Creative Destruction and Constructing the Built Environment

From the first industrial revolution to the fourth

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First published in 2022 by Construction Economics Research, Kurmond, Australia.

www.constructioneconomicsresearch.com

ISBN 9780-0-6454977-0-0 eBook
ISBN 9780-0-6454977-1-7 Paperback
ISBN 9780-0-6454977-2-4 Hardcover

Cover photo: Getty Images.

Construction
Economics Research

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Introduction

… craftsmen, mechanics, inventors, engineers, designers and scientists using tools, machines and knowledge to create and control a human-built world
Thomas Hughes[i]

I was once attacked by a colleague for, as he put it, 'not considering the great mass of people employed in construction'. We were working for a government inquiry into collusive tendering and discussing recommendations to improve productivity and efficiency in the final report. At the time there were significant changes affecting the Australian industry that had far more impact than the legislative and regulatory reforms the inquiry led to. The industrial relations system was moving from a centralised award based one to a more decentralised system with enterprise bargaining and site agreements. International contractors were entering the market and the larger engineering and architecture practices consolidating. As the industry began to recover from a speculative office building bubble and the economy rebounded from a deep recession, construction employment increased and continued to grow for the next few decades. Construction as used here refers to all the firms and organizations involved in design, construction, repair and maintenance of the built environment.

Where these longer run trends were going was not obvious at the time. There have been significant changes in the range of activities and types of firms involved in construction of the built environment over the last few decades. Two trends underpinning those changes were the increasing use of multi-disciplinary project teams as the boundaries between professional disciplines became less distinct,[ii] and the inhouse versus outsourced decision about provision more common.[iii] Facilities management is an example, an activity that used to be done internally but is now often outsourced, sometimes but not always to construction contractors. Consultants bid for work as contractors, and contractors do consultancy and project management. Urban planning was once primarily associated with design, but is now linked to real estate and development. The process of structural change in industry occurs as technology, institutional and firm capabilities develop and change over decades.[iv]

One motivation for this book is a belief that the development of modern construction can provide a framework for understanding how current technological changes might impact firms and industries today. When considering the relationship between construction of the built environment and technological change the past is really the only guide available, so the starting point for this discussion is the first industrial revolution in England at the beginning of the nineteenth century when modern construction and its distinctive culture began to form, followed by the twentieth century's attempts to industrialise construction. This history is important because, after more than 200 years of development, construction of the built environment happens today within an established system of production based on a complex framework of rules, regulations, institutions, traditions and habits that have evolved over this long period of time.

