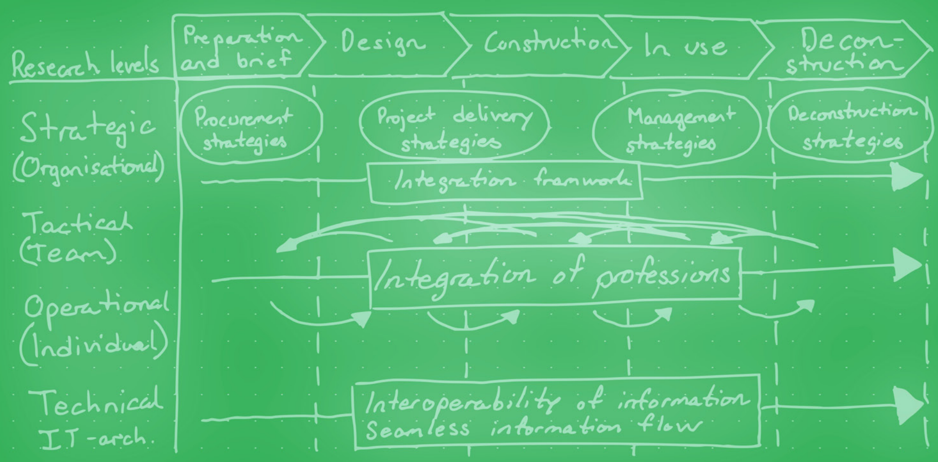
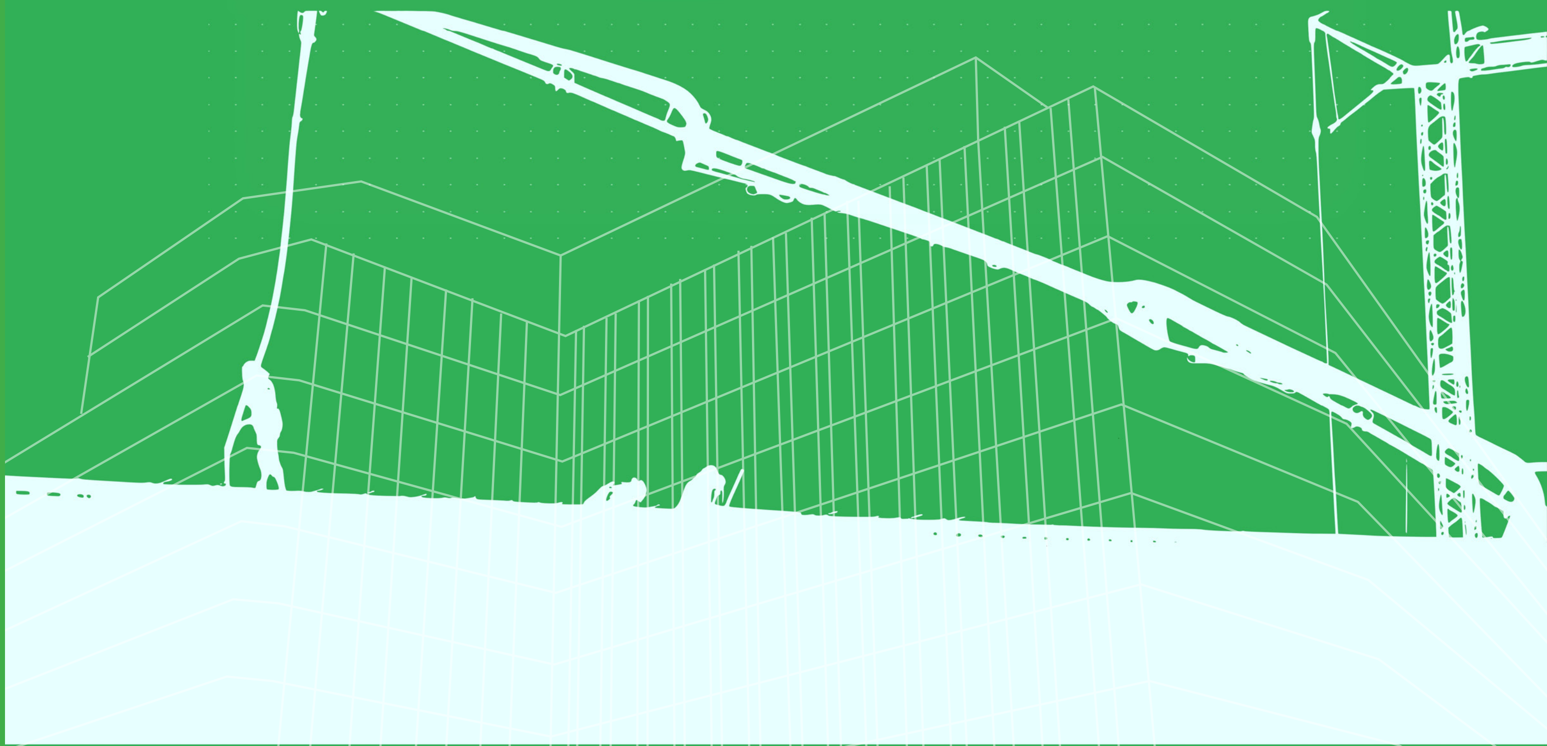
Publication 417

