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Industry 4.0 Deployment in the Construction Industry: A Bibliometric Literature Review and UK-based Case Study

ABSTRACT

Purpose: Industry 4.0 is predicted to be a game-changer, revolutionizing commercial and manufacturing practices through improved knowledge utilization and efficiencies. The barriers however, are significant, and the construction industry remains notoriously slow to take up innovations. This study reviews the research work in Industry 4.0 as it relates to construction, and examines a leading UK-based construction firm to ascertain the prognosis for Industry 4.0 roll-out; the impediments and opportunities.

Methodology: A multistage mixed philosophies and methods approach was adopted for this study. First, an interpretive epistemological lens was used to synthesise extant literature as a means of contextualising the present study. Second, an empirical case study using a post-positivist stance and inductive reasoning was conducted to explore practitioner acceptance of Industry 4.0 in the UK construction context.

Findings: Findings from the literature review indicate studies in Industry 4.0 to be a relatively new phenomenon, with developed countries, and Germany in particular, leading in the field. The range of opportunities are many, but so too are the barriers to enablement. Findings from the case study provide real-world corroboration of the review; practitioners are sanguine about Industry 4.0's potential to reinvigorate the construction industry, but also note that implementation remains curtailed by residual managerial practices dependent on 'human interaction.'

Originality: Research in Industry 4.0 is limited, with the emphasis being on technology application. This paper, by contrast, maps the totality of work carried out so far, with an assessment of Industry 4.0's progression, potential, and degree of uptake within the UK construction industry.

Keywords: Construction industry, Industry 4.0, Case study, Bibliometric analysis

INTRODUCTION

The rise of digital technology for industry is known by various terms, including Industry 4.0, the fourth industrial revolution, or simply "I4." Encapsulated in this concept is the attempt to create fully automated, wireless machine functions, integrating a complex array of digital tools, technologies and programming languages, that act in unison (Xu and Duan 2019). For brevity, the terminology I4 will be used within this manuscript. As an emergent term, I4 was originally

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coined by the German government in 2011, who sought to computerise production trains using the latest advancements in the German manufacturing sector (Bhatkar, 2017). Since its conception, a disparate array of I4 applications have evolved and developed to the point where they now permeate contemporary manufacturing processes. These applications include: cloud-based storage (Geng and Lui, 2016); fuzzy systems theory (Zhou *et al.,* 2016); steelwork design and construction (Zeman, 2017); and rapid product assembly installations (Wolfartsberger *et al.,* 2017). Digital solutions that exhibit this symbiosis are capable of visualising an entire production line and consequently able to autonomously optimize logistics related production decisions (Sony and Naik 2019). This transformation of industrial processes has made it possible to gather and analyse data in real-time, making work-runs more flexible, leading to faster, optimal, more efficient production (Flynn *et al.,* 2017). These advances are the benefits of direct machine-to-machine communication. Through I4, technological advancements, manufacturing production has become increasingly cost-competitive (Zhong *et al.,* 2017).

I4 represents a coalescence of advanced technologies, including (but not limited to): artificial intelligence (Sony and Naik 2019); big data (Trotta, and Garengo 2018); internet of things (IoT) (Trappey *et al.,* 2017); sensor-based technologies (Pereira *et al.,* 2017); 3D printing (Oesterreich and Teuteberg 2016); cloud computing (Craveiroa *et al.,* 2019); and cybersecurity (Fisher *et al.,* 2018; Parn and Edwards, 2019). A summary of I4 technologies is provided as Table 1. This intersectionality provides a hyper-efficient cyber-physical environment by allowing machines to interact and communicate directly with each other (M2M), with instant communication and optimised decision making thus providing an agile manufacturing environment (Pereira *et al.,* 2017; Syberfeldt *et al.,* 2015). More recent developments have advocated the development of a '*dark factory*' (Mills, 2019) where humans are wholly replaced by automated machine productions lines and robots linked via smart sensor networks (Mace, 2017), unmanned air vehicles (UAVs) (King, 2017), machine learning (Gerrard, 2018) and cloud computing (Chia, 2018). It is this automation that facilitates a process of manumission, relieving humans of vigilant intervention (Blanco *et al.,* 2017).

<Insert Table 1 about here>

The benefits of I4 are also applicable to construction. Pereira *et al.* (2017) contend that most construction companies now understand the importance of adopting I4 applications in order to augment business success. However, in stark contrast to advanced industries adoption of

technology, the construction industry is notoriously characterised by an antipathy towards new innovations (Edwards *et al.,* 2017). This reticence lies in a variety of objections, including: exorbitant costs associated with adopting new technologies (Chhetri *et al.,* 2017); training resources needed to apply technological innovations (Sony and Naik 2019); and an unwillingness to rupture traditional systems, processes and procedures entrenched within the construction industry (Oesterreich and Teuteberg 2016). Early innovators are needed to spearhead adoption of new technologies, and by outperforming competitors, stimulate wider adoption. However, in the construction sector, heavily dependent on integrated value chains sharing uniform technologies, disruptive innovations tend only to alienate adopters from up-stream and down-stream collaborators unable or unwilling to follow in those innovations (Xu and Duan 2019; Craveiroa *et al.,* 2019).

Moreover, at a human level, preceding the I4 revolution, researchers such as Bauer *et al.* (2015), observed that workers in developed countries were overburdened with work – suffering late-night shifts, or required to take work home. Overwork negatively affects work-life balance (Solis, 2018), reducing labour productivity rates (Sommer, 2018), whilst simultaneously eroding workplace safety (Thompson, 2018). Eroded work-life balance is particularly chronic in construction. In response, Sony and Naik (2019) contend that I4, as embedded within advanced 'smart' manufacturing practices, has the potential to automate the whole organization, thereby alleviating human managerial burdens.

Against this backdrop, a significant tension emerges as to the potential for I4 deployment within the construction sector. On the one hand, I4 technologies – artificial intelligence, big data, internet of things, sensor-based technologies, 3D printing, cloud computing and cybersecurity, amongst others – portent a fourth wave revolution in manufacturing and construction. This is recognized with little open dissent. But at the same time, the construction industry has been and remains notoriously lax in technology uptakes. Given this entrenched antipathetic culture, it remains unclear whether the lip-service in praise of I4, can find traction within the construction industry. Consequently, this study aims to: i) conduct a thematic literature analysis of I4 applications within wider industry but also reflect specifically upon developments within contemporary construction practice (Edwards *et al.,* 2017); and ii) present a case study analysis of I4 adoption within a UK-based major construction management consultancy.

RESEARCH METHOD

This research was conducted in two stages viz: i) a bibliometric literature review; and ii) a UK-based case study of a major construction consultancy. The head of digital operations at the case consultancy was interviewed on the firm's response and transition to I4. Subsequently, a focus group discussion was conducted with senior company employees on perceived benefits of I4, along with barriers to uptake.

