th century. The development of the infrastructure

[5] Unless otherwise stated this and the next section draw from Murray (2021) presented at the University of Cambridge Digital Economics & Policy Online Workshop on Construction and Infrastructure.

and construction industry was driven by the rapid growth in Britain's urban population, the accumulation of wealth, and the emergence of new materials and new technologies like cast iron and steam power, which created a need for increased specialization in design and construction. The development of Britain's railways in the 19th century, and the introduction of the Joint Stock Companies Act of 1844, were pivotal as the opportunity to invest extended from a few wealthy individuals to the broader middle class.

The Institution of Civil Engineers (ICE), created in 1818, began to formalize the roles of consulting engineers and contractors and to encourage standard practices in construction. At the time there was a focus on rail. Given the risks associated with railway construction, contractors relied on banks to provide their working capital and to cover their losses on projects. By the early 20th century, companies would engage in bidding and tender processes dominated mostly by consulting engineers. Most consulting engineering firms were unlimited liability partnerships; the fees they could charge were fixed by the ICE, and companies were forbidden from advertising their services or competing on price. Instead, contractors competed on reputation. Profit came from firms delivering a final project for a lower cost than the project price for which they had tendered.

The war and the postwar government brought nationalization, with the creation of large publicly owned enterprises like British Railways and the Central Electricity Generating Board. The investments that governments made through such entities in motorways, civil aviation, power generation and telecommunications enabled the consultants and contractors to grow and specialize. Despite the many shortcomings of the nationalized infrastructure companies, they developed their own technical capabilities and invested in research in universities and in their own laboratories. Computers began to be used in engineering design and construction planning, and the rate at which the construction industry accumulated know-how accelerated. By the early 1970s, British contractors were recognized around the world for their capabilities.

This process went into reverse in the late 20th century. Following the 1979 election of the Conservative Government, the UK government privatized national infrastructure companies, deregulated engineering consultancy, and sold or outsourced many technical functions that had developed within the public sector. Firms involved in construction of big projects increasingly competed on low price for government-funded contracts and contracts in the privatized infrastructure industry. As governments outsourced more of the services that had been provided from within the public sector, some contractors reinvented themselves as facilities managers and service providers. For example, in 2001, Tilbury Douglas – a respected construction company founded in the 19th century – rebranded itself as Interserve plc and diversified into maintenance and facilities management through a series of acquisitions. It became one of the largest contractors in Britain before it issued a series of profit warnings and went into administration in 2019. In March 2021 what remained of the company changed its name back to Tilbury Douglas.

4. Current structure of UK infrastructure industry

There are almost 25,000 companies making up the civil engineering construction sector in Britain, the vast majority with fewer than 25 employees (ONS 2020).[6] The sector is composed of some large companies (Table 1) and a patchwork of SMEs and micro-businesses. This market structure is changing thanks to digitization and automation as described below (Ostarvik 2014; Whyte 2019), with the innovations integrating and optimizing processes but involving higher fixed costs (Pittman 2018; Cao and Hall, 2019; Griffin et al. 2019). The continuous deployment of technology in the industry is recognized as critical for continuing innovation (WEF 2018; Barbosa et al. 2018; Oti-Sarpong 2019). One important change is that industrialized construction increasingly includes off-site manufacturing, namely the use of prefabricated components, or kits-of-parts, made in a factory to high and consistent quality for subsequent installation in their final positions in a structure on site (Goodier and Gibb 2007, Dunlop Taylor 2020). The present-day use of off-site manufacturing has been embedded in applications of digital technologies (Jin et al. 2018). Another important change is the progressive outsourcing of engineering design, often overseas, through the use of digital design and information tools, known as Building Information Management (BIM). These and other digitally-enabled innovations are described further below.

Table 1: Top 5 UK Project Managers, Total UK Staff, Annual UK Fees, 2015 & 2021

	Staff 2015*	Staff 2021	% Change	Annual UK fees £m 2014/2015	Annual UK fees £m 2020/2021
Mott MacDonald	5933	7,059	19%	394.5	868
Turner & Townsend	1897	2,907	53%	183.5	273
Arcadis	3700	3,881	5%	309	462
Aecom	7423	6,679	-10%	644	-
Gardiner & Theobald	672	867	26%	103	161
Total	**19640**	**21393**	**9%**	**1634**	**1764** (excl. Aecom)

[6] These are GB, not UK figures i.e. Northern Ireland is excluded.

Source: Building UK

* Mott Macdonald figures reflect acquisition of JN Bentley, and include Franklin + Andrews Limited

Turner & Townsend figures reflect acquisition of Thinc Group Holdings Pty Limited

Arcadis figures reflect acquisition of Hyder Consulting in October 2014 and incorporation of EC Harris surveyors; Aecom figures reflect merger with URS in October 2014

The changing character of major construction projects has had implications for the industry structure, the companies involved, the environment and for people (Oesterreich and Teuteberg 2016). Through companies like those listed in Table 1, new services have emerged including project management, construction taxation and legal support services, value and risk management consultancy, and specification and design management. Contractors charge separate fees for these services, whereas they were provided previously as part of a total fee. As engineering consultancies have moved into programme and project management and delivery, so too have major contractors, whose profitability has also been squeezed despite their practice of contracting out substantial parts of the on-site work to a large number of sub-contractors.