Research Roadmap
Information Integration in Construction





International Council
for Research and Innovation
in Building and Construction

Title Research Roadmap for Information Integration in Construction

Serial title 417

Year 2019

Editor Rasmus Rempling

Language English

Pages 83 p.

Key words Information, Integration, Construction, Building, Team work, Sustainability, Integrated design

ISBN 978-90-6363-09-66

Publisher CIB General Secretariat
Van der Burghweg 1
2628 CS, Delft
The Netherlands
E-mail secretariat@cibworld.nl
www.cibworld.nl

Credit Cover photo: The picture taken by Rasmus Rempling is an illustration of the proposed research framework and from a photo of the casting of the new rail road viaduct connecting the harbour in Gothenburg with the Swedish national rail road.

CIB

Research roadmap report Information Integration in Construction

Note from the authors

This Roadmap is developed for a challenging Global environment where fundamental paradigms such as data generation and analysis, are shifting at a seismic rate, while change in Construction Industries across the Globe is, in the main, confined to large-scale projects and slow. Against this background, the authors set out to also give a 'voice' to small-to-medium-scale projects through which the construction output Worldwide is delivered. Hence, project scale was one of the key considerations throughout this Roadmap.

Moreover, the authors conceptualized data integration by taking the realities of 'doing business' in construction into consideration. The emergent framework facilitates the discussion of knowledge and data integration at organisational, team, operational and technical levels across key project phases. This approach recognizes that business is done through projects but change can only come about if appropriate organizational structures and processes are put in place.

Last, but not least, the authors strived to ensure that data integration was not considered solely from a technical perspective. Organisational, team and individual aspects of data integration were integrated in the research framework. Through our work the individual's willingness to collaborate emerged as a critical driver for high levels of integration, while our survey did identify "Reluctance to work across professional boundaries" as a major barrier to integration. Hence, we conclude that research on integration should pay due attention to the individual.

Rasmus Rempling, Esra Kurul, Akponanabofa Henry Oti (2019)

TG90 Members:

Coordinators: Keith Hampson; Adriana Sanchez Gomez; Rasmus Rempling

Members: Paul Akhurst Heap-Yih, John Chong; Xiangyu Wang; Peng Wu; John Gelder; Judy Kraatz; Sherif Mohamed; Erezi Utiome; Sittimont Kanjanabootra; Xianbo Zhao; Geoffrey Shen; Anita Ceric; Marianne Forman; Kim Haugbølle; Frederic Bougrain; Sonia Lupica Spagnolo; Youngsoo Jung; Jasper Mbachu; Robert Amor; Ole Jonny Klakegg; Vegard Knotten; Torill Meistad; Marit Støre-Valen; António Aquiar Costa; Jan Bröchner; Christina Claeson-Jonsson; Anna Kadefors; Göran Lindahl; Liane Thuvander; Kristian Widén; Henry Abanda; Esra Kurul; Akponanabofa Henry Oti; Francis Edum-Fotwe; Wim Bakens; Ruben Santos; Daniel Månsson

Dr Rasmus Rempling

Rasmus is a structural engineer and Associate Professor at Chalmers University of Technology, located in Gothenburg, Sweden. His research interest ranges from information management - in the whole life-cycle at all levels: strategic, tactical, operational and technological – to structural design and assessment and material mechanics. Within these areas, he performs research and supervises PhD's. During his PhD he focused on the mechanical response of normal concrete subjected to cyclic loading. He has proposed - together with his colleagues – numerical models for analysing concrete behaviour on macrolevel as well as meso-level. He was co-coordinator of the EU-project Pantura - Low disturbance urban construction - and has worked internationally with design rules for concrete. Currently, Rasmus do research on data driven design with focus on sustainability and integration of construction engineering in the design stages.

