

Digital concrete: productivity in infrastructure construction

Draft submitted to NBER/CRIW Conference on Technology, Productivity, and Economic Growth 2022

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Construction is a large sector of the UK economy and official statistics show that construction productivity has flatlined despite adoption of advances in digital technology and increased outsourcing. We examine the evolution of the UK construction industry, and the scope of its digitisation, 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. We focus on two possible explanations for this piece of the productivity puzzle: time lags, and mismeasurement.

Key words: Productivity, digitisation, construction, infrastructure
JEL codes L10, L11, L16

1. Introduction

The construction sector 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 (negative 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 (e.g. Goodrum, Haas & Glover 2010), including a significant increase in the use of digital tools from the design stage all the way through to maintenance. Work by the BLS to improve deflators for some parts of the sector has gone some way to resolve the puzzle in U.S. data (Sveikauskas et al 2016), but this project did not consider the activity shifts within the sector or the implications for deflators of the ongoing digitisation of construction.

In this paper we explore the impact of digitisation on the structure and productivity of the UK’s civil construction sector, including implications for measurement of output and prices. Our focus will be major projects and civil engineering rather than residential construction; civil construction has had and likely will continue to have more digitisation, and there are fewer complexities related to land use and land values. In the infrastructure sub-sector there has been substantial change in market structure since 1980, along with accelerating technical change. The use of computer-aided design (CAD) tools has steadily commoditised the design stage, leading to considerable outsourcing to countries such as Brazil, India and Poland. On sites, much construction activity is now contracted out to specialist sub-contractors. In between, both consultants and major contracting firms seek to capture value through

¹ Bennett Institute, University of Cambridge, ESCoE, and The Productivity Institute; we gratefully acknowledge funding from Office for National Statistics (ONS) as part of the research programme of the Economic Statistics Centre of Excellence (ESCoE), and The Productivity Institute funded by the UK Economic and Social Research Council (grant number ES/V002740/1). Our thanks to participants in workshops at the University of Cambridge, NBER and the Productivity Institute, and to the many industry participants we interviewed, particularly John Pelton, Simon Murray, Mark Enzer, Kevin Reeves, Melissa Zanocco, Josh Martin, Sam Stacey and Bart van Ark. We are also grateful to our colleagues Qian Chen, Campbell Middleton, Danny Murguia, and Jennifer Schooling for their helpful insights and comments.

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 CAD, whose major benefit is reduced construction time. 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. While all these developments are widely recognised in the industry, these changes are seemingly not yet reflected in output, price and productivity statistics, which could be due either to gradual implementation of the technologies across the sector, or to measurement issues such as failure to quality-adjust deflators (although there may well be other reasons for productivity headwinds, such as planning restrictions).

In this paper, we first set the scene with 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 describe 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: 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. Others still, such as Brazil and Saudi Arabia, are falling further behind. 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. In comparison to some other countries, the productivity record of the UK industry is relatively good.