Bibliographic literature review

The literature review followed a mixed philosophies method in which interpretivism (Maskuriy *et al.,* 2019) was adopted to conduct a systematic review (Fisher *et al.,* 2018; Roberts *et al.,* 2019; Al-Saeed *et al.,* 2019) of extant literature using the Scopus journal database. Scopus has been extensively used by a myriad of researchers within the construction discipline (Sony and Naik 2019) due to its strong coverage of predominantly journal articles, but also because of its automated analytical capabilities (i.e. automated graphics and trends analysis) as well as database download facilities. Scopus's innate capacity to interrogate literature ensures that contemporary developments in the recently accelerating I4 field are adequately captured. The search located literature on I4, using terms and developments used in this arena, drawing on key terms returned from initial searches. The aim of the literature search was twofold. Firstly, to profile and describe the current status of research in the field broadly, but also with a focus on construction. Secondly, the literature sought to identify the documented spectrum of enablers and barriers to technology implementation as a basis for informing and developing the subsequent case study survey (data collection) instrument.

Case study

Following the literature review, and identification and development of suitable research interview questions, key informants within the target company were interviewed. A post positivist approach to the case study was taken (Fisher *et al.,* 2018), using an inductive paradigm (Maskuriy *et al.,* 2019), with the aim of assessing the impact of identified enablers and barriers, as described in literature, on a specific UK company operating within the construction sector (Trotta, and Garengo 2018).

The case study utilized a major multinational construction design UK-based consultancy firm, which offered itself and the expertise of its employees to this study. The firm shall remain unnamed, but is here described. It was founded in the Netherlands in 1888, now with 350

branches operating in 40 countries. The study centred on the Birmingham office, UK, which currently employs 27,000 people and has an annual turnover of £2.9 Billion. Typical consultancy services provided include management consultancy, design and engineering construction. Recent projects include: the A2 motorway in the Netherlands, London City Airport, and Hotel Brooklands Racetrack in the UK (Sony and Naik 2019).

The company's stated values include the vigorous pursuit of innovative technology as a means of winning over market share. Motivation for cooperating in the study stemmed from the firms interest in: i) gauging the rate of I4 adoption within a typical consultancy serving the UK construction industry; ii) identifying opportunities to expand adoption throughout the sector globally; iii) improving the cost-effectiveness, productivity performance efficiency and quality of delivery of construction activities throughout the whole life cycle; and iv) automating construction activities, and thus reducing or removing human interface, errors or omissions from processes (Craveiroa *et al.,* 2019). Similarly, the case construction company was chosen for this study as a representative example of a substantial UK-based construction organisations with an awareness of I4 as a potential industry game-changer.

As noted, I4 implementation in construction holds out the promise of radically transforming the sector with reduced construction times, lower costs, fewer risks materializing, and greater client satisfaction. At the same time, grafting I4 within the sector is complicated by negative cost-benefit analyses, and a general complacency on how to manage the resulting organizational disruption and transition (Trappey *et al.,* 2017). Understanding this dynamic through this case is a objective of this study.

Interview and focus groups

In the first instance, an interview was conducted with the head of digital operations of the case company. He is highly experienced as a programme and project manager, in addition to being responsible for the digitalisation of the business. His role requires the development of digital strategies across various aspects of the business, impacting as much as 40% of firm's revenue stream. A major concern in the quest for digitization was how to improve the firm's capacity to deliver voluminous residential projects in the UK. The subject was thus an experienced expert able to inform on the perceived viability, opportunities and challenges offered by I4 to firms active in the construction sector. Microsoft Teams application was used to record the interview.

Armed with broad findings offered by the literature and the specific insights offered by the head of digital operations, focus groups were subsequently arranged. Individuals selected for inclusion in the focus groups had over five years' experience working within the construction and civil engineering industry, being thus deemed sufficiently knowledgeable to make a meaningful contribution to this study (Trotta and Garengo, 2018).

A two-phase process was adopted for these focus groups. First, participants were invited to offer their views and opinions on the barriers and enablers of I4 within the construction and civil engineering industry. Due to the geographical spread of this multinational business, not all invitees could attend the focus groups as scheduled. Thus, international colleagues were posted questions arising from the sessions and invited to response using a recorded video link. Second, upon qualitative analysis of the phase-one results, the findings were presented to key supply chain members and clients to assess the degree of agreement regarding responses. This 'waterfall' approach ensured that the findings from the participating case company could be validated.

Ethical considerations

Given the commercial nature of the participating company, confidentiality of information gathered had to be preserved. Consequently, and at the outset of the research, all study participants were invited to complete and sign a consent form expressing their desire to contribute to the study and assurances were given that they could withdraw at any time during the research undertaking (Fisher *et al.,* 2018). This protocol ensured that participants could offer unbiased opinions, free from managerial or other external pressures. Full anonymity of participants was also assured (Craveiroa *et al.,* 2019).

The outcomes of the literature review, and case study interview and focus group explorations on I4 uptake within the subject UK firm, are set out in the following section.

LITERATURE REVIEW OF I4

To measure the extent of research conducted in the specific field of I4 within the construction industry, a keyword term search was conducted within the Scopus database using the term '*industry 4.0 in the construction industry.*' Retrieved sources were reviewed for related key-

word terms which were then fed back into the search. This search was conducted in November 2019 and it should be noted that several citations for 2020 are included as 'early cite' publications. Scopus was used because it represents the most extensive digital catalogue of peer-reviewed literature (e.g. scientific journals, books and conference proceedings) and covers a diverse range of scientific sectors including: science, engineering, medicine and social sciences (Fisher *et al.,* 2017). Moreover, database facilities within Scopus allows users to export database searches as comma-separated values (CSV.) files, as well as analyse and visualize search results (Trotta, and Garengo 2018).

Retrieved publications were processed to generate a summative description of the state of research in I4; including chronological publications frequency, source country, and research discipline. From there, content was analysed; with enablers and barriers of I4 identified and catalogued. Figure 1 presents a time series of the annual frequency of publications between the period 1964-2020. The time series is relatively flat-lined until 2014-2015 when a notable surge occurs. This is most likely attributable to the announcement, March 2012, that the I4 concept was to be elevated to one of the ten official projects within Germany's 'High-Tech Strategy 2020' action plan. The spike in research here suggests an autoregressive response from academia to that policy document (Sony and Naik 2019). Notably, I4 publications within the construction sector rose from two papers in 2013 to 111 papers in 2018; though a dip to 75 papers in 2019 was recorded. It is to be expected that other papers will be published prior to the close of 2019. Overall, while there is a growth in academic interest within the construction sector, the relatively small contribution from this sector speaks to the lag in innovation take-up characteristic of the construction industry.