The changing structure of the industry has also involved more internationalization. The Engineering News Record, a source of industry statistics, reports that the leading 225 companies globally generated $71.88 billion in design revenue in 2018 from projects outside their home countries, up 11.3% from $64.59 billion in 2017. This is a significant increase from 2002 when the top 200 firms generated $18.9 billion in revenue from projects outside their home countries. Thus, as an example, project design has become highly commoditized, the use of outsourcing to countries such as Brazil, India and Poland widespread, and the price of these services has reportedly fallen. The latter is consistent with the considerable reported variation in median salary among project professionals from country to country. Relative to the UK, Brazil, India and Poland provide lower (labour) cost alternatives.

Table 2: Annualized Project Management Salary (in USD) by country

Country	N=	Median Salary USD
United States	34430	$120,000
Australia	1011	$103,789
Germany	1280	$99,512
UK	849	$87,993
Singapore	664	$79,464

Canada	2083	$73,761
UAE	406	$71,345
France	1138	$68,222
South Korea	130	$65,363
Saudia Arabia	297	$62,400
Japan	886	$62,331
South Africa	588	$54,688
Mexico	1115	$43,674
Brazil	969	$35,489
FIndonesia	73	$35,360
Peru	588	$32,363
China	1664	$28,932
India	622	$26,917
Colombia	942	$25,560
Nigeria	221	$23,370
Egypt	170	$11,765

Source: Project Management Institute (2023); market exchange rates https://www.pmi.org/-/media/pmi/documents/public/pdf/learning/salary-survey-thirteenth-edition-non-members.pdf?rev=16bd8bb399034b588bdb59631c7cc97d

An important defining characteristic of the UK industry today is its organizational separation from clients. This contrasts with some other industries where continuing services are becoming a more significant part of value creation in the 'servitization" process, although this is also starting to change. Contractors and their supply chain still tend to have limited involvement with clients upfront in the feasibility stage of a project. The lack of integration along (sometimes global) supply chains is manifested in a wide-scale use of on-site sub-contracting and multiple tiered interfaces and significant transaction costs. These include large overhead costs in contracting and co-ordination, and (often inappropriate) risk transfer to sub-contractors. This structure in turn has led to an industry that tends to be focused solely on cutting costs rather than adding value. As described by Farmer (2016:17), "[T]hose tiers of the industry closest to clients or indeed forming parts of clients"organizations themselves have effectively become process managers for a wider cascaded supply chain rather than having direct delivery control by employing their own workforce."

The intensified competition in the industry has seen many contractors reduce their overheads by selling off their plant (capital assets), reducing their technical staff and sub-contracting much of the work they had done themselves. Today, it is still common for 80% of the value of an infrastructure project to be subcontracted to specialist suppliers and contractors. And many of the engineers, estimators and construction managers that previously used to enable these companies to deliver complex projects have been replaced by vertically integrated commercial managers and experts in contracting (Murray 2020). As described below, digitization opportunities are causing new shifts in the sector. But today the UK construction industry is dominated by a few large international consulting firms with more than 50,000 staff and more than $10bn in revenues and a long tail of smaller firms. The larger firms are publicly quoted or owned by private investors. These companies provide technical, professional and construction services, including project managing construction and contracting with construction firms. In 2019 there were four UK based construction companies with an annual turnover exceeding £3 billion (Table 3). The turnover of the UK's largest construction firm Balfour Beatty was almost twice that of competitor Kier Group in 2019 and was £600 million up from 2018. Balfour Beatty's revenue was significantly bigger than other companies on the market, including having a revenue three times that of Amey UK.

Table: 3: UK Top Five construction firms by 2021 turnover (in millions of British pounds), 2014 to 2021

Firm	2014	2015	2016	2017	2018	2019	2021
Balfour Beatty	8,793.00	8,444.00	8,215.00	8,234.00	7,802.00	8,405.00	8,263.0
Kier Group	2,954.30	3,275.90	4,082.30	4,282.30	4,512.80	4,479.40	3,328.5
Morgan Sindall Group	2,219.80	2,384.70	2,562.00	2,792.70	2,972.00	3,071.00	3,212.8
Amey UK	2,167.90	2,531.90	2,591.00	2,581.30	2,581.30	2,667.80	2,406.8
Interserve Grp	2,913.00	3,204.60	3,244.60	3,666.90	3,666.90	3,225.70	2,263.7

Source: The Construction Index, https://www.theconstructionindex.co.uk/market-data/top-100-construction-companies/2022

Large firms contract with a multitude of smaller contractors under what is sometimes described as adversarial circumstances. Small firms will have awareness of digital construction-related tools but lack familiarity with the software systems (Vidalakis et al. 2019). The resulting structure of the construction industry is thus characterized by extreme fragmentation in three dimensions: horizontal, vertical and longitudinal (Fergusson 1993). Horizonal fragmentation is the result of an intensive project-based, trade-by-trade competitive bidding environment of traditional project deliveries. In the context of lump-sum bids, for example, clients will tend to choose the "lowest qualified bidder" from those qualifying general contractors. In turn, these bidders solicit lump-sum bids from multiple specialized subcontractors, either at large, or from a list of approved prequalified subcontractors. Processes happen sequentially and are not co-ordinated. And since subcontractors tend to be less digitized than contractors, the system benefit across the supply chain of technology adoption is diluted.