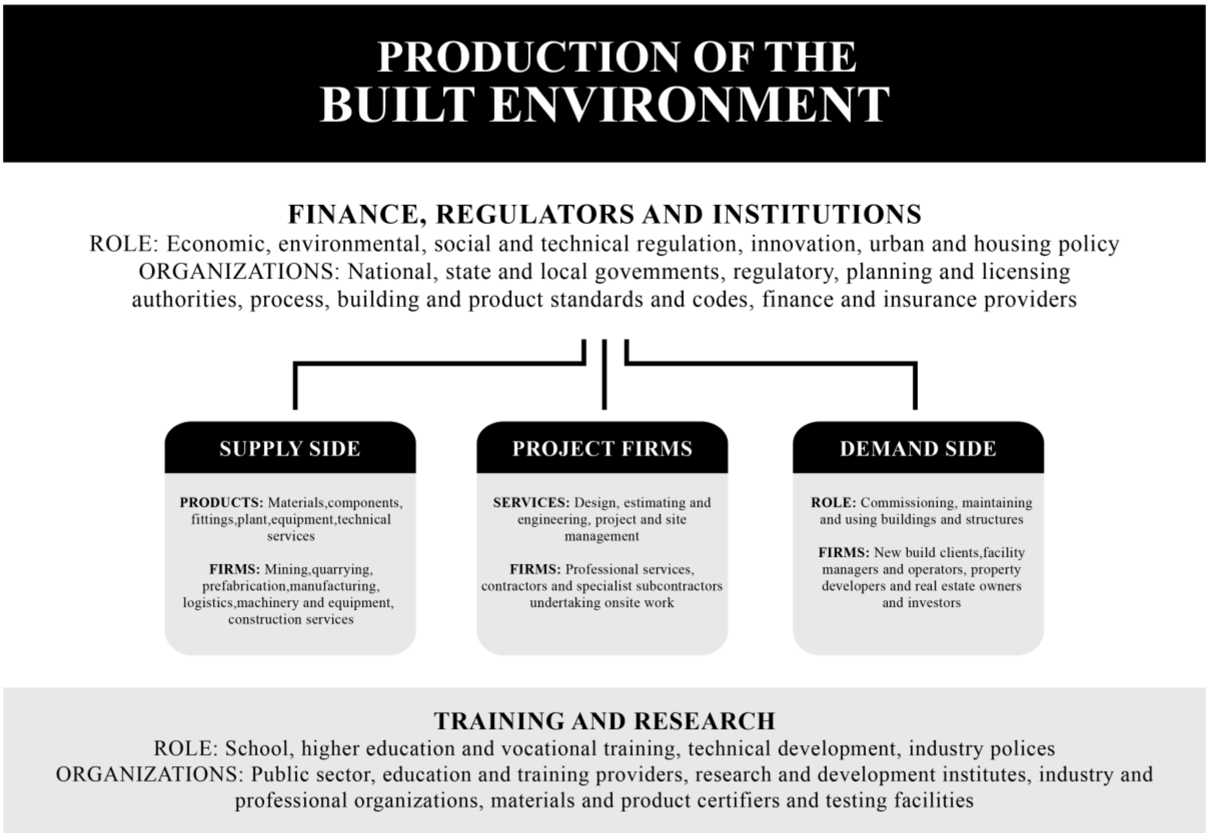
But how useful is history and how can it be used? Are there appropriate historical examples or cases to study to see if there are lessons relevant to the present? The answers depend to a large extent on context, because a key characteristic of the history of technology is the importance of institutions and the political and social context of economic outcomes.[v] Also, understanding how policies were developed in the past and how effective they were requires understanding the changing context of policy implementation. However, as economist Paul Samuelson pointed out 'history doesn't tell its own story and 'conjectures based on theory and testing against data' are needed to uncover it.[vi] Drawing the right lessons from history is a nuanced exercise.

Over time industries and products evolve and develop as their underlying knowledge base and technological capabilities increase. The starting point for a cycle of development is typically a major new invention, something that is significant enough to lead to fundamental changes in demand (the function, type and number of buildings), design (the opportunities new materials offer), or delivery (through project management). Major inventions give a 'technological shock' to an existing system of production, which leads to a transition period where incumbent firms have to adjust to the new business environment and new entrants appear to take advantage of the new technology.[vii] Economist Joseph Schumpeter called this process creative destruction,[viii] and it leads to the restructuring and eventually consolidation of industries. That is what happened to construction and related suppliers of professional services, materials and components after the first industrial revolution.

The drivers of development for industries in the twenty-first century are emerging technologies such as augmented reality, nanotechnology, machine intelligence, digital fabrication, robotics, automation, exoskeletons and possibly human augmentation. Collectively, these digital technologies are described as a fourth industrial revolution, and their capabilities can be expected to significantly improve as new applications and programs emerge with the development of intelligent machines trained in specific tasks.[ix] Innovation and technological change is pushing against what are now long-established customs and practices of the industries in the diverse value chain that designs and delivers the projects that become the built environment.