<Insert Figure 1 about here>

Regionally, 55% of published papers (298 papers) came from European institutions, with 21% (62 papers) from Asian institutions (Figure 2). Following were contributions from the Americas, Africa and Oceania, accounting for further 15% (45 papers), 6% (19 papers) and 3% (8 papers) respectively. Germany alone heads the rankings with 16% (48 papers). Again, this relates to Germany's announcement that I4 was to be made central to its strategy plan. China and the USA were the second and third highest contributor to the I4 field, with 11% (34 papers) and 9% (28 papers). Notably, with the exception of Malaysia, all other countries listed can be classified as developed countries. Prima facie, this indicates that I4 adoption is a preserve of

interest to only the advanced economies, with important implications regarding the widening of the technology gap between the North and South economies.

<Insert Figure 2 about here>

The distribution of academic research by subject discipline reveals that construction management or civil engineering management is essentially unrepresented and sorely wanting (Table 2). Rather, the top five contributing sectors to the field are: i) engineering 30% (199 publications); computer science 15% (97 publications); materials science 7% (46 publications); business, management and accounting 6% (39 publications); and mathematics 5% (31 publications). Moreover, many of the publications are authored by a multidisciplinary team of academics – each of whom brings a specialist knowledge contribution to the work. This finding serves to substantiate anecdotal evidence and speculation that I4 research requires multidisciplinary teams of experts in order to develop industry solution applications to sector problems.

<Insert Table 2 about here>

Enablers for I4 adoption

The I4 enablers – factors augmenting adoption – are many and varied (Table 3). One the one hand, advances in technology allow controls and decisions to be taken out of human hands, leaving machines to act faster and more efficiently. Moreover, greater connectivity between nodes within the manufacturing or other processes, facilitate greater access to information supporting optimal decision making. Added to this, the results emerging lead to higher competitiveness on the suppliers' side, and greater added value for the customer. Elements such as Big Data (Liao et al., 2017), IoT, Artificial Intelligence (Fisher *et al.,* 2017), Robotics (Wang, 2019), Cloud Computing (Talukder, 2012) and Cybersecurity (Pereira *et al.,* 2017), are all being studied across numerous applications, and while construction management is neglected as a specific context of study, the findings may be considered instructive and applicable to the construction industry.

<Insert Table 3 about here>

Barriers to I4 adoption

While the enablers to I4 are significant, so too are its barriers (Table 4). The literature review identified these to be a combination of high implementation costs, together with low knowledge at the human level, or fit with current practices at the organizational level, compounded by a substantial lack of needed long-term planning. All these handicaps are especially prominent characteristics of the construction industry, suggesting barriers to be particularly high for this sector. Specifically, research indicates the barriers to be: technology acceptance (Sony and Naik, 2019), implementation cost (Slowey, 2015), high requirements for processes and equipment (Xu and Duan, 2019), individual hesitance (Craveiroa *et al.,* 2019) and lack of knowledge (Lin *et al.,* 2014).

<Insert Table 4 about here>

In summary, I4 is a relatively new research field led by Germany and pursued mostly by developed western countries. While numerous disciplines are represented, the field of construction management is conspicuously under-represented. The enablers and barriers, both being significant, suggest strong tensions confronting firms towards I4 adoption. Given the needfor them to overcome major obstacles, it would seem clear that the detractors are especially magnified for the construction sector.

CASE STUDY

The literature review confirms the new but rising interest in I4 as a transformative technological movement set to radically alter industrial competitiveness. It also reveals an inertia from the construction management discipline in catching this wave. Given the significant enablers and also the important barriers, the question remains as to how the construction industry sees the rise of I4, and what their responses to this rise are. With this question established from the above analysis, we turn to a case study of a major UK-based construction firm. This firm was selected, firstly because access was granted, but more to the point, because: i) it is set in the UK, a major developed country, with a substantial research presence in I4; ii) its focus of business operations is construction, and in particular construction consultancy, covering many types of projects across many jurisdictions, and thus an excellent archetype of the kind of construction firm set to benefit from I4; and iii) it is proactively attempting to absorb I4 capabilities into its systems.

An initial interview was conducted with the head of digital operations, and following this focus group interviews were conducted with key senior employees. The scope of the interviews was to determine perceptions on the value of I4 for the firm, current I4 roll-out strategies, and then to assess the effectiveness of the firm's I4 adoption measures with a prognosis for the business's future challenges and fortunes.

Interview with head of digital operations

The role 'head of digital operations (UK)', was created in 2017, as a response to the decision to digitize the firm, including the digital transformation to each line of business. At the time of the interview, the firm had just announced its 2019 digital strategy. The fundamentals of the strategy emphasized enhancement of productivity, automation, management of data, digital asset management, and a 100% utilization of building information modelling (BIM) across projects. The agenda was ambitious, with the scope of digital transformation not only likely to be disruptive to current work regimes, but also challenging to integrate as a seamless digital platform. The difficulties were multiple: coordination and alignment between the various digital initiatives, as well as linking to subsidiaries overseas, and between projects and business arms. These problems have already been identified as barriers (Mills, 2019).

In exploring these challenges, the interviewee conceded that the goals were prioritized, as a matter of practicality, with the primary objective being '100% BIM' – here the ambition was to see BIM employed on all the firm's projects. Thus, the first identified barrier was the impracticality of delivering comprehensive change, across the board, at one time.

Even so, the ambition in adopting BIM on all projects was also hampered. The transition to BIM was undertaken by decentralizing roll-out downstream, and through use of specialist consultants.

However, a major requirement for BIM to work successfully is an environment of high collaboration across multiple disciplines and organizations. The interviewee revealed that digitalisation was being slowed by externalities such as a lack of collaboration across partnering firms in the value chain. Indeed, digitization could only progress as the rate of its weakest link, and without similar commitments to BIM as expressed by the case study firm, they were being curtailed in their efforts to transition to I4. This again speaks to the relative lack of interest (or perceived need) by construction firms to innovate. Simply, bigger

companies are unable to align with each other as needed, and smaller firms do not see a need. Yet for I4 to be effective as an integrative paradigm, firms which conduct business with each other must also be integrated. The interviewee expressed the view that most companies are merely surviving, simply doing only the minimal necessary in the digital sphere to keep pace.

A second impediment was the lack of required skill sets. The interviewee noted that there were simply not enough people who could work with BIM. Raising skill sets through training was an obvious solution, but a time-consuming and expensive one. Moreover, there were practical difficulties in lifting skills, such as absence of trainers and training materials. The use of a digital handbook that focuses on the benefits of BIM and also incorporates a guide to use 4D BIM was raised as a solution as was consideration of the Microsoft Sway site which introduces individuals to novel software technologies. Again, these ideas are rudimentary and do not constitute a comprehensive solution.