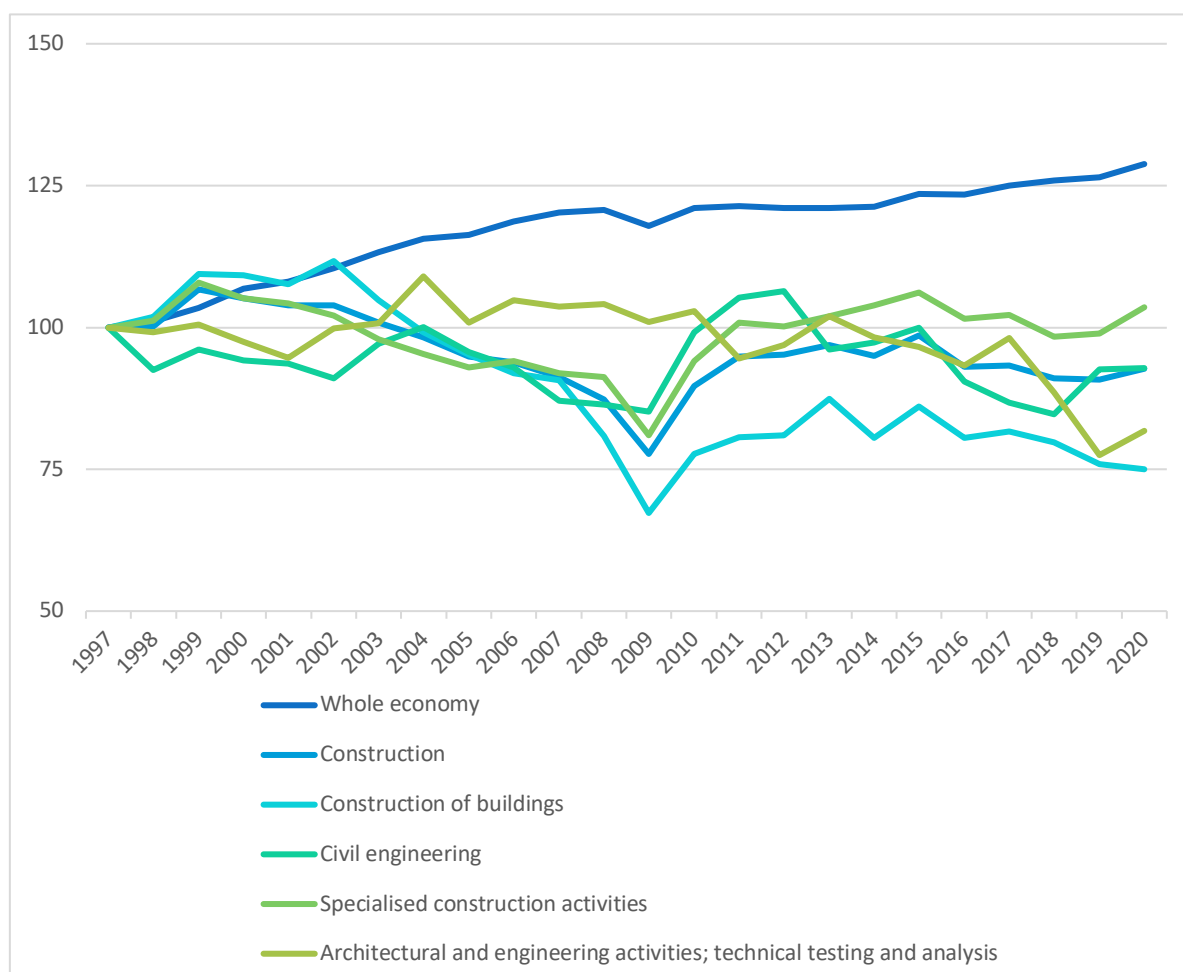
However, all sectors of construction have seen their productivity grow more slowly than the rest of the economy (Figure 1), and over a long period its labour productivity has been flat and its TFP declining (Figure 2). As a result, infrastructure assets have become relatively more expensive over time. This is in contrast with a few smaller countries—notably Australia, Belgium, and Israel—which have combined high measured productivity levels with comparatively fast growth. The upturns of productivity in Figures 1 and 2 tend to coincide with economic slowdowns. This may be due to less productive workers entering the industry in high output periods and diluting overall productivity, as construction is relatively labour intensive compared to other industries that have been more easily able to automate.

Our main focus is on SIC 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 15% of the whole construction sector (at current prices) in recent figures, although with substantial variation at different periods.