How technological change affects these industries differs from more widely studied industries like computers, automobiles or aerospace because of the number and diversity of firms involved in designing, constructing and managing the built environment. With the range of separate industries these firms come from, construction of the built environment is the output of a broad industrial sector made up of over a dozen individual industries. Not an 'industry' narrowly defined, but a broad industrial sector that is organised into a system of production with distinctive characteristics.[x] A second difference is the age of these industries, many of which are mature industries in late stages of their life cycle.[xi] These differences create a different context for questions about industry, innovation and technological change, about how firms compete and how the system of production is organised as fourth industrial revolution technologies like digital twins and drones spread through construction and the pace of digitization increases.[xii]

Figure 1. Organization of the system of production



Source: Based on Gann, D. M. 2001. Putting academic ideas into practice: technological progress and the absorptive capacity of construction organizations, *Construction Management & Economics*, 19 (3), 321-30.[xiii]

As well as the contractors, subcontractors and suppliers for new builds, there are also many firms and people mainly engaged in the alteration, repair and maintenance of the built environment. The broad base of small firms is a distinctive feature of construction, and these family-owned firms engaged in repair and maintenance work will largely continue to use the materials and processes they are familiar with. Old technologies can survive long after the innovations that eventually replace them arrived, such as the telegraph, fax machine and vinyl records with telephones, email and CDs.[xiv] Stone, tile, brick and wood have been widely used materials for millennia, and industrialized materials like corrugated iron and concrete are ubiquitous. For maintaining and repairing the existing stock of buildings and structures, many of the skills, technologies and materials found today will continue to be used far into the future. That does not mean firms mainly involved in repair and maintenance will not be affected in some way by the fourth industrial revolution.[xv]

Figure 2. Functions of the built environment

<table>
<tr><th>FUNCTION</th><th>PAST</th><th>PRESENT</th><th>FUTURE</th></tr>
<tr><td>Accommodation : Where we stay</td><td colspan="3" rowspan="5">One of the characteristics of construction is that a large part of the present industry maintains the legacy of the past industry</td></tr>
<tr><td>Workplace : Where we make things</td></tr>
<tr><td>Services : Where we get things</td></tr>
<tr><td>Logistics : How things get to us</td></tr>
<tr><td>Infrastructure : How it works</td></tr>
</table>

Construction of the built environment has characteristic organizational and institutional features because it is project-based with complex professional and contractual relationships.[xvi] How firms utilise technology and develop technological capabilities differentiates them within this location-based system of production. Emerging technologies in design, fabrication and control have the potential to transform construction over the next few decades, possibly less, and the book suggests firms will follow low, medium or high-tech technological trajectories, determined by their investment in the emerging technologies of the fourth industrial revolution.[xvii]

There are, however, few specific predictions, beyond a broad view of what future construction might look like. That view is based on successful solutions being found for the many institutional and technical problems involved in transferring fourth industrial revolution technologies to construction. Without downplaying the difficulty of those problems, similar challenges have been met in the past, but those solutions led in turn to a reorganization of the system of production.

There are very many possible futures that could unfold over the next few decades as technologies like artificial intelligence (AI), automation and robotics develop.[xviii] However, the key technology underpinning these further developments is intelligent machines operating in a connected but parallel digital world with varying degrees of autonomy. These are machines that have been trained to use data in specific but limited ways, turning data into information to interact with each other and work with humans. The tools, techniques and data sets needed for machine learning are becoming more accessible for experiment and model building,[xix] and new products like generative design for buildings plans, drone monitoring of onsite work and 3D concrete printers are available.

Intelligent machines are moving from controlled environments, like car manufacturing or social media, to unpredictable environments, like driving a truck. In many cases, like remote trucks and trains on mining sites, the operations are run as a partnership between humans and machines. There are also autonomous machines like autopilots in aircraft and the Mars rovers. As well as rapid development of machine intelligence, technological change in the form of new materials, new production processes and organizational systems is also happening. Sensors and scanners are widely used, 3D concrete printing is no longer experimental, cloud-based digital twins are available as a service, and online platforms coordinate design, manufacture and delivery of building components using digital twins.