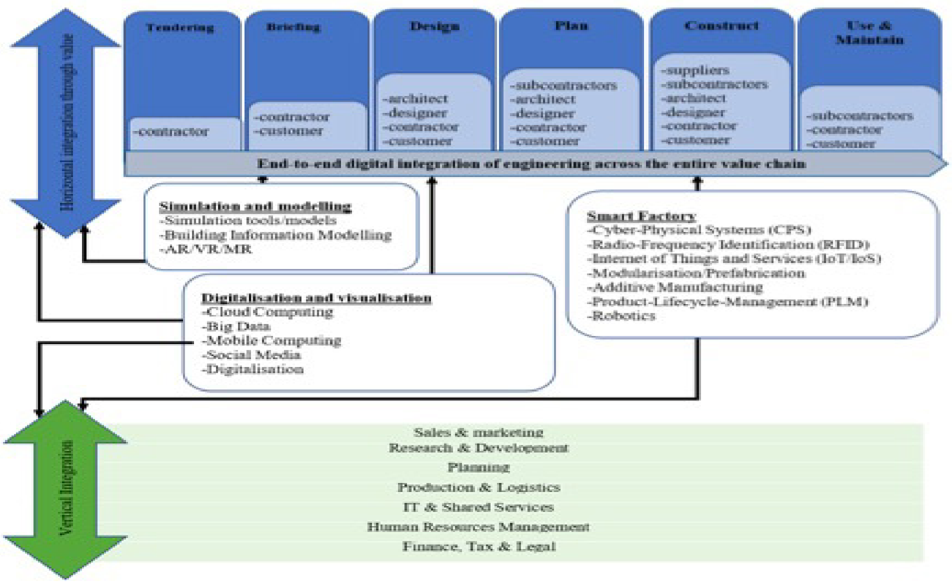
As a result, the industry delivers bespoke products and is thus unable to deliver process efficiencies resulting from learning and repetition. Vertical fragmentation occurs because each project stage requires a different set of stakeholders, decision-makers and values. The decoupling of different stages can give rise to self-interested behaviour and project participants passing costs on to participants in subsequent stages. Longitudinal fragmentation occurs because project teams disband at the end of individual projects and are selected on future projects by fresh competitive bidding. Taken together, this means that there are significant transaction costs in all infrastructure projects, with substantial fragmentation of work on-site in particular among the many subcontractors. Furthermore, the lowest price continues to drive tendering processes. Procurement methods can therefore exacerbate segregated, adversarial and competition-based approaches over integrated, collaborative and partnership-based based methods (Hall et al. 2018). Integrated project delivery, an emerging form of project organization attempts to address this shortcoming (Hall & Scott, 2019).

It follows that the procurement and commercial arrangements in the current industry structure are entrenched with unusually high levels self-employment and unaligned contractual and incentive structures coupled with distrust, a lack of transparency and inefficiencies. This structure acts as a barrier to investment (ORR 2019). Further, years of downward output price pressure and rising input costs have disincentivized long-term capital investments and ingrained low risk behaviours. As Lewis & Offer (2022) observe, while technological innovations mainly originate in the private sector, commercial finance is often too risk averse or has too short an investment horizon to implement costly new technologies in long-lived infrastructure projects whose externalities (such as network effects or spillovers between supply chain participants) cannot be internalized. In the next section we first describe the digital changes under way.

5. Digitizing concrete: technology and future productivity trends

As noted, digitization has spread significantly at the design and build stage, with building information modelling (BIM), but industry participants agree that there is a lot of remaining scope in terms of adopting digital technologies. Major companies such as Crossrail, Ferrovial/Heathrow Airport, Mott MacDonald, Anglian Water, Highways England, and Sellafield among others have pioneered a range of other digital innovations. Despite the success of these companies in creating their own production systems or restructuring their supply chains to deliver their desired outcomes, there has been limited wider adoption across the construction industry. Nevertheless, different elements of digitization offer the promise of some productivity gains. Figure 4 illustrates the points in the value chain at which digitization can operate. Although presented as a linear sequence here, stages can take place simultaneously or with a different order and involve a mix of processes and actors in different parts of the world (Oesterreich and Teuteberg, 2016).

Figure 4: Impact of digital technologies on the construction value chain



Source: Oesterreich and Teuteberg, 2016

5.1 Building Information Modelling

Building Information Modelling (BIM) is defined as the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions (ISO 2018). It is used as a broad term describing the process of creating and managing digital information about a built asset such as a building, bridge, highway or tunnel (HM Government 2012). For example, the Infrastructure Project Authority defines BIM as: "A combination of process, standards and technology through which it is possible to generate, visualize, exchange, assure and subsequently use and re-use information, including data, to form a trustworthy foundation for decision-making to the benefit of all those involved in any part of an asset's lifecycle. This includes inception, capital phase procurement and delivery, asset and facility management, maintenance, refurbishment, and ultimately an asset's disposal or re-use" (IPA 2021: 56). BIM also facilitates more collaborative ways of working by allowing for more efficient methods of designing, creating and maintaining assets. Increasingly it underpins information management processes (PWC, 2018). BIM is now widely used across the sector (Figure 6).

5.2 Design for manufacture and assembly (DfMA) and offsite manufacture

DfMA is a design approach that focuses on ease of manufacture and efficiency of assembly by standardization of components. Traditionally, DfMA has been applied to sectors such as the design of automotive and consumer products, both of which need to efficiently produce high quality products in large numbers. The large construction contractors have begun to adopt DfMA for the offsite prefabrication of construction components such as concrete floor slabs, structural columns and beams. The use of prefabrication and other off-site construction methods on infrastructure projects "offers an alternative to this current construction status-quo by promising transformative improvements across the asset lifecycle in time, cost, quality and health and safety," KPMG (2016:3). In addition, the implementation of DfMA for project delivery is considered to hold the potential for significant productivity improvement by reducing problems of cost overruns, delays and safety concerns, among others (Hall et al. 2018).