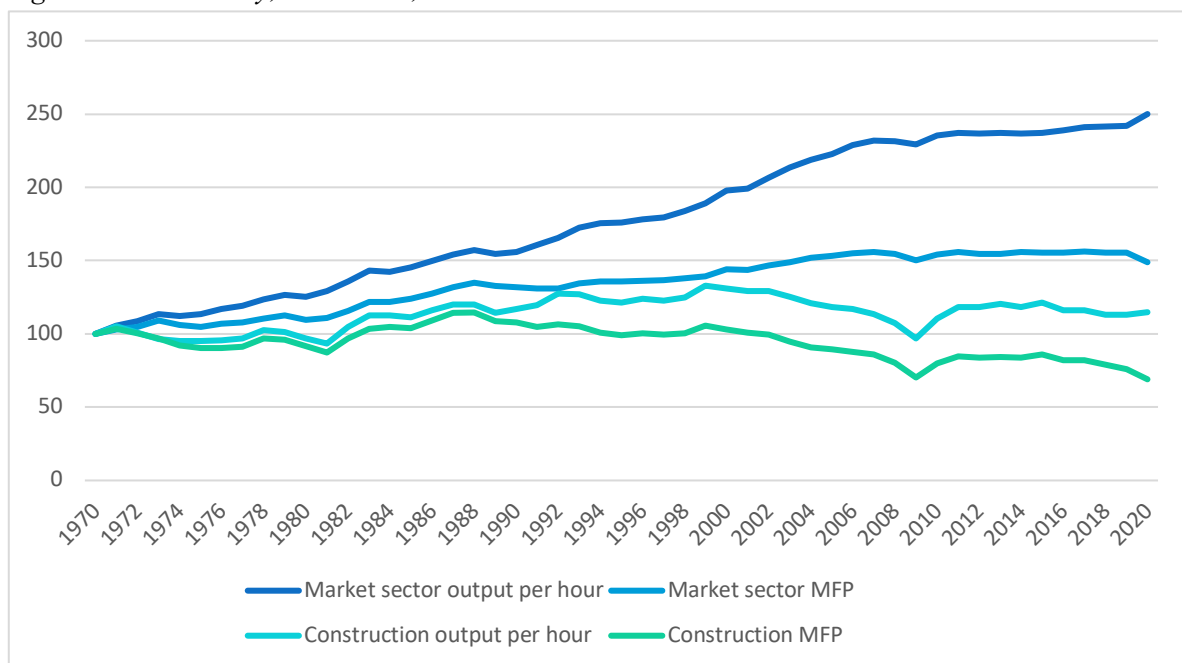
The intermediate expenditures used to calculate nominal value added have shifted over time from materials to services (architectural, engineering and technical services). In 2018, compared with 1997, the share of intermediate spending on computer services rose 1.3% points and on architectural, engineering, technical and testing services 2.7% points, while the shares of all other categories in total intermediates expenditure declined (by 4% points in the case of cement and similar construction materials). The shift can be summarised as more intangibles and less material being used, in this most material of industries. This is reflective of the progression of digitisation and the way this is changing the structure of the industry, as we detail below. Real value added in construction as a whole and the civil engineering sector has increased more slowly than for the whole economy; for civil engineering the volume terms index was just 102.2 in 2020, from 100 in 1997. Prices applied to the revenue data to construct a volume-terms output measure have trended upward significantly since at least the late 1990s, with the exception of a small dip in the post-financial crisis period. The double deflation of volume-terms construction output may need to take account of the fact that it is harder to measure the price of the services taking a growing share of purchases of intermediates as compared to materials inputs.

Figure 1: Productivity Growth Index, 1997-2020, 1997 = 100



Source: Martin (2021)

Figure 2: Productivity, 1970-2020, Index 1997=100



Source: Martin (2021): MFP ‘multifactor productivity’ is used for TFP

Input series for labour and capital services are required to calculate TFP. ONS figures show that there has been a gradual upskilling in the labour force (although around one third still have no qualifications), so hours could be quality adjusted to reflect the higher average qualification level; the share of hours worked by the most highly educated 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 will be linked to the increasing technological sophistication of the sector but we do not consider it further here.

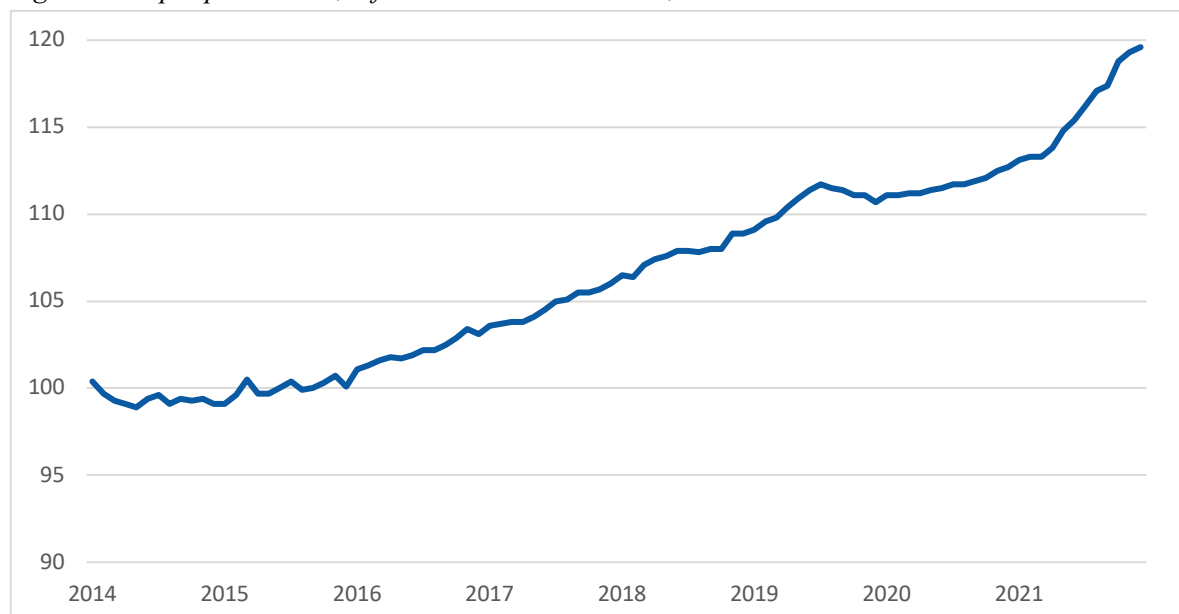
Capital stock measures include the usual tangible assets, software and R&D but not data or other intangibles; capital services used have grown quickly over time. The proportion of the sector’s capital stock in the form of IT hardware and recorded intangibles has increased significantly from 6% in 1997 to 14% in 2020 (Martin 2021). There has been a sharp increase in capital services used in the sector over that period, implying capital deepening.