The book argues a period of restructuring of construction similar to the one that occurred in the second half of the 1800s is about to start. That was when the new industrial materials of glass, steel and reinforced concrete arrived, bringing with them new business models, new entrants and an expanded range of possibilities.[xx] The development of modern construction was not, however, a smooth upward path of progress and betterment. It went in fits and starts as new inventions and innovations arrived, slowly then quickly, often against critics of the modern system of production and workers, fearing technological unemployment and lack of government support during a time of technological transition, who resisted new technology and sometimes sabotaged equipment.[xxi] The issue in the past, like today, was in fact not the availability of jobs but the quality of skills during the diffusion of new technologies through industry.

The only previous comparable period of disruptive technological change in construction of the built environment is the second half of the nineteenth century. Between 1850 and 1900 construction saw the rise of large, international contractors, who reorganized project management and delivery around steam powered machinery and equipment. In particular, the disruptive new technologies of steel, glass and concrete, which came together in the last decades of the century, led to fundamental changes in both processes and products. If that is any guide, we can expect technological changes to operate today over the same three areas of industrialization of production, mechanization of work, and organization of projects that they did then. And today, just as in 1820 when no-one knew how different construction would be and what industry would look like in 1900, we can’t see construction in 2100. That is a long way out, and we can only guess at the level of future technology. We can, however, use what we already know from both history and the present to form a view of what is possible over the next few decades based on what is currently understood to be technologically feasible.

Decarbonisation will be another challenge in the near future for construction of the built environment. Here industry responses to changes in consumer demand is significant, for household heat pumps and rooftop solar for example, but governments have the important role through their building standards and codes, such as solar mandates for new buildings and building codes that require full electrification of new housing. Adapting to climate change by retrofitting the built environment and making cities and infrastructure more resilient will be done by construction firms within a detailed and complex regulatory and policy environment and requires targeted industry policies to be successful.

It should be clear that the role of the technologies discussed here will be to augment human labour in construction of the built environment, not replace it. Generative design software does not replace architects or engineers. Optimization of logistics or maintenance by AI does not replace mechanics. Onsite construction is a project-based activity using standardized components to deliver a specific building or structure in a specific location. The nature of a construction site means automated machinery and equipment will have to be constantly monitored and managed by people, with many of their current skills still relevant but applied in a different way. Nevertheless, in the various forms that building information models, digital twins, AI, 3D printing, digital fabrication and procurement platforms take on their way to the construction site, they will become central to many of the tasks and activities involved. Education and training pathways and industry policies with incentives for labour-friendly technology will be needed.[xxii]

Because construction involves so many firms and people the technology driven changes discussed here will have significant and profound economic and social consequences. This would be a good opportunity for government and industry to work together to develop policies and roadmaps for those firms, and to support 'the great mass of people' employed in construction of the built environment who will be affected by them. The future is not determined, although technological change and creative destruction continue to reshape and restructure industry and the economy, decisions made today create the future.

Outline of the Book

Chapter one introduces two ideas that provide the framework for the book: general purpose technologies (GPTs) and Joseph Schumpeter's idea of creative destruction.[xxiii] Major new technologies are not common.[xxiv] Although GPTs are rare they are powerful. As well as becoming widely used by existing industries they create new industries around new products and services. Schumpeter described the ongoing process of structural change in the economy, as the contributions of different industries to total output rises or falls over time, as creative destruction. Through diffusion of new technologies new industries are created and established industries face new entrants and have to restructure. For Schumpeter this was technological progress, driven by new goods and new production processes, with competition between firms not about costs and prices but research and development (R&D) that leads to new products, new methods of production and new forms of organization. Successful firms grow and thrive, unsuccessful firms are taken over or fail.

The following chapter looks at the origins of the modern system of construction of the built environment. Chapter two is on the emergence of general contractors and professional services during the transition from the craft system of production to an industrialized system based on competitive tendering with documentation for design, estimates and forms of contract. At the same time as these changes in the method of procurement were happening, the scale and scope of construction projects was increasing, new types of buildings were required by clients, and work was being mechanised. This history shows how the modern industry developed in the United Kingdom (UK), responding to changes on both the demand side, for new types of buildings, and on the supply side, with new materials and methods.