5.3 Digital twins

A digital twin is a digital representation of a physical asset, system, or process, which receives data from its physical counterpart. The data is used to simulate the impact of an action virtually before making changes in the real world (UK Parliament POST 2021). The term 'Digital Twin 'is commonly associated with smart manufacturing and Industry 4.0, with the 'twin' part dating back at least to the 1960s. As part of the Apollo program, for instance, NASA created 'twins 'of the Command Module, Lunar Module and Lunar Rover. The twins all stayed on the ground but were used extensively for maintenance, support and troubleshooting (SCCANZ 2020). In construction, digital twins jointly owned by engineers, construction majors and customers can in principle be used as a means of optimizing the operation and maintenance of physical assets, systems and processes (Sacks et al. 2020). By analyzing the virtual model, opportunities can be exploited and actual problems prevented in the physical twin. Artificial intelligence (AI) and analytics can update the digital twin as its physical twin changes. 'Smart' components connected to a cloud-based system can gather data using sensors which allows analysis of real-time status and comparisons with historical data. For example, if sensors detected a queue of traffic on a road, the digital twin would be updated to reflect this and might signal to traffic lights in the physical world to alter their operation, improving traffic flow. Likewise, digital twins can be used for urban planning, as in Singapore, Glasgow, Boston, and Jaipur, and to assess the impacts of proposed changes such as how much additional energy demand a new development might generate. The UK's National Digital Twin Programme is exploring the potential to create a national model, which would connect digital twins of separate elements of national infrastructure. As part of this, the Centre for the Protection of National Infrastructure is developing an Information Management Framework to allow secure and consistent data sharing between digital twins (UK Parliament Post 2021).

5.4 Sensors in infrastructure assets

Both during construction of new infrastructure assets and for existing infrastructure there is an increasing use of sensors. Examples include fibre optics, wireless sensor networks, low power sensors based on micro electro-mechanical systems, and computer vision enabling data harvesting. This can lead to considerably enhanced efficiencies, cost reductions, resilience and adaptability with benefits for the construction industry during the construction stage, and subsequently for the operator served by the infrastructure and their customers. The subsequent gains will include for instance reduced delays and downtime, and lower maintenance costs. For example, the Centre for Smart Infrastructure and Construction at the University of Cambridge has developed fibre optic sensor technologies that enable continuous strain measurements, a key element of materials testing that captures the impact of external forces on stationary objects, for lengths of up to 10 km. This technology has been used to monitor a 100 year old former Royal Mail Railway tunnel during construction of Crossrail's Liverpool Street Station tunnels very close beneath. It has also been used to monitor the performance of deep shafts and retaining walls at other Crossrail sites.[7]

5.5 Data

The adoption of digital technologies entails a huge increase in data generation. In addition to use of cloud capacity, platforms that enable both the gathering and distribution of data from different sources in one place are required (Sategna et al. 2019). Their adoption enables users across the project value chain to co-ordinate better and achieve process improvements. Improved methods of data collection, storage and sharing would address a persistent challenge of poor co-ordination within the construction industry. Data is also at the heart of BIM, digital twins and digital construction more generally. However, currently the data sets available during and at the conclusion of construction projects are usually of low-quality. There is largely paper-based reporting, poor documentation practices, unprioritized and unorganized data, low

[7] Crossrail has been opened as the Elizabeth Line.

reliability repetitive reporting, multiple data and metadata standards and a lack of system connectivity. Hence when a project moves from construction to operation, the operations team is generally tasked with reconstructing a vast amount of the “as-built” or “as-is” BIM at great time and expense (Hunhevicz et al. 2022). The productivity potential lies in enabling sharing data and digital models through information management systems (CDBB 2021). Collecting, storing and sharing complete, high-quality data sets at the end of the project requires that data gathering should take place from as early in the project as possible. Doing so calls for both technological and process related innovations. Blockchain has been proposed as potentially transformative (Hunhevicz et al. 2022). But in any case, standardization and governance around data sharing will be essential.

5.6 Implementation of digital tools

A key aspect of improving construction productivity using digital tools is improving the information flow between the complex interfaces of various supply chain participants, systems, and also across the total lifecycle of assets. Multiple obstacles will have to be overcome for the industry-wide adoption. These include foundational BIM, common data standards and environment, asset information management, design automation, and digital platforms for end-to-end delivery. Nevertheless, the industry perceives a major opportunity to create value or to reduce inefficiency through data and information sharing. This includes common data standards and the creation of a common understanding of the digital environment. It also includes the development of basic tools that enable data sharing so that all stakeholders can work with a consistent set of data models. Fundamentally reducing the friction in data sharing is something that needs to be addressed, given the structure of the supply chain and sub-contracts described earlier. In addition to technological applications, this will require the development of commercial relationships between parties in the supply chain, based on a mutual interest to share data, and may require policy intervention to enable or co-ordinate. An understanding of the data value chain, and valuing digital assets, would be helpful in improving performance. Digital twins, data, and related information are intangibles that are challenging to capture in traditional financial reporting, or in national accounts. Yet the examples of productivity gains achieved by companies deploying digital twins or using data purposively have been impressive (see Box 1).

Box 1 – Examples of digital technology deployment

Anglian Water

Anglian Water is the largest water and wastewater company in England and Wales geographically, covering 20 per cent of the land area. It has been trialing new technology to find and measure leaks in water mains. Sensors measure the variation of electricity passing through the pipe walls, as current does not pass through non-metallic pipe walls but will pass through a defect or leak. Therefore the bigger the defect the larger the electricity flow. The technology can detect any holes as small as a centimetre in diameter as well as estimating how much water is lost in litres per second, meaning the company can prioritize repairs accordingly. According to the company, the adoption of these and other digital developments, including advanced analytics through a Digital Business Twin saved £1.4 million in operating costs in 2021.