Output prices for the infrastructure sector are more volatile than for construction as a whole while following the same profile. The published index has shown an acceleration recently, up 3.7% in the year to December 2021 (Figure 3).

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 40 years (or longer), 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) and the digital transformation that is now under way. While productivity stagnation might be attributed to the extreme fragmentation and decentralized project organization that still categorises 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 price index, infrastructure construction, 2015=100



Source: ONS

<https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/datasets/interimconstructionoutputpricendices>

3. A brief history of the UK infrastructure sector²

The origins 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 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 specialisation 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 formalise 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

² Unless otherwise stated this and the next section draw from Murray (2021) Evolution of the UK Construction Sector, as presented at the University of Cambridge Digital Economics & Policy Online Workshop on Construction and Infrastructure, and the discussion at that workshop.

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 specialise. Despite the many shortcomings of the nationalised 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 recognised 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 privatised 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 privatised infrastructure sector. 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 the rump of the company changed its name back to Tilbury Douglas.

4. Current structure of UK infrastructure industry

There are almost 350,000 companies making up the construction sector in the UK (ONS 2020), and perhaps another 30,000 manufacturers and materials suppliers in its supply chain. The sector is composed of some large companies and a patchwork of SMEs and micro-businesses. This market structure is changing thanks to digitisation and automation (see Ostarvik 2014; Whyte 2019), increasing efficiency by integrating and optimizing processes (Pittman 2018; Cao and Hall, 2019; Griffin et al. 2019). The continuous deployment of technology in the industry is recognised as critical for continuing innovation (WEF 2018; Barbosa et al. 2018; Oti-Sarpong 2019). One important change is that industrialised construction includes off-site manufacturing, namely the use of prefabricated components, or kits-of-parts, developed in a factory for subsequent installation in their final positions in a structure on site (Goodier and Gibb 2007). 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 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.

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). 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 general 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.

Table 1: Top 5 UK Project Managers (2021) Chartered Project Manager and Total Staff Count Changes, 2015 & 2021

Firm	Total UK Chartered Project Management Staff			Total UK Chartered Staff			Total UK Staff		
	2015	2021	% Change	2015	2021	% Change	2015	2021	% Change
Mott MacDonald	869	1,272	46%	3,033	3,673	21%	5933	7,059	19%
Turner & Townsend	755	1,132	50%	1363	2,093	54%	1897	2,907	53%
Arcadis	876	684	-22%	2645	2,319	-12%	3700	3,881	5%
Aecom	714	460	-36%	3527	2,588	-27%	7423	6,679	-10%
Gardiner & Theobald	151	297	97%	508	679	34%	687	867	26%
Total	3365	3845	14%	11076	11352	2%	19640	21393	9%