Why would be experience of the industry so many years ago be relevant today? There are two parts to the answer. The first is that the late nineteenth century is the only other period of comparable disruptive technological change we have. The second is that the effects of technological change on industry structure and performance might again be in the same key areas as industrialization, mechanization and organization of projects and processes, but in the twenty-first century these effects will be heightened and quickened by the network effects associated with digital platforms and AI. Because industry structure (the number and size of firms) is fundamentally determined by technology,[xxv] the emergence of new technologies and periods of rapid change can lead to new industries. Such creative destruction will also extensively restructure existing industries.

Chapter three starts with the three dimensions of technological change in nineteenth century construction identified by engineering historian Thomas Peters: construction was industrialized with standard components and mass production using new materials like steel, plate glass and plastics; sites were mechanized with steam powered railways, cranes and excavators; and new forms of project management were required to maximise efficiency of the machinery.[xxvi] Fourth industrial revolution technologies can be expected to work along these same dimensions in the twenty-first century.

The chapter then introduces Thomas Hughes' industry life cycle, which he based on his study of the development of electricity generation, as a method of analysing the processes underlying the role of invention, innovation and new technology in the evolution of an industry over time.[xxvii] The stages and cycles of the life-cycle are applied to construction and the role of invention and innovation in those stages discussed, as are the characteristics of a long-established industrial sector identified by Hughes. Examples of the effects of GPTs and the role of incremental innovation are given.

Because construction requires inputs from materials, manufacturing and professional service firms, these industries have been included in the discussion about how technological change has affected the industries involved in production of the built environment since the first industrial revolution. More than two hundred years later construction of the built environment is a technocratic system of production, based around standards and codes, contractually defined professional roles, and with a high degree of technological lock in due to the culture, age and complexity of the system. The 'embeddedness' of the construction technological system is found inside the professional institutes and organizations, trade and industry associations, government regulations and licensing, standards and codes, insurance and finance providers and regulators.

Chapter four is on modern construction and industrialized building, or offsite production of components, pods or modules. The technological base of offsite manufacturing is a mix of those from the first, second and third industrial revolutions, like factories, computers and lean production. This has not become a widely used system of production – manufactured buildings have succeeded in specific but limited markets. Instead, onsite construction continues to have a deep, diverse and specialised value chain that resists integration because it is flexible and adapted to economic variability. The chapter reviews progress on offsite production in construction, followed by four short studies of industrialized building, The three cases of Sears Modern Homes, Legal & General manufactured houses and Katerra had different problems: two failed, and the 1990s Japanese automated building systems were only used for a small number of buildings. The chapter then looks at the development and potential of software platforms for integration of procurement, design, and manufacturing in modern methods of construction.

Chapter five begins with an outline of the range of technologies that are included in what has become known as Industry 4.0, and its close relative Construction 4.0. Progress is found at the technological frontier, where startup firms apply the tools and techniques of the fourth industrial revolution. Funding for construction tech startups began to increase in 2018 and examples of funding, firms and products are provided, outlining the technological frontier in construction of the built environment in the early 2020s. Two technologies are discussed in more detail.

The first is artificial intelligence. By combining, managing and integrating data from many sources with analytical and machine learning capabilities, AI can make reliable predictions about the state of the world.[xxviii] Applications of this form of task oriented narrow AI in construction are generative design, the operation and maintenance of plant and equipment, daily progress on a construction site or monitoring the condition of a building. Although there are technical challenges involved in applying machine intelligence, it is not unrealistic to think they will be solved as the capabilities of deep learning and cloud-computing improve and increasing digitization provides more construction-related data.