National Highways (Highways England)

National Highways aims to develop a virtual twin of England s motorways and major road network to predict the time and location of maintenance issues, replacing drawings and static 3D models with dynamic and data-rich digital twins, pdf documents with databases, and file exchange with shared cloud exchange. National Highways also aims to introduce smart materials able to partly automate manual routine maintenance. For instance, it will be easier to identify when and where potholes occur, and integrate live data from sensors on the road surface with a digital twin.

Laing O Rourke DFMA Modern Methods of Construction

Laing O Rourke is a pioneer in modern methods of construction (MMC). The company has invested in DfMA aiming for 70% of the construction be taken offsite, claiming big gains (60%) in process efficiency, and time needed (30%). Apart from efficiency and speed, 'DfMA 70:60:30' is also aimed at improving product quality, reducing material waste and supporting the creation of a more digitally-skilled workforce. Its £200M Centre of Excellence for Modern Construction in Nottinghamshire employs 400 people, who design and precision manufacture offsite a range of components for use in major building and infrastructure projects, such as twin walls, floor slabs, pillars, facades and digital modular bridges to span roads and railways.

Jacobs *Replica* Digital Twin Software

Jacobs *Replica* digital twin software is a suite of object-oriented blocks and libraries developed since 2001. Models are assembled within a customizable interface to simulate numerous aspects of a system simultaneously. The software can simulate large, interconnected, multi-component resource systems from drinking water supply to energy generation. Capturing and visualizing results related to fluid dynamics, operations and controls, and process and water quality, for example, enables understanding of tradeoffs in the system.

Sources: Company documentation

Digitization is likely to change the structure of the industry further. Data science and related skills will be needed (and are scarce). There has been some upward trend in skill levels in the industry (ONS 2021); it seems likely that the new technologies could increase demand for both highly skilled workers (complementary to the technology) and low skilled workers (to the extent some activities are routinized). As noted, the traditional engineering consultancies and design companies are seeing their activities being outsourced and commoditized. Equally, the current contractor model in construction is slowly changing. The traditional smaller (sub-)contractors are being gradually replaced by manufacturing companies making components offsite. The on-site contract is expected to increasingly become an assembly process, with certain specialists doing ground engineering to get the structure off the ground.

The potential for digitizing the industry is seen by participants as significant, albeit aspirational: "Perhaps as much as 50 per cent of the cost of producing high-performing built assets can be eliminated," is a representative comment (Stacey 2021). Digitization should enable less costly and faster construction, higher and more consistent quality assets (as quality is easier to monitor in a factory than it is on-site with many sub-contractors), and ongoing reductions in operational expenditures thanks to the sensors embedded in new infrastructure, cutting maintenance costs and down-time. However, achieving these elements of productivity gains may not be achievable within existing contractual relationships and business models; rather, there needs to a wider restructuring of business models and supply chain relationships, including data sharing among parties to major projects. Indeed, the industry lacks a consistent performance measurement framework that enables learning and better decision-making (Murguia et al 2022).

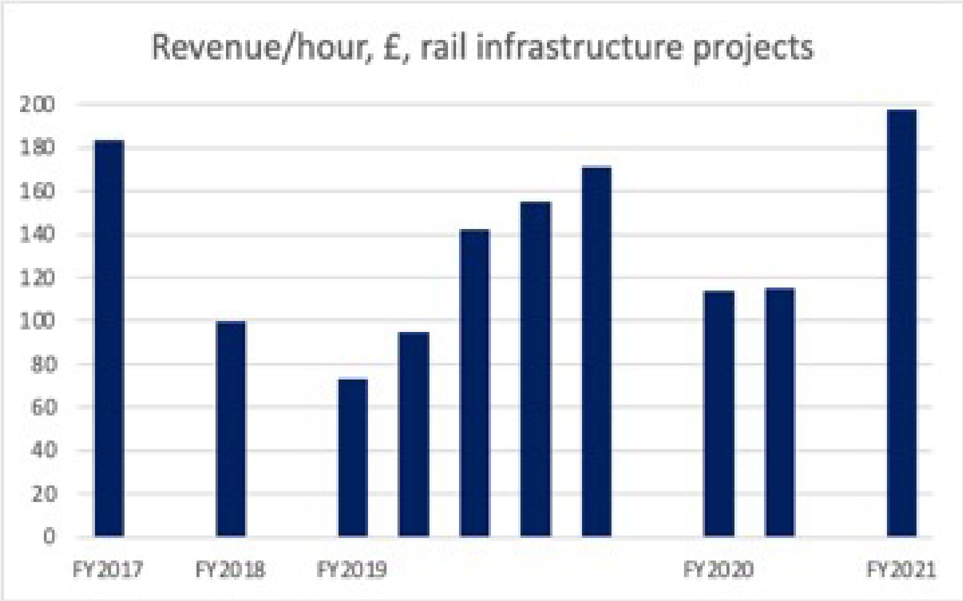
This description of the way the benefits of using digital technology are related to the structure of contractual relationships in the sector makes it clear that – as in many other sectors – there is likely a "productivity J curve" (Brynjolfsson, Rock & Syverson 2021). The effective use of digital technology even within a single firm requires organizational change and learning, such that productivity might even decline initially. The process of adoption is likely to be even slower when contracting between different firms is involved, particularly with regard to digital technology as it may significantly shift the information asymmetries (Williamson 1985). While there is certainly industry hype about the potential of digital tools, there is productivity potential from the use of digital in infrastructure, as the use of different aspects of the technology continues to diffuse across the sector and as new assets are built and demonstrate the gains. However, in addition to the time lag for digital adoption to occur and to deliver productivity gains, there may be some considerations relating to productivity measurement..