Source: Building UK

The changing structure of the industry has also seen an increase in internationalisation. The Engineering News Record, source of annual industry statistics, reports that the leading 225 companies 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 International Design Firms generated \$18.9 billion in revenue from projects outside their home countries. Thus, as an example, project design has become highly commoditised, the use of outsourcing to countries such as Brazil, India and Poland widespread, and the price of these services has subsequently fallen. The latter is consistent with the considerable 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
Switzerland	374	\$140,983.00
United States	7575	\$115,000.00
Australia	890	\$113,664.00
Germany	815	\$106,498.00
Netherlands	174	\$101,711.00
United Kingdom	788	\$96,326.00
Ireland	340	\$95,728.00
Belgium	138	\$92,737.00
New Zealand	284	\$88,886.00
Canada	4152	\$81,869.00
Hong Kong	215	\$81,805.00
Sweden	240	\$79,630.00
Singapore	868	\$74,936.00
Japan	764	\$73,448.00
France	451	\$72,993.00
South Korea	191	\$71,678.00
Qatar	31	\$69,231.00

South Africa	516	\$67,698.00
United Arab Emirates	801	\$67,690.00
Italy	1260	\$62,223.00
Spain	1004	\$59,830.00
Chile	148	\$59,187.00
Saudi Arabia	990	\$53,328.00
Portugal	251	\$47,864.00
Poland	272	\$47,289.00
Russian Federation	119	\$39,629.00
Taiwan	168	\$38,829.00
Mexico	708	\$38,785.00
Malaysia	448	\$35,274.00
Philippines	213	\$35,188.00
Peru	311	\$33,108.00
Colombia	452	\$32,175.00
Indonesia	106	\$31,119.00
China	503	\$30,623.00
Brazil	859	\$29,951.00
India	1743	\$25,633.00
Turkey	273	\$24,664.00
Nigeria	318	\$21,108.00
Egypt	236	\$17,858.00
Pakistan	173	\$13,803.00

Source: Project Management Institute (2021); market exchange rates

An important defining characteristic of the construction industry today is therefore its structure including its organisational separation from clients. This contrasts with some other industries where continuing services are becoming a more significant part of value creation, although this is starting to change with infrastructure. Contractors and their supply chain 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 multiple 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’ organisations 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 saw many contractors reduce their overheads by selling off their plant, 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 sub-contracted to specialist suppliers and contractors. And many of the engineers, estimators and construction managers that used to enable these companies to deliver complex projects have been replaced by vertically integrated commercial managers and experts in contracts (Murray 2020). As described below, digitisation 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. Large firms contract with a multitude of small contractors under what is sometimes described as an adversarial circumstances.

Table: 3: UK Top 6 construction firms based on revenue (in millions of British pounds), 2014 to 2019

Firm	2014	2015	2016	2017	2018	2019
Balfour Beatty	8,793.00	8,444.00	8,215.00	8,234.00	7,802.00	8,405.00
Kier Group	2,954.30	3,275.90	4,082.30	4,282.30	4,512.80	4,479.40
Interserve	2,913.00	3,204.60	3,244.60	3,666.90	3,666.90	3,225.70
Morgan Sindall Group	2,219.80	2,384.70	2,562.00	2,792.70	2,972.00	3,071.00
Galliford Try	1,767.80	2,348.40	2,670.00	2,826.00	3,132.00	2,862.50
Amey UK	2,167.90	2,531.90	2,591.00	2,581.30	2,581.30	2,667.80

Source: The Construction Index

The resulting structure of the construction industry is thus characterised by extreme fragmentation in three dimensions: horizontal, vertical and longitudinal (Fergusson 1993). Horizontal fragmentation is the result of an intensive project-based, trade-by-trade³ 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. As a result, the industry delivers bespoke products and is unable to deliver process efficiencies. 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 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).

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 disincentivised 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 internalised. We return to this in discussing the