The second is additive manufacturing (3D printing) and digital fabrication.[xxix] There are now dozens of 3D concrete printing machines available, ranging in size from desktop printers to gantry systems that can build three and four stories. Suppliers offering manufacturing on demand with print farms (factories with many machines) makes local production of many building components possible, with an onsite or nearsite fab producing many of the concrete, metal, plastic and ceramic fittings and fixtures for a building. This does not suggest the end of mass production of standardised components – economies of scale are the economic equivalent of gravity. However, the potential effects of onsite and nearsite production on the role of contractors and the organization of projects are significant. Underpinning digital construction are digital twins of projects using building information modelling (BIM). The chapter closes with an argument for government policies promoting digital construction with BIM mandates.

Industry policy is the subject of Chapter six.[xxx] Governments can have major impacts through regulation, tax, education, training, innovation and R&D policies, and through purchasing policies. Public policies specifically for construction of the built environment are also subject to the effects of policies for contentious issues like housing and infrastructure development. The two policy areas discussed are BIM mandates and building standards and codes. The experience of the UK and the US are used as examples, with a discussion of the construction reform movement's promotion of offsite manufacturing in the decades before the new UK industrial strategy with a BIM mandate was launched in 2011.

Another area where governments can promote industry development is through building standards and codes. Building characteristics like materials, access, ventilation and fire safety are regulated by standards and codes, and contractor accreditation for standards is often required by clients. The performance of the built environment is to a large degree measured against the baselines set by standards for health and safety, environmental management and process control. Although agreeing new standards is a lengthy process, they are universally accepted and applied because of the rigorous scientific and engineering research they are based on. Therefore, an important element in a strategy to increase innovation in construction of the built environment is to increase funding for testing laboratories.

Decarbonisation of both the construction and operation of the built environment will be crucial in reducing and eliminating greenhouse gas emissions. Building energy codes provide a tool for governments to mandate the construction and maintenance of low-energy buildings. To do this, the energy use of buildings must be monitored and managed, and buildings must be built and retrofitted to use less energy. A built environment carbon budget is required, and a global standard for determining greenhouse gas emissions for cities is under development. Examples of the effectiveness of energy codes are discussed.

In chapter seven, three technology adoption and implementation trajectories for construction over the next few decades are discussed. These trajectories can be low-tech, medium-tech and high-tech. What differentiates the three is firstly the investment by firms in development, and secondly which new technologies are taken up, which leads to the different trajectories for firms. On the low-tech path firms continue with business as usual. They are followers not technological leaders, and change is slow across the large number of these small local firms. This part of construction continues on a path of incremental innovation, similar to the present, becoming smarter and better at managing and using information as time goes on.

Firms on a medium tech path are upgraded and modified. These firms invest considerably more in technological development, making significant choices on which technologies to pursue and invest in. Those technologies, in turn, require changes to the way firms are organised and the way they organise their projects. Some businesses are much better at this than others. The companies on this path are technology leaders, using digital twins and developing platforms for their supply chains. The high-tech path outlined is a hybrid production system based around AI and digital fabrication about a decade in the future. New production technologies automate many tasks and materials, and machinery becomes smart and networked with embedded processors. Humans partner with machine intelligence to accomplish many tasks, and use robots or exoskeletons for most physical work, with remote control of automated or semi-autonomous plant and equipment, while fabricated and modular components combine with automated systems and specialised onsite assembly robots to transform the building process.

Despite the extent of technological change expected over the next few decades, some new industry will not appear to undertake construction of the built environment. However, that does not mean it will not undergo creative destruction as a result of future, but foreseeable, developments in AI, automation and robotics. Economies grow by upgrading the products and services they produce and export, but the technology, capital, institutions and skills needed to make new products are found in related products with common labour and capital requirements. This network of relatedness between products means industries develop goods and services close to those currently produced.[xxxi] However, with the wide range of new production technologies currently emerging, such as 3D printing of concrete, automated machinery and materials like engineered wood, construction of the built environment is a laboratory for the fourth industrial revolution. Because it is not possible to know now which of these technologies will work at scale, the role of industry policy as facilitator is to promote digitization and decarbonization through revised building standards and codes, and to provide opportunities for new methods of production, organization and management to be tested and trialled on projects.