6. Measurement challenges

In this section we consider some measurement issues relating to classification, quality adjustment of input and output price indices, and maintenance and depreciation.

The industry has begun to collate, through the Infrastructure Projects Authority, more detailed statistics on revenues and costs. One of its key metrics is project revenue per hour of labour. For 55 projects started between 2017 and 2021, this figure (excluding two large defence outliers) averaged £183.50, but with a large standard deviation of £286. The projects include a large variety, from road and rail schemes to flood defences and hospitals. Even within categories, the revenue per hour worked varies substantially, with no trend evident over the four years available; for example Figure 5 shows the revenue per hour for rail projects as an example.

Figure 5: Revenue/hour worked, rail infrastructure projects



Source: IPA; project level data; year indicates start date of project

The industry also uses the concept pre-manufactured value(PMV) , which refers to the total costs incurred up to work starting onsite, excluding the design and consultancy stage, expressed as a percentage of gross costs. These costs include raw materials, components, off-site manufacture, assembly and transportation. A higher PMV for a project is understood by those in the industry to reflect higher onsite productivity thanks to waste reduction, faster delivery speeds and better integration of activities. This figure varies considerably, even excluding lumpy defence projects, ranging from 10% to 88%. For example, for the rail projects shown in Figure 5, the PMVs (where available) range from 20% to 77%, demonstrating the challenge of dealing with great heterogeneity and lumpiness of infrastructure projects for the purposes of economic measurement. What's more, the industry approach differs from the economic definition of productivity, not least as these figures are all in current prices. PMV is imperfect and has been criticized within the industry on the grounds that it does not necessarily measure (or result in) improved productivity of projects as a whole. Nor do these industry figures make it easy to draw any conclusions about changes over time, given the variation and lumpiness.

6.1 Sector classification

in any case, productivity measures based on official statistics could potentially miss important changes in the structure of the construction industry because Section F, Division 42 in the Standard Industrial Classification does not account for construction-related activities such as architectural and engineering activities and off-site manufacturing. Architectural and engineering businesses sit in professional, scientific and technical activities (division 71, Section M) while modern methods of construction, such as modular and offsite construction, are likely classified as manufacturing (Section C across several divisions). The performance of architectural and engineering services follows a very similar trend to the series for the construction industry in the statistics, however, with a slow productivity growth record. Expanding the scope of construction to include these activities would thus have little impact on current measures of productivity (ONS 2021). However, the fact that engineering and other services have a similarly lacklustre productivity record is even more surprising than for the construction sector itself, as these are exactly the parts of the process that have most extensively digitized to date.

The transition to offsite manufacturing using DfMA is less extensive although increasingly implemented in major projects by some key firms. Of the small selection of the reported DfMA case studies, the reported benefits focus on the time savings (Davies 2013) followed by improved and more consistent quality and safety. Sinclair et al., (2016) found a 20–60% reduction in construction programme time, and greater programme certainty. Gao et al., 2019 also document significant time savings. There has been no consistent data collection although industry bodies are developing measurement frameworks (van Vuuren and Middleton 2020).

If the offsite manufacturing is carried out by a division of a firm whose principal activity is construction, such as Laing, the activity will be reported in the construction sector (Section F); published annual reports do not break the revenues associated with the activity out separately. Dunlop Taylor (2010, 2020) reports, based on industry and marketing databases combined with FAME data, that other offsite manufacturing is recorded in manufacturing (Section C) across several different sub-sectors (23, 24, 25). He found that about half the value added from offsite manufacture was due to large companies (over 1200 employees). Using a random sample of the identified firms, he found that current price value added in 2018 was about £1.7bn, just under 6% of all value added by new UK construction. Even if offsite manufacture provides a substantial lift to the productivity of a major project, it would have to grow substantially to shift the overall sector-wide productivity figures. Taylor's figures indicate that (in current price terms) the gross output of offsite manufacture has grown about 2% a year and valued added about 0.6% a year from 2000-2018.

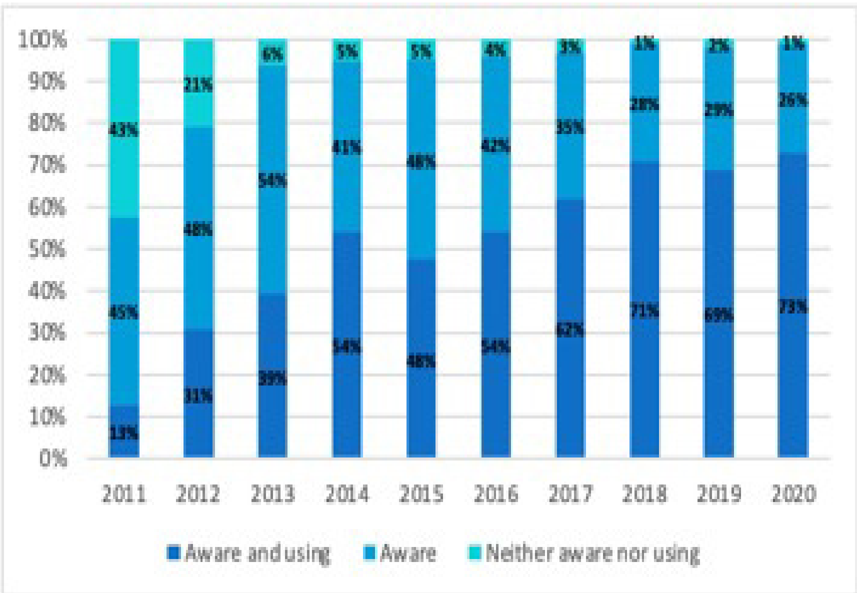
We conclude that while the changing structure of the sector has some implications for interpreting productivity figures, these are not yet large.