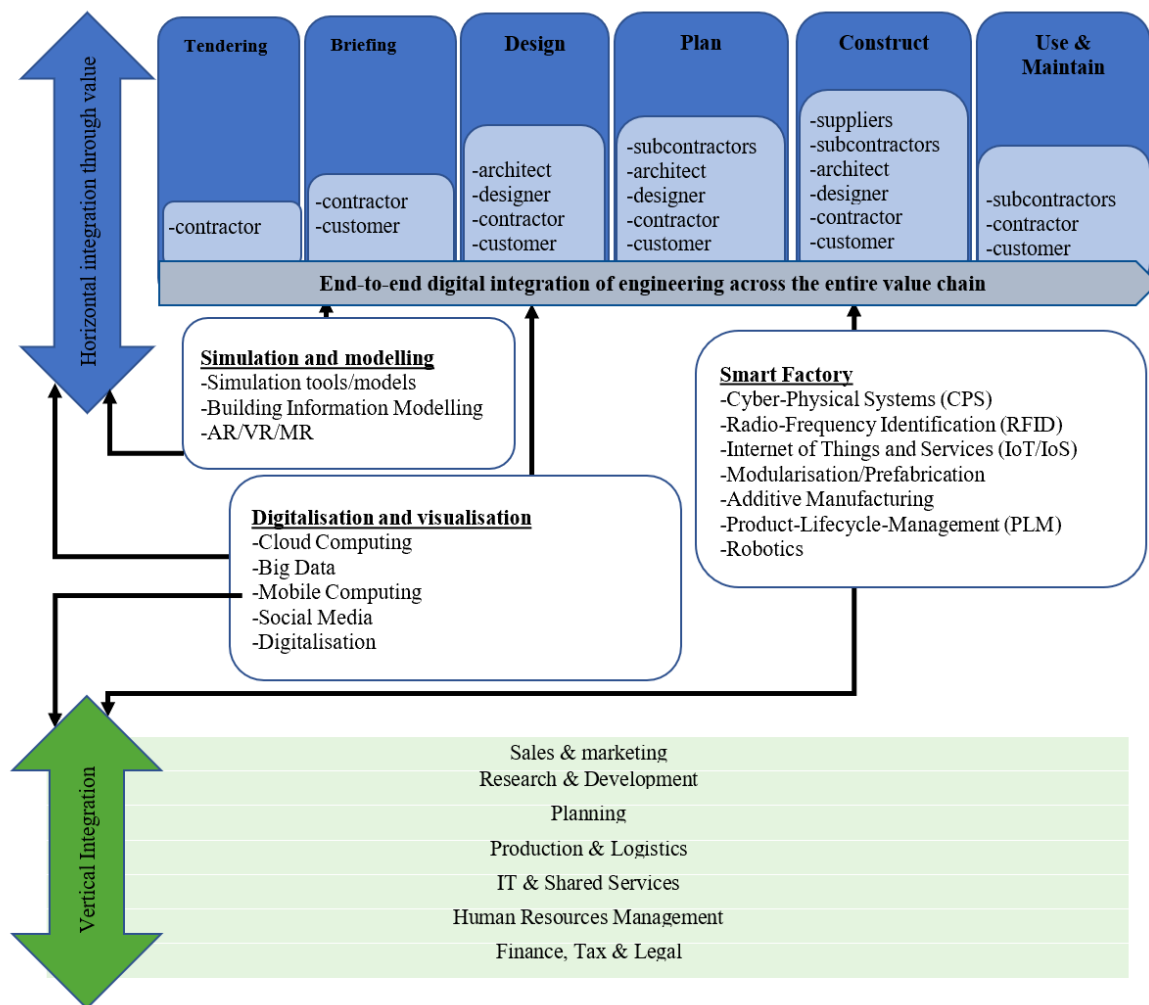
³ Architects, engineers (mechanical, electrical, structural), building contractors, subcontractors

impact of both digital and the decarbonisation imperative on future productivity. In the next section we first describe the digital changes under way.

5. Digitising concrete: technology and future productivity trends

As noted, digitalisation 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 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 digitisation offer the promise of productivity gains. Figure 4 illustrates the points in the value chain at which digitisation 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

In international standards 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, visualise, 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.

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 simplification. 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. Construction contractors have begun to adopt DfMA for the offsite site prefabrication of construction components including, but not limited to, 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 to these and other benefits widely recognised in academia and industry, 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 can be used as a means of optimising the operation and maintenance of physical assets, systems and processes. By analysing the virtual model, opportunities can be exploited in the real physical twins, and actual problems prevented. 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 novel technologies such as fibre optics, wireless sensor networks, low power sensors based on micro electro-mechanical systems and computer vision enable data harvesting for smarter and proactive asset decisions. The appeal of this technology is that it can lead to considerably enhanced efficiencies, economies, resilience and adaptability with benefits for the construction industry during the construction stage, and subsequently for the economy served by the infrastructure. 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 optics 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 the 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 retain walls at Crossrail's Pudding Mill Lane, Limmo, Stepney Green and Paddington Station sites.