The interviewee also revealed an interest in considering a shift away from the conventional transactional office in which interactions are physical, and moving to cloud-based systems which enable more people to work on the same task from different physical locations, with the view to enhancing their efficiency. Curiously, the interviewee did not believe that such a platform would actually affect the bottom line. The implication, rather, was that such an arrangement would somehow improve employee flexibility and thereby enhance the firm's poor work-life balance. Once more, the ideas appeared still to be at an embryonic stage, lacking specific clarity or actionable steps. In the interviewee's words:

"... We are really pushing for this automation, but you only really achieve efficiency by enabling the individuals to spend 50% of their feed time on another project. If the individuals don't utilise their full capacity, then technically all we're doing is adding cost to the project."

Though the interviewee expressed enthusiasm for I4, it was clear that the current organizational structure and systems were delivering results without it. A tension was evident between the future vision and the current working operations. The challenge, not perhaps fully appreciated, was that this firm required a fully-fledged organizational change strategy; not just an I4 strategy. The fundamental factors of organizational change include process, people and technology (Harold Leavitt,1964). Moreover, McKinsey Global Institute Research (McKinsey, 2017) has noted that the major issue in digital transformation stems from the size of the firm.

While small firms can rely on informal communication channels and agile decision making, larger firms are dependent on at-distance communication links that grow exponentially with the size of the firm, its projects, offices, clients, and suppliers.

Focus group content analysis

A focus group session was set up, and questions were distributed to participants for discussion. A questionnaire format was used to prompt discussion since certain invitees were unable to attend the session due to duties or being located at distance. Thus, the questions were then also distributed via the Microsoft Teams application to the greater worldwide business. 83 participants in total completed the questionnaire. The distribution of respondents represented a number of professions, but were mostly Quantity Surveyors and Project Managers; 41% and 25%, respectively (Figure 3).

<Insert Figure 3 about here>

A preliminary analysis of the terminology and word frequency generated by the focus group discussions is presented in Figure 4. These words are typically associated with other words in sentences, and this association is depicted as Figure 5. A thematic summary of content is provided as Figure 6. As can be seen, the centrality of terms ‘business’ with ‘digital’ confirms the association. Also evident, and perhaps more revealing, is the frequency with which the terms ‘work’ and ‘employees’ come up; 11% and 9%, respectively. Here we see the concern regarding the impact of I4 on the working lives of the firm’s employees. Thus, while the case-study company was managing its current business profitably, the undercurrent within the conversation was less about the impact of I4 on competitive advantage and profitability, and more about the impact it would have on the working lives of company workers. Specifically, given the current poor work-life balance, the conversation explored whether I4 would provide relief for time poor managers, or add an extra burden to their already full work lives.

<Insert Figure 4 about here>

The revealed message is that the success of digitalisation relies on employee buy-in. And for this to happen the benefits to the employees, not just for the firm, need to be evident for employee cooperation to be harnessed. In the short term, I4 would be a disruptor, adding to the anxiety, stress and work-load of employees. And here-in lies a clue as to why I4 is notoriously

unable to gain traction in the already over-worked construction industry. A further theme centred on the terms 'data,' 'project,' and 'UK,' all at 8%. Thus, secondary to concerns about the impact on work, was the recognition of the potential benefits of a more digital working environment to enhance productivity.

<Insert Figure 5 about here>

<Insert Figure 6 about here>

Focus group narratives

Complementing the meta-thematic findings, above, are further specific observations and narratives, below. The individuals highly valued digital literacy, with more than 90% citing an interest in enhancing their digital competency. The participants acknowledged that technology would transform their different roles, particularly where manual and repetitive tasks were automated.

"By adopting virtual reality, both clients and end users will be able to improve their engagement levels and experiences, thereby contributing to the project bids and securing new work lines across diverse industries." – Architect

Interestingly, it was the role of quantity surveyor that was anticipated to see the greatest changes under I4. This was not just because of the heavy representation of quantity surveyors in the sample, but a view shared across the conversation. Specifically, this would occur at the pre-contract stage where analytical skills were used to formulate cost estimates. Similarly, the respondents argued that the conventional 'take off' style of employing printed drawings to measure by hand would be replaced by BIM models. Furthermore, it was noted that the industry has progressed towards measurement systems that are paperless as well as computing programmes that undertake such tasks more efficiently through export to Microsoft Excel. CostX enables engineers to measure and take off diverse BIM models – both 2D and 3D. The application also empowers them to calculate cost estimates precisely from the developed measurements.

"The role of quantity surveyors will be significantly transformed… There is high potential to minimise costing and quantification. However, I still believe that the role of quantity surveyor

in managing tenders and contracts will be important as it is less autonomous." – Quantity Surveyor

The broad benefits of I4 aside, it also became clear that when it came down to specifics participants were still not sure of what they wanted of I4, how it could be applied, what the cost-benefits were, and indeed, what adjustments and training were needed. There was debate on whether certain tasks could in fact be improved using I4, or whether I4 was prone to complicate matters more than alleviate work-loads. There was even some lateral discussion about the benefits of making certain tasks less, rather than more technologically driven, as a move to increase efficiency.

"There is a need to comprehend the diverse tools used and when they ought to be deployed. I believe that there must be an understanding on when they should be employed since the ambiguity on this complicates matters." – Project Manager

Despite the advantages of technology, there are several limitations. One of these is relationship management. An observation made is that soft skills are still required by quantity surveyors and project managers in order to succeed in delivering projects. Human relations remain at the core of efficient work teams. Due to the multi-disciplinary nature of construction arrangements, there is the need for companies to work in unison in order to ensure that bespoke products are delivered. In the same way, input from responsible parties across projects should be managed sensitively to enhance outcomes. I4 was not seen as a surrogate for human interaction.

"I believe that digital technologies will eventually transform the management of relationships. However, the 'human touch' aspect of building and relationship maintenance will require to be undertaken by an expert." – Quantity Surveyor

CONCLUSION

Industry 4.0, or I4, represents the 'fourth industrial revolution' – one in which magnitudinal efficiency improvements are expected from machine-to-machine (M2M) interactions, data exchange, and decision making. On top of this efficiency gain is the long-awaited promise that humans will not need to devote their life to the workplace, letting robots and intelligent machines do all the work.

I4 was spearheaded by the German government in 2011, seeking to computerize production. That initiative spawned a spike in research in I4, led by Germans, but pursued by a core of western developed nations. Conspicuous by its absence was research on I4 within the context of construction management. Construction stands to gain immensely from I4 adoption and implementation, at least in theory, since its future trajectory lies in prefabrication and advanced manufacturing and engineering, bringing together significant frontier technologies in communications, materials, energy, logistics, as well as information management and facilities management. Compounding this is the construction industries entrenched reputation for resisting innovations.

Thus, this study set out to survey the state of research on I4, with an emphasis on identifying the enablers and barriers to its integration. Since this work rests largely in other sectors, not construction, a further step was included in which a case study investigation of a construction company's efforts in I4 roll-out were explored.