6.2 Input prices

Measurement of (output and input) prices in the infrastructure sector is inherently challenging as the projects are distinctive, and quality is hard to measure. These challenges will have larger implications for interpreting productivity statistics.

There is industry evidence that the use of BIM and outsourcing of the design stage is widespread (Figure 6). Survey evidence of design and other construction professionals (NBS 10th National BIM Report) suggests nearly three quarters of the construction industry uses BIM, which has been mandated in public sector projects since 2016. The NBS 2019 survey reported growth in BIM awareness and adoption, from 10% in 2011 to over 70% (NBS 2020). During this period, in 2015, the UK Government reported that the delivery of the Level 2 BIM programme enabled a 20% savings on CAPEX as recorded by Cabinet Office (now IPA) case studies against the 2009/2010 benchmarks (HM Government 2015). Moreover, a Cabinet Office Benchmarking Report in 2016 estimated that BIM enabled £3bn in capital savings between 2011 and 2015. Use of BIM can also improve safety and save time due to improved co-ordination. Incoroprating reduced costs and improved quality in design would also affect the deflator and hence measured productivity of (upstream) Division 71. Anecdotal evidence in the industry suggests the price of these design services has in fact declined significantly in recent years. However, there remains variation in sub-contractors' adoption and implementation of BIM, which are mostly related to company size.

Figure 6: BIM Adoption in the UK 2011 to 2020



National Building Specification (NBS) (2020)

Two potential factors influencing price declines for design, intermediate services and off-site manufacturing include internationalization and standardization. Business, professional and technical services have been among the most rapidly growing services sectors in developed countries (WTO 2021). At the same time, these services ranging from legal to management services, and from architectural to advertising services became one of the main export sectors in certain developing economies, such as India and Brazil. In Brazil for example, in 2007 services accounted for 45 per cent of Brazil's total commercial services exports, totalling US$10 billion, with architectural, engineering and other technical consultancy services the largest subsectors, followed by legal services. Consistent with assertations made by Keune (2007), today, work is outsourced to countries in Asia, Central and South America, Eastern Europe and beyond. As Ribeirinho et al. (2020) argue "greater standardization will lower the barriers to operating across geographies. As scale becomes increasingly important to gaining competitive advantages, players will increase their global footprints—especially for low-volume projects in high-value segments such as infrastructure." This too will have an impact on prices as in the long term, increased competition could lead to price reductions and quality improvements.

Another consideration in terms of input costs is waste. The construction industry currently produces a huge amount of waste. "Construction, demolition and excavation accounted for an astonishing 62% of the UK's total waste in 2018," (Defra 2021; see also Osmani 2012). In both 2012 and 2016, construction and demolition waste in the UK was around 120 million tonnes per annum (GCB,2020; Osmani 2012). In 2012 this included an estimated 13 million tonnes of unused material (Osmani 2012). A large portion of the waste cannot be recycled. There are strong environmental pressures to reduce waste, through the use of digital tools such as BIM and DfMA improving co-ordination and reducing uncertainty about the on-site construction process (CDBB & CSIC 2020).

These shifts suggests that there is a case for looking in more depth at the revenue and price data to consider sampling (are prices for outsourced services being effectively captured?) and quality adjustment, including input price effects of the gradual shift toward offsite manufacture. One aspect of quality adjustment is the impact of higher quality construction on asset lives; if these lengthen, the capital stock will depreciate more slowly. Using firm-level detail to construct price indices could also affect intermediates prices used in double deflating value added. Price indices should be adjusted for the higher quality of BIM-enabled construction, and ONS is considering whether it can use proxies such as change orders, non-conformance reports, or accident reports.

6.3. Servitization, output quality and output prices

Sensors are increasingly embedded in new infrastructure. Sensor technology is capable of producing vast amounts of data to help streamline operations and to monitor the health of infrastructure. Part of the change in industry structure being brought about by digitization is the increasing provision of ongoing services by the infrastructure companies to their customers subsequently operating services, a process of 'servitization 'familiar from parts of manufacturing. These include monitoring the condition of the asset and also embedded digital services such as signalling systems or information systems. The process is shifting value added along the supply chain. Monitoring of the condition of the asset brings benefits of reduced uncertainty, improved safety, and the averting of closures or service disruption and resulting time savings (compared to the counterfactual), all with corresponding cost savings (KPMG 2016; WPI Economics 2020).

To the extent that the servitization of infrastructure assets is carried out by construction companies, the benefits in terms of reduced operating costs and quality improvements will be reflected in the sector's revenues and value added. Yet there would also be downstream gains – for example, for train operating companies experiencing reduced delays and disruption, which are costly for them in terms of lost revenues, fines and compensation as well as repairs. It is also improving the quality of the sector's output: service providers and their users experience fewer delays, reduced maintenance needs, greater safety, and reduced risk of asset failure (or greater resilience). Work by the US BLS (Sveikauskas et al 2016) to improve measurement of the construction sector through better price indices made little difference to the productivity performance of the highways sector, the closest sector to infrastructure they considered. However, this work did not account for potential quality change. A dramatic example of the potential is the sensor system operating on Japan's high-speed Shinkansen network: the sensors detected via seismometer the impending 2011 earthquake and automatically halted trains on the network in the affected area, likely saving many lives. The process of embedding sensors is incremental as relatively few infrastructure assets are built each year (although there is also considerable retrofitting, for instance of fibre-optic monitoring of stresses in London's 100 year old Tube tunnels (Soga & Schooling 2016)), but there are nevertheless quality improvements over time that it would be desirable to capture in output prices. One type of quality indicator for example would be reductions in delays. Digitization in infrastructure construction will be reflected in economic gains in adjacent sectors. Train services and rail tracks are complements, and it is not clear that allocating productivity gains due to sensors on the track to the train operating company is the right way to measure the creation of economic value.