5.5 Data

The adoption of digital technologies entails a huge increase 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). This will enable 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 co-ordination within the construction industry. Currently data sets at the conclusion of construction projects are usually of low-quality. There are largely paper-based reporting, poor documentation practices, unprioritized and unorganized data that is difficult to find, low reliability of the information, 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. 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, standardisation 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 is the first UK water company to trial new technology to find and measure leaks in water mains. The company uses 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 prioritise 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. The plan is to replace drawings and static 3D models with dynamic and data-rich digital twins, pdf documents with databases, and file exchange with cloud permissions exchange. National Highways also aims to introduce smart materials able to sense and heal themselves, and to automate manual routine maintenance. As a result, it will be easier to identify when and where potholes and other problems occur, and integrate live data from sensors on the road surface with a digital twin. Beyond the digital roads strategy, National Highways has set out to transform services across asset management, operations, customer-focused and corporate functions; increase access to data and technology to improve decision-making and overall working; and improve delivery of digital, data and technology services.

Laing O'Rourke DFMA Modern Methods of Construction

Laing O'Rourke is a pioneer in modern methods of construction (MMC) around the globe. The company has invested in DfMA 70:60:30, a pioneering offsite production approach, which aims for 70% of the construction be taken offsite into a controlled environment, delivering big gains (60%) in process efficiency, and timing (30%). Apart from efficiency and speed, DfMA 70:60:30 is also improving product quality, reducing material waste and supporting the creation of a more diverse and digitally-skilled workforce. In the UK, the £200M Laing O'Rourke Centre of Excellence for Modern Construction in Nottinghamshire, Europe's most advanced concrete products manufacturing facility, employs 400 people, who work closely with digital engineers and project teams to design and precision manufacture a range of components for use in major building and infrastructure projects. These include twin walls, floor slabs, pillars, high quality facades and our new 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 by its engineers. Models are assembled within a customizable interface to simulate numerous aspects of a system simultaneously. The software is able to perform extended period simulations of 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. Replica has been applied on hundreds of projects throughout the world.

Digitisation is likely to change the structure of the industry further. Data science skills will be needed (and are scarce). 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 contractors are being gradually replaced by manufacturing companies making components offsite. The on-site contract will increasingly become an assembly process, with certain specialists doing ground engineering to get the artefact off the ground. The potential for digitising the industry is seen by participants as significant: "Perhaps as much as 50 per cent of the cost of producing high-performing built assets can be eliminated." (Stacey 2021) Digitisation 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 by applying digital technologies and related innovations to existing contracting relationships and business models; rather there needs to a wider restructuring of business models and contractual supply chain relationships, including data sharing among parties to major projects.

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 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). However, in addition to the time lag for digital adoption to occur and

to deliver productivity gains, there may in addition be some productivity measurement considerations, in particular concerning price indices used to deflate revenues. We turn to these next.

6. Productivity measurement challenges

Much of the productivity promise of digital in infrastructure lies in the future, as the use of different aspects of the technology continues to diffuse across the sector and as new assets are built. In this section we consider some current measurement issues relating to classification, quality adjustment of input and output price indices, and maintenance and depreciation.

6.1 Sector classification

Productivity statistics could potentially miss important changes in the structure of the construction industry in practice because SIC Section F does not account for construction-related activities such as architectural and engineering activities and off-site manufacturing. Architectural and engineering businesses sit in the professional, scientific and technical activities part of the SIC 2007 classification, (division 71, Section M of SIC 2007) 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 (Martin 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 digitised 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, the activity would be reported in the construction sector. Otherwise, purchases of offsite manufactures and improvements in the manufacturing process (in speed and quality) could be captured in the manufacturing sector across a number of different sub-sectors and would affect intermediates prices in civil construction used in double deflating value added.