The findings confirm that the construction industry remains significantly under-represented in I4 research. Further, a significant body of both enablers and barriers can be identified from the emerging body of research on I4. These were put to senior management of the case study firm for consideration and validation. Expert opinion from within the firm confirm the following:

- I4 is indeed the way of the future, and must be embraced.
- Largely, for construction however, the emphasis centres on BIM.
- The earlier stages of construction, where quantities, costs, schedule and plans are developed, remain more suited to digitization – specifically, quantity surveyors were considered a profession likely to be most impacted.
- Implementation in construction, however, suffers additional burdens, with firms being more dependent on each other up and down the value chain than, say, manufacturing, and thus I4 cannot work for any one firm unless all firms fall in line behind digitization.
- Scale, too, was a mitigating factor, with the construction industry rife with small firms for whom I4 has little value, but who heavily populate the construction sector and on whom larger firms depend.
- Training was raised as an issue – I4 capable people are scarce, with trainers few and the resources required to train people significant and expensive.

- Ultimately I4, while a perceived strategic game-changer, is also a major disruptor, and in order for it to be effectively grafted into an organization, significant organizational change management would need to be undertaken – a task that again industry seems unprepared for.
- Successful I4 implementation requires the ascent of the employees it would affect, and in this regard the motivation to cooperate seems to be contingent on whether I4 would indeed reduce work-hours and work-stress, not just improve the bottom line – and on that point the jury remains out.

These findings are important in confirming the lag in I4 uptake in the area of construction management – both in research and in practice. They show a way forward by identifying the barriers and enablers affecting the sector, and in this regard can be expected to guide industry as it moves to confront the I4 challenges and opportunities. Indeed, there are also limitations. This is an exploratory study, using a single case study. An industry-wide study would enhance the generalisability of the findings indicated here.

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Table 1 – Characteristics of I4 Technologies

I4 Technology	Description	Features	References
Artificial intelligence (AI)	AI (or machine intelligence) provides a artificial simulation of the human biological brain using computer systems. Techniques adopted could include for example: neural networks; fuzzy logic; and genetic algorithms.	AI replicates the human capacity to learn and problem solve but at an exponential accelerated rate. This enables AI to solve bigger problems expediently. More recent developments in artificial superintelligence mean that machines can now replicate the multifaceted intelligence of human beings.	Sony and Naik (2019); Turner (2018); Shi, (2019)
Big data	Big data is simply data that is too large to analyse and interpret using traditional data processing applications. Big data can be formally defined incorporating the 5V's which identifies its features, namely: 1. *Volume* - the size of the data set; 2. *Velocity* – the amount of data generated against a specific time frame and translated into real time for analysis; 3. *Variety* - data from different formats; 4. *Value* - what information is needed from the data?; and 5. *Veracity* - how trustworthy is the data being collected?	Big data analytics provides a systematic means of gathering, analysing and interpreting (via the extraction of information from) large data sets.	Trotta and Garengo (2018); Wang (2019)
Internet of things (IoT)	IoT represents a complex system of interrelated computing devices, mechanical and digital machines, objects and people that are connected via unique identifiers that allow them to gather and share big data over a network system without human intervention.	IoT enables industry and commerce to collect and analyse big data sets streamed from inter-connected assets, people and places to gain invaluable (and actionable) insights in a public or industrial environment.	Trappey *et al.,* (2017); Zhang, (2018)
Sensor-based technologies	A wireless sensor network (WSN) consists of a set of spatially distributed sensors to either monitor either: 1. Physical; and/or 2. environmental conditions (such as heat, pressure, humidity or movement) within the built environment. Cumulatively, the WSN cooperatively forwards data and information via a network to a central (often cloud based for I4) location.	Sensors can be categorised into two areas. 1. analog sensors such as: accelerometers, light sensors, sound sensors, pressure sensors, and analog temperature sensors; and 2. digital sensors such as: switches, infrared detectors, digital accelerometers and digital temperature sensors.	Pereira *et al.,* (2017); Sittón-Candanedo (2019)
3D printing	3D printing (or additive manufacturing) allows a three-dimensional physical object or structure to be created from a computer aided design (CAD) model.	The benefits of 3D printing are myriad but include: greater quality control; unlimited shapes and geometry configurations to be constructed such as complex parts for machines, airplanes and cars; cost effectiveness because parts can be created at a fraction of the price compared with standard means of production such as forging, moulding and scolding	Oesterreich and Teuteberg (2016); Adamidis, Alber and Anastasopoulos (2019)
Cloud computing	Cloud computing is a model for allowing convenient, on demand access from anywhere, to a shared pool of computing resources. These can include, servers, storage, networking, applications and services that can be rapidly provisioned and released.	The cloud model includes five essential characteristics viz: 1. *On demand self-services* which allows users to quickly and automatically gain access to the IT resources without requiring any additional human interaction; 2. *Broad network access* which is the ability to access a service from any standard mobile device that is connected to the network; 3. *Resource pooling* to share computing, networking and storage amongst multiple customers; 4. *Rapid elasticity* which allows a user to quickly scale or grow or shrink cloud capabilities to match user demand; and 5. *Measured service* which automatically controls and optimises resources provided by leveraging a metering capability at	Craveiroa *et al.,* (2019); Xu, (2019)

Cybersecurity	Cyber security seeks to protect hardware, software and data within an organisation from malicious threats (e.g. hackers), cyber terrorists and/or industrial espionage.	some level of abstraction appropriate to the type of service (e.g., storage, processing, bandwidth and active user accounts). Cyber security enables a business to implement rigorous security standards to: protect corporate data assets at rest and in motion; apply detailed access controls to limit who can acquire information; and monitor and prevent malicious behaviour.	Fisher *et al.,* (2018); Parn and Edwards (2019); Trappeyet *et al.,* (2017).