Setting this conceptual issue to one side, developing a quality-adjusted output price index will require collection of additional data from the industry and agreement about what quality characteristics might be included, for example in a hedonic output price index. The potentially useful data is held across a large number of client organizations, mainly public sector, and relates to projects that are quite distinctive. These can be divided into sectors that consist of somewhat more similar projects (communications, education, health, energy, transport, flood defence etc) and we are continuing to work with the Infrastructure Projects Authority to access the project data, which would include revenue per hour and input costs, with a view to developing an aggregate index.

Finally, a wider set of quality considerations concerns the environmental impact of built assets, an issue of intense discussion in the industry. Improved environmental performance might be linked to digital technology – for example, 'smart 'motorways that can reduce congestion and pollution – or to other factors such as the use of different materials (less concrete, more recyclable materials) in construction. Economic statistics are concerned with measurement of outputs not outcomes, so we do not consider this further here; and yet from the user perspective these are also quality improvements.

6.3 Maintenance, capital stock and capital services

The lifetime of infrastructure projects can be long. In the UK, Victorian bridges and sewers, and even Roman roads (albeit much maintained and upgraded) are still in use in the 21st century. Many infrastructure assets undergo upgrades or enlargement, significantly extending their lives. Many in the industry are arguing for measurement of its output in terms of the services delivered to end-users on a whole lifetime basis, including environmental impacts. This outcome-based approach speaks to the debate about wider measures of the economy than are captured in current definitions of GDP (Heys et al., 2019; Foxton et al., 2018).[8] On the other hand, there has been much commentary on the depreciation of some infrastructure such as roads due to inadequate maintenance over time. Maintenance and appropriate

[8] There are three types of maintenance: corrective, preventative and predictive. Corrective maintenance refers to repairs made after a problem or failure occurs; preventative maintenance refers to scheduled repairs made based on past experience of need; and predictive maintenance occurs because data for an asset indicates that a failure is imminent. While digital sensors aim to reduce total maintenance needs by replacing more costly corrective and preventive with predictive spend, this largely lies in the future.

depreciation affect calculation of capital stock and capital services for TFP measurement. In the standard growth accounting framework, (real) capital stocks are estimated using the perpetual inventory method, with assumed (geometric) depreciation rates applied and an assumption of constant asset life (Jorgenson & Stiroh 2000).

$$K_{jt} = K_{j(t-1)} (1 - \delta_j) + I_{jt} (1 - \delta_j / 2) - O_{jt}$$

where:

K_{jt} = real net stock for year t for asset type j

δ_j = annual depreciation rate for asset type j

I_{jt} = real investment for year t for asset type j

O_{jt} = other changes in volume of assets for year t for type j (often assumed to be zero)

Equivalently,

$$K_{jt} = K_{j(t-1)} + Ij_t - Oj_t - Mj_t$$

Where:

$$M_{jt} = K_{j(t-1)} \delta_j + I_{jt} \delta_j / 2,$$

real depreciation (consumption of fixed capital) year t for asset j.

Some portion of the infrastructure in use has been depreciated to near-zero and is delivering no measured capital service. This part of the capital stock is thus underestimated. On the other hand, , some assets may be delivering lower than measured capital services due to inadequate maintenance. Recent work in the US for the Bureau of Economic Analysis (BEA) (Bennett et al 2020) highlighted the latter problem, reporting that investment in many types of infrastructure had not kept pace with depreciation, with rising average age of assets. They found variation between asset types and called for more research on maintenance spending, asset life, and appropriate depreciation rates. Another consideration will be the role of intangible assets as the sector digitizes, and particularly the measurement of data assets. Digital assets themselves are generally thought to have shorter lives, but in the case of infrastructure their introduction is likely to reduce maintenance requirements and lengthen the material, steel and concrete, asset lives. The appropriate choice for digital concrete is an open question and will vary considerably between types of asset. A further issue, which we do not pursue here, is how to assess productivity over the whole lifetime of infrastructure assets, taking into account reduced maintenance and downtime costs, and the environmental benefits of longer asset lives.

7. Conclusions

We have considered the puzzle of slow productivity growth in construction of infrastructure projects, in the face of evidence of rapid adoption of digital technologies, from two perspectives: the possibility that there are delays in the resulting productivity gains; and the possibility of mismeasurement. Both seem likely to contribute to the flat productivity performance of the sector – along with other factors we have not discussed here such as regulatory burden or low skills. In terms of the productivity lag, the current fragmented structure of the industry in the UK involves high transactions costs. Digital technology and information management could considerably reduce these, but this will require far greater co-ordination and data sharing, along with changes to business models and contracting. In terms of the measurement challenges, quality-adjusted input prices seem likely to have declined by more than implied by the current index given the considerable digitization and outsourcing that has already occurred upstream, while output quality gains and the impact on productivity of adjacent sectors are statistical issues needing further investigation.

The UK sector's flat productivity performance to date is perhaps not so puzzling in the light of the issues we have discussed here. But it is important to note that productivity J-curve implementation delays and the measurement questions with regard to price indices, quality adjustment or sectoral shifts are inter-related: the further the digitally-enabled restructuring of the infrastructure sector that is under way proceeds, the more acute the potential productivity mis-measurement will become.

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