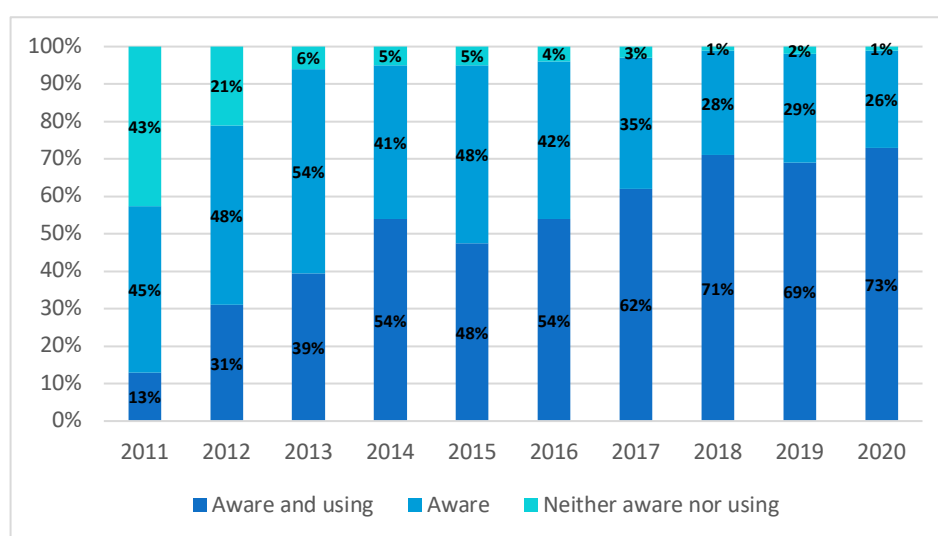
6.2 Measurement of input prices

Measurement of (output and input) prices in the infrastructure sector is inherently challenging as the projects are distinctive. Nevertheless, some trends are evident.

There is industry evidence that the use of BIM and outsourcing of the design stage is widespread (Figure 5). Survey evidence (NBS 10th National BIM Report) suggests nearly three quarters of the construction sector 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 dated March 2016 estimated that BIM supported the delivery of £3bn capital project delivery savings between 2011 and 2015 following the formation of the BIM strategy. Use of BIM can also improve safety and save time due to improved co-ordination. Reduced costs and improved quality in design would affect the deflator and hence productivity of Division 71. Anecdotal evidence in the industry suggests the price of these design services has declined significantly in recent years. This suggests that there is a case for looking in more depth at the revenue and price data for Section F to consider sampling of the data (is there the equivalent of an outlet substitution bias) and quality adjustment.

Figure 5: 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. The 2008 edition of International Trade Statistics (ITS) considered business, professional and technical services to be among the most thriving services sectors in developed countries (WTO 2008). At the same time, these services ranging from legal to management services, and from architectural to advertising service 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 assertions made by Keune (2007), today, work is outsourced countries in Asia, Central and South America, Eastern Europe and beyond. As Ribeiro 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).

6.3. Servitisation, output quality and output prices

Sensors are increasingly embedded in new infrastructure. Sensor technology is capable of producing vast amounts of data to provide to streamline operations and to monitor the health of infrastructure. Part of the change in industry structure being brought about by digitisation is the increasing provision of ongoing services by the infrastructure companies to their customers subsequently operating services, a process of 'servitisation' 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 servitisation 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. However, this work did not account for 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 due to eg track failures, signal faults, or required maintenance stoppages. The issue is that digitisation in infrastructure construction will create 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.

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 organisations, 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.⁴ 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 depreciation affect calculation of capital stock and capital services for TFP measurement.⁵ 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,

$$K_{jt} = K_{j(t-1)} + I_{jt} - O_{jt} - M_{jt}$$

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

⁴ 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).

⁵ 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.

Some portion of the infrastructure in use has been depreciated to zero and is delivering no measured capital service. This part of the capital stock is 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 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 digitises, and particularly the measurement of data assets. Digital assets are generally thought to have shorter lives, but in the case of infrastructure their introduction is likely to reduce maintenance requirements and lengthen asset lives. The appropriate choice is an open question and will vary considerably between types of asset.

7. Conclusions

We have approached the puzzle of slow productivity growth in construction of infrastructure projects, in the face of evidence of rapid adoption of digital technologies in the sector, from two perspectives: the possibility that there are simply delays in productivity gains showing through; and the possibility of mismeasurement. Both seem likely to contribute – along with other factors we have not discussed 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 could considerably reduce these, but it will require far greater co-ordination and data sharing. In terms of the measurement issues, we have identified productivity in the architectural and engineering sector (where prices seem likely to have declined by more than implied by current figures and considerable outsourcing has occurred, input prices in the double deflated construction sector value added, and output quality improvements and gains in complementary sectors, and lastly measurement of capital services, as issues needing further investigation. We continue to work with the industry to gather data that will help address these questions.

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