Figure 1 – Frequency of Publications 1964-2020

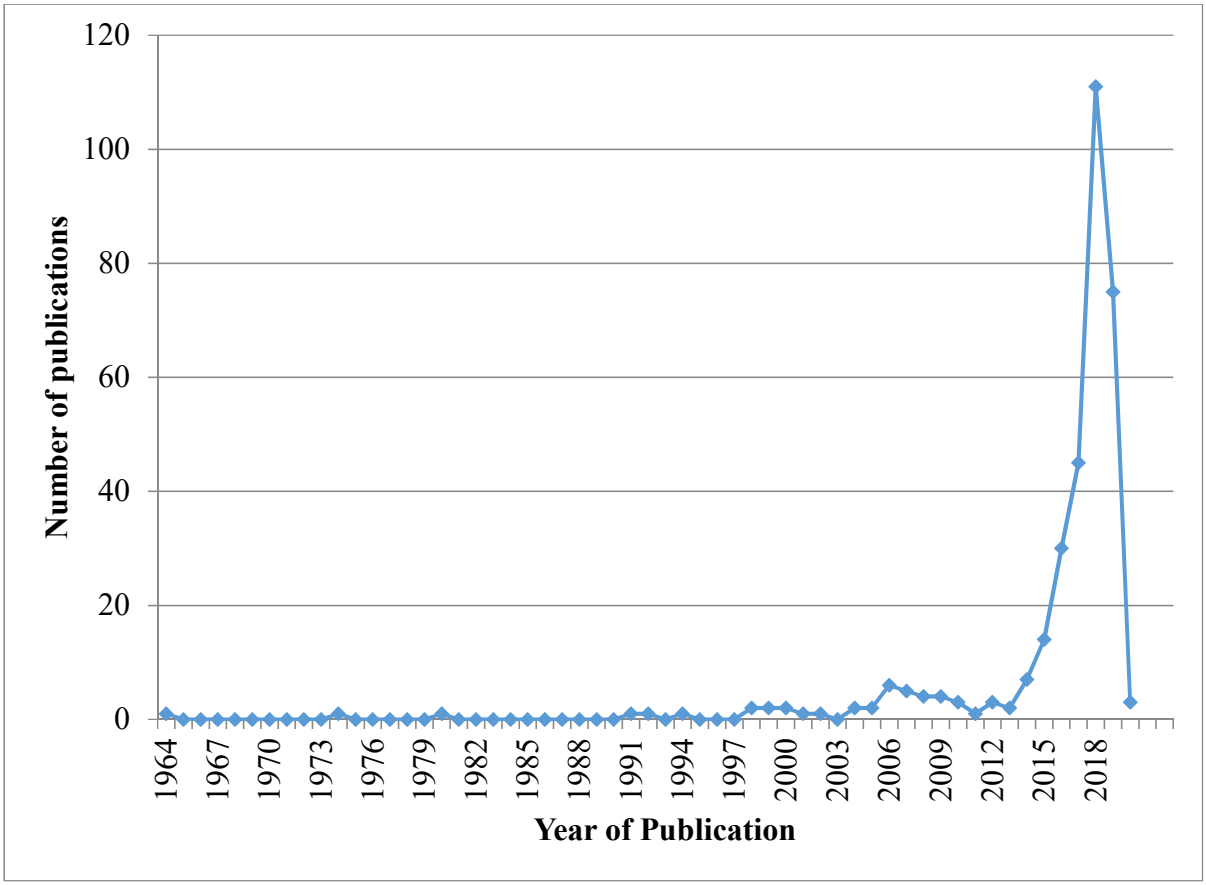

Figure 2 – Publications by Country

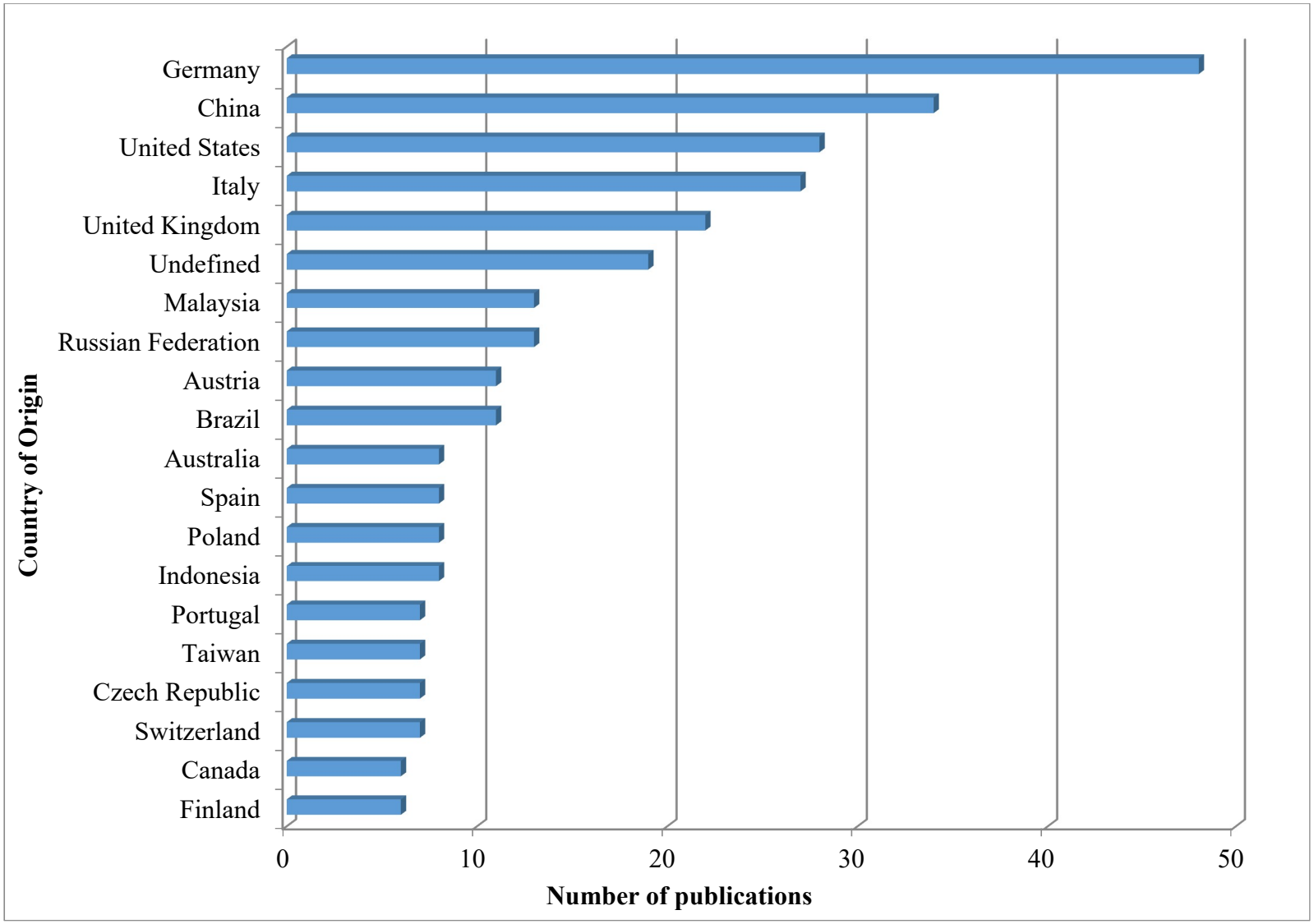

Table 2 – Distribution of Publications by Academic Discipline

Academic Discipline	**Number of publications (No.)**	**Percentage (%)**
Engineering	199	30.38
Computer Science	97	14.82
Materials Science	46	7.02
Business, Management and Accounting	39	5.95
Mathematics	31	4.74
Medicine	29	4.42
Environmental Science	28	4.27
Decision Sciences	26	3.97
Social Sciences	26	3.97
Energy	25	3.81
Physics and Astronomy	23	3.51
Chemical Engineering	22	3.36
Earth and Planetary Sciences	20	3.06
Chemistry	14	2.15
Economics, Econometrics and Finance	11	1.68
Agricultural and Biological Sciences	6	0.92
Biochemistry, Genetics and Molecular Biology	6	0.92
Arts and Humanities	3	0.45
Multidisciplinary	2	0.30
Pharmacology, Toxicology and Pharmaceutics	1	0.15
Psychology	1	0.15
Total	655	100