The Conclusion in chapter eight argues the technologies discussed like BIM, digital twins, AI, digital fabrication and procurement platforms will become central to many of the tasks and activities involved in construction of the built environment. While this might take a decade or more, as these fourth industrial revolution technologies become more competitive and their knowledge base deepens, the development path taken in construction will be distinct and different from the path taken in other industries. This path dependence varies not just from industry to industry, but from firm to firm as well.

There is a technical Appendix on measuring the economic role of built environment industries with two proposals for revising construction statistics. The data from national statistical agencies using the *System of Industrial Classification* can be used to measure output and employment of the industries involved in construction of the built environment. More accurate and complete data would be provided by a built environment sector satellite account, which could be regularly produced by national statistical agencies as for other sectors like tourism and agriculture. Finally, the current SIC structure of construction statistics should be revised to incorporate the work done by construction trades into the main categories of residential building, non-residential building and engineering construction.

Introduction

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[iv] Powell, C.G. 1980. *An Economic History of the British Building Industry 1815-1979*, London: The Architectural Press.

[v] Misa, T. J. 2009. History of Technology, in *Companion to the Philosophy of Technology*, J. K. B. Olsen, S. A. Pedersen, and V. F. Hendricks (eds.), Chichester, UK: Wiley-Blackwell, 7-17.
Many studies are focused on the invention and diffusion of specific technologies, among other examples discussed here are tractors in agriculture, electricity generation, concrete and wooden frame housing. Another approach is a case study of a demonstration or flagship project, such as a new seed variety, power plant or building.

[vi] Samuelson's 1947 *Foundations of Economic Analysis* was the template for the many economics textbooks that followed. In a 2009 interview at the age of 94, his advice was 'Have a very healthy respect for the study of economic history, because that's the raw material out of which any of your conjectures or testings will come'. https://www.theatlantic.com/politics/archive/2009/06/an-interview-with-paul-samuelson-part-two/19627/

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[ix] Sawhney, A., Riley, M. and Irizarry, J. (eds.) 2020. *Construction 4.0: An Innovation Platform for the Built Environment*, Abingdon: Routledge.

[x] The Appendix discusses this idea and provides details on the economic role of built environment industries.

[xi] The implications of Thomas Hughes' industry life cycle for construction are analysed in chapter 3. Hughes, T. P. 1987. The evolution of large technological systems, in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, W. E. Bjiker, T. P. Hughes, and T. J. Pinch (eds.), Cambridge, Mass.: MIT Press.

[xii] Although wildly optimistic about the future, the key points Kelly makes about data, cloud-based AI and unbundling of products and services are important. Kelly, K. 2016. *The Inevitable: Understanding the 12 Technological Forces That Will Shape Our Future*, New York: Random House.

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[xxi] Many examples of worker resistance in the nineteenth and twentieth centuries can be found in Munn, L. 2022. *Automation is a Myth*, Stanford University Press.

[xxii] Rodrik, D. and Stantcheva, S. 2021. Fixing capitalism's good jobs problem, *Oxford Review of Economic Policy*, 37: 824-837.

[xxiii] Schumpeter, J. 1942. *Capitalism, Socialism and Democracy*, New York: Harper.

[xxiv] Lipsey, R.G., Carlaw, K. I. and Bekar, C. T. 2005: 13. *Economic Transformations: General Purpose Technologies and Long-term Economic Growth*, Oxford: Oxford University Press. They include two organizational GPTs: mass production and the factory system; and lean production and the Toyota system.

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[xxvi] Peters, T. F. 1996. *Building the Nineteenth Century*, Cambridge, Mass.: MIT Press. Chapter 3 has more detail on these dimensions and examples of them at work.

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