Table 4 - Barriers to I4 Adoption

Barriers	Features	References
Implementation Cost	According to K. Slowey 2015, technology implementation of I4 incurs high cost in possessing and operating technology. It must be noted that some technology isn't fully developed and is subject to constant enhancement or evolvement. With the current average profit margins in the UK construction industry operating at 1.5-2%, it is clear that unnecessary risk is not feasible and may hinder the success of any project. One would suggest that the commercial risk may imbalance the Cost Vs Value fundamentals. It is important to note that training fees for technical equipment may become costly to an owner. Such training may require out of house specialist to train the current work force for operation, taking up valuable time and money. Other concerns for employees are, will the adoption of I4 technology replace the demand for manpower? Trainees may be reluctant to adopt such technology if one feared job losses or redundancy.	Sutrisna et al., (2015) Griffin *et al., (*2019)
Technology Acceptance	Lin et al,. (2014) mentioned the uncertainty of new technologies and whether it will be beneficial to companies in the construction industry. Research concludes that this uncertainty may affect new technology acceptance. This has led to conservatism and caused an impact on the ability of employees to adapt those technologies. Again, technology falls down to commercial and operational risk which companies are attempting to avoid. One would suggest that proven I4 technology would say the market to invest and the risk has been swallowed by another investor.	Neugebauer et al., (2016) Sony and Naik (2019).
High Requirements	To transform and move forwards with new I4 technology there needs to be a knowledgeable or competent operator either to maintain or utilise the technology. Need for employee development and training, combining the need for integration skills is a necessity for the adoption of I4 technology. For example, Amazon in the USA have now development machine only distribution warehouses, thus reducing the need for skilled warehouse staff. Whilst this may seem a commercially viable option, there still will be a requirement for skilled operators and maintenance staff.	Talukder, (2012) Fisher *et al.,* (2017).
Lack of Knowledge	According to R. Neugebauer (2016), adopting I4 technology may impact the way production or operations are carried out. This can lead to disruption in workplace culture, work organisation as well as productivity. Although there are many experienced employees across the industry who are willing to adopt new technologies, there are others who may be reluctant due to lack of skills or motivation to learn new processes. Through the above mentioned barriers, it can be concluded that construction companies feel hesitant to adopt new technology within their operations.They claim that by adopting such technologies their productivity may reduce due to the requirement of highly skilled employees, change in organisations culture, motivating the working staff and ultimately avoiding risk.	Liao et al., (2017) Trotta, and Garengo (2018).
Poor Long-Term Planning	An I4 technology launch does not guarantee success within any organisation in the future, especially without stringent monitoring. Project planning should consider the possible long-term outcomes and risk assessments. Ideally, a team would be assigned not only to oversee the entirety of the launch process, but also the ongoing usage after the implementation phase is over.	Pereira *et al.,* (2017); Syberfeldt *et al.,* (2015).
Insufficient Support	Once the technology is launched, users are expected an outlet for addressing their issues and inquiries. Prompt assistance should be readily available for users to contact, lest it be likely that users become reluctant to comprehend and embrace the technology.	Oesterreich and Teuteberg (2016); Adamidis, Alber and Anastasopoulos (2019)

Table 3 - Enablers for I4 Adoption

Enablers	Feature	References
The Internet of Things	IoT change has gone beyond appliances which are connected through internet. In the modern era, the integration of technologies such as embedded systems, machine learning, and wireless. IoT is essential to the evolution and inception of I4. Sensor devices connected physically, gather data instantly. This could prove very valuable within construction industry and can be utilised within the processes of manufacturing.	Sutrisna et al., (2015) lin et al. (2014)
Cloud Computing and Big Data	Utilising enhanced analytics, big data can be altered into meaningful information in order to meet the objectives of the business. Organisations can analyse, seek, and analyse the actual value of big data. Whereas, cloud computing provides affordable and flexible ways to support operations within business. From backing up information and remotely working to storing large sets of data.	Sony & Naik, (2019) Craveiroa et al, (2019)
Artificial Intelligence and Robotics	Smart machines such as digital assistants, expert systems and autonomous devices have altered the process of manufacturing. Enhancements in Artificial Intelligence and robotics have disturbed the construction industry due to lack of knowledge. These enhanced technologies might create a negative impact on the workers. Adopting AI and Robotics within the construction industry will most likely enhance the productivity within construction industry, as most of the work will be operated through automation.	Liao et al., (2017) Sony and Naik, (2019)
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Cybersecurity	Across all industry communication methods of communication has expanded significantly. It may be possible for team members from around the world to work on the same projects. Currently we are seeing an increase in platforms such a Microsoft teams, SharePoint and remote access digital software mechanisms. Digital security is also a critical aspect which needs to be addressed within industry. Hackers and criminals are now using more significant methods to gain access to sensitive information; therefore, the less technology savvy employee may struggle at preventing data loss or fraud by not being fully competent with new systems.	Slowey, (2015) cf. Trappey *et al.,* (2017)
Increase your productivity	Technology allows businesses to speed up production processes. You can analyse how your staff are spending their time and introduce processes to make your systems more efficient. Task management tools allow you to stay on top of daily responsibilities so you don't miss anything.	Sutrisna et al., (2015) Griffin *et al.,* (2019)
Improve flexibility	Communicating with your co-workers has been transformed over the last 20 years, with numerous technological advancements making the ability to work in other places possible. Users can now connect with their colleagues at any given time from any location, improving your company's flexibility to deal with queries quickly and efficiently. This improves teamwork across the whole business.	Oesterreich and Teuteberg (2016); Adamidis, Alber and Anastasopoulos (2019)
Technology keeps business safe	Manual record keeping caused many businesses problems due to the way records were maintained and stored. Modern technology allows companies to *keep records safe* and implement systems that can only be accessed internally by the correct people. Encrypted passwords offer increased levels of security, making it difficult for computer hackers to access data and preventing private information from being leaked. Technology has changed every aspect of the workplace and businesses will continue to enjoy the benefits as new inventions are introduced.	Talukder, (2012) Fisher *et al.,* (2017).
Better Customer Services	A business can't survive without customers, so using technology to improve their dealings with your company can pay big dividends. Interactive websites, online chat support services and 24/7 customer service via social media can set you apart from the competition and help increase your profits.	Pereira *et al.,* (2017); Syberfeldt *et al.,* (2015).

Newman, Chris; Edwards, David; Martek, Igor; Lai, Joseph; Thwala, Wellington Didibhuku ; Rillie, Iain (2021), Industry 4.0 Deployment in the Construction Industry: A Bibliometric Literature Review and UK-based Case Study, *Smart and Sustainable Built Environment*. (https://doi.org/10.1108/SASBE-02-2020-0016)

Figure 3 – Job distribution of participants

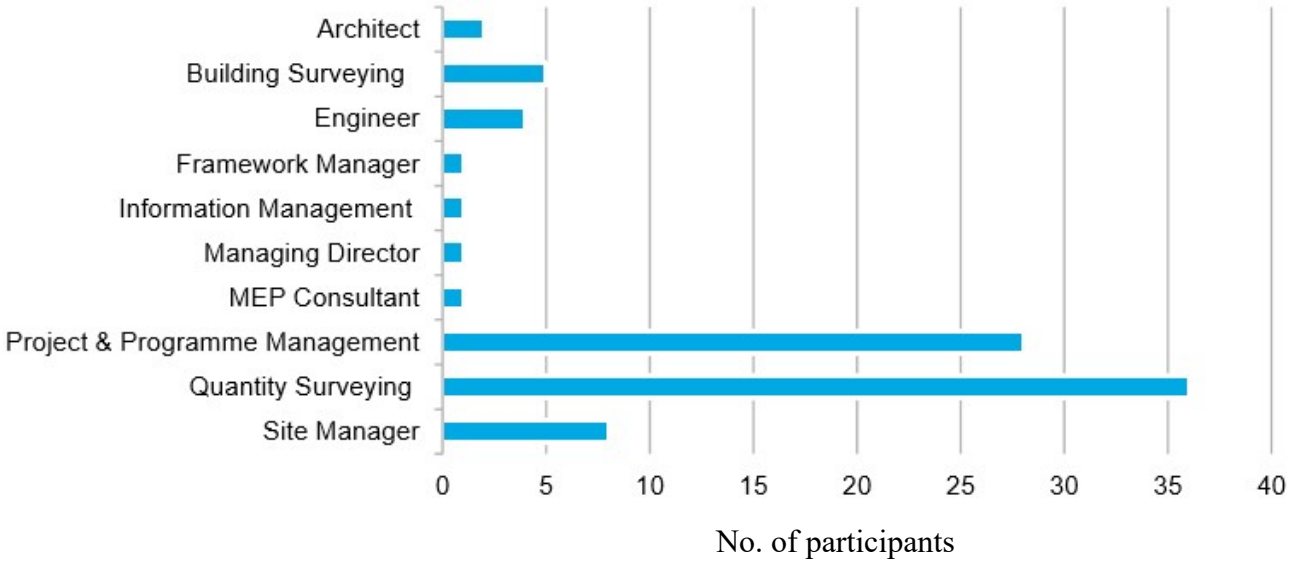
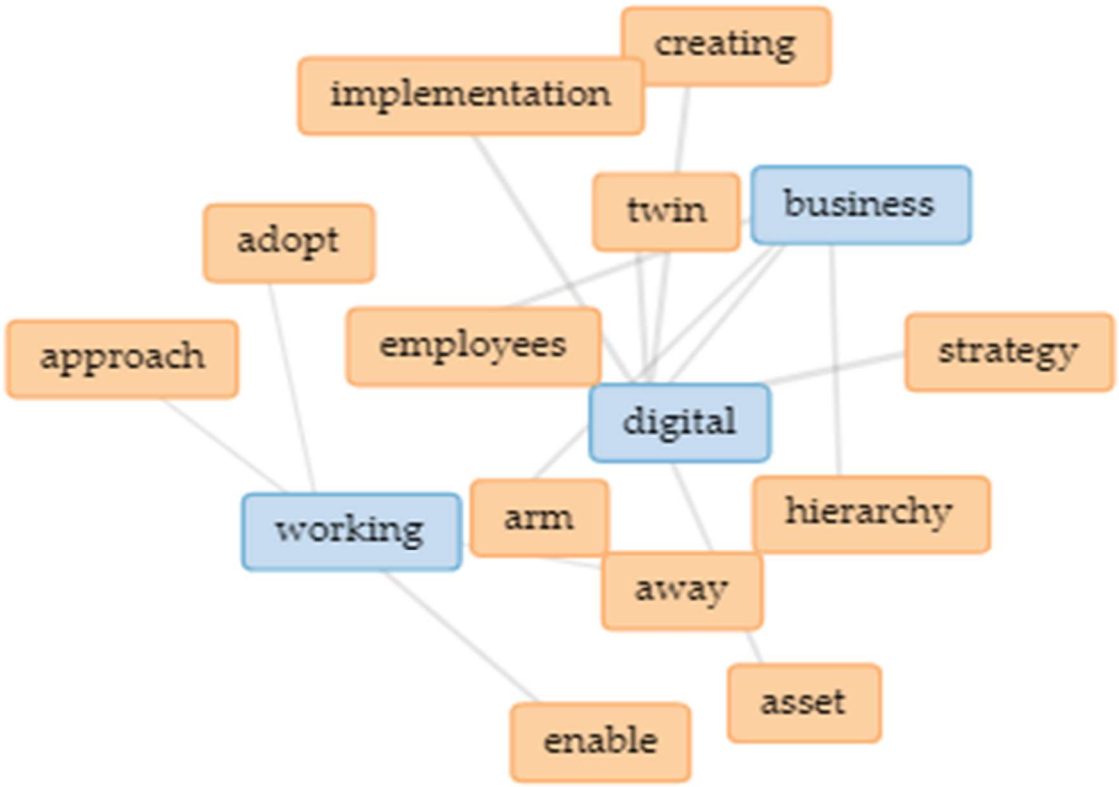


Figure 4 - Terminology Word Cluster

Newman, Chris; Edwards, David; Martek, Igor; Lai, Joseph; Thwala, Wellington Didibhuku ; Rillie, Iain (2021), Industry 4.0 Deployment in the Construction Industry: A Bibliometric Literature Review and UK-based Case Study, *Smart and Sustainable Built Environment*. (https://doi.org/10.1108/SASBE-02-2020-0016)

Figure 5 - Word Cluster Link



Newman, Chris; Edwards, David; Martek, Igor; Lai, Joseph; Thwala, Wellington Didibhuku ; Rillie, Iain (2021), Industry 4.0 Deployment in the Construction Industry: A Bibliometric Literature Review and UK-based Case Study, *Smart and Sustainable Built Environment*. (https://doi.org/10.1108/SASBE-02-2020-0016)

Figure 6 - Thematic Analysis

	Phrase	Sample Size	Sample Percentage
Industry 4.0	Digital	17	20%
Working Environment	Business	14	16%
	Working	10	11%
	Employees	8	9%
Delivery	Data	7	8%
	Project	7	8%
	UK	7	8%
Performance	Strategy	6	7%
	Time	6	7%
	Cost	5	6%