Dr Esra Kurul

Esra is a Reader (Associate Professor) in Organisational Studies in the Built Environment at Oxford Brookes University (OBU), UK. She has a PhD in Environmental Studies (2003- UCL, UK), a MA in Conservation Studies (Building) (1997- University of York, UK); a BArch, Middle East Technical University (1993,Turkey), and a PG Cert: Teaching in Higher Education (2006-OBU, UK). Esra's research focusses on real-life problems in the built environment. It is interdisciplinary and is undertaken in collaboration with industrial partners when appropriate. Its natural outcomes are: significant peer-reviewed external research funding, substantial body of high quality peer reviewed publications, an international reputation, and developing recognition for impact. Esra has a wealth of experience in leading externally-funded projects, line-managing and mentoring post-doctoralresearch fellows and assistants, and supervising PhD, masters and undergraduate students. Having set it up, Esra has been a pivotal member of the Smart Construction Research Group at OBU..

Dr Akponanabofa Henry Oti

Henry is a Lecturer in Civil Engineering at the University of Bolton, UK. With several years of industry and teaching/research experience, Henry trained as a civil engineer from the University of Lagos (1998) and has a Masters in Water and Environmental Management (Loughborough University, 2002). He has a PhD from the University of Nottingham (2014) and a PgCert in Teaching in Higher Education from Oxford Brookes University (2016). Henry's expertise is in extending building Information modelling (BIM) applications to multi-dimensional subjects in building and civil engineering. Some of his several published works include a proposed BIM-based integration of sustainability credentials into the early phases of structural design, using performance data from building management systems (BMS) simulated in a BIM environment to inform building design/operation and the integration of lessons learned knowledge in BIM.

Content

1 Introduction

1.1 Aim & Scope

In 2014, the International Council for Research and Innovation in Building and Construction (CIB) established a new Task Group on Information Integration in Construction (TG90). One of the tasks of the group was to produce this Research Roadmap. This roadmap formulates an agenda for new R&D projects and/or initiatives that focus on data, information and knowledge integration in construction so that construction sectors globally can respond to significant challenges such as Climate Change. Its objectives are to:

- illustrate the significance of data, information & knowledge integration for the construction sector globally;
- present a framework for conceptualising information & knowledge integration at organisational, team, operational and technical levels across the key project phases;
- identify current gaps in research and practice;
- present demonstration projects where data, information and knowledge have been partially integrated;
- present an agenda for R&D and novel initiatives to close the gaps identified in research and practice.

As such, this Roadmap plays a significant part in TG90's effort to contribute to making information integration a reality by:

- developing more appropriate business and procurement models, including contractual frameworks; and
- suggesting alternative approaches to project team composition and governance; and information architecture.

Integration is discussed and evaluated in the context of large and complex projects as well as of small-to-medium-sized projects throughout this Roadmap. The comparison of integration in these two domains, which the authors argue are fundamentally different, underpins this Roadmap. Initial observations are that integration in the former types of projects requires more formal approaches such as Integrated Design & Delivery Solutions . Such approaches have widely been studied by other CIB Task Groups, Working Commissions, e.g. W065, W070; and priority theme groups on data and information integration, e.g. Integrated Design & Delivery Solutions. There is a plethora of publications (Goulding and Arif, 2013; Owen et al., 2013; Bosher et al., 2016; Haugbølle and Boyd, 2016), including agendas for research (Office of Rail and Road, 2018), that deal with data and information integration within large, complex projects where failure to do so would have a catastrophic impact on delivery. Perhaps as a result of this significant impact, the discussion on why and how data, information and knowledge integration can be achieved in small-to-medium-sized projects is limited. This Roadmap will contribute to closing this gap in the literature, and thus complement the work of other CIB Task Groups, Working Commissions, and priority theme groups.

This Roadmap is developed for a challenging Global environment where:

- China, US, and India will account for 57% of the growth forecast in construction (Global Construction 2030, 2015);
- the construction industries and their markets, e.g. ageing population, are changing;
- there is an emphasis on maintenance, refurbishment and replacement projects, including infrastructure;
- designing for life, flexibility and deconstruction are gaining prominence;
- energy provision, security, managing demand & supply are important issues;
- data and technological solutions for its effective use are abundant but significant barriers to adoption exist, specifically for small-to-mid-size projects.

The Roadmap is conceived as a vision statement for rising up to the above Global Challenges, while simultaneously dealing with such persistent industry issues as fragmentation, low levels of innovation and productivity; as well as skills shortages. The Roadmap conceptualises data, information and knowledge integration at organisational, team, operational and technical levels across key project phases. It posits that integration in large, complex projects is different from that in small-to-mid-sized projects; and suggests avenues at research for effective integration in these two contexts.

It also complements "Integrating Information in Built Environments" - a book edited by Sanchez et al.(2017), which was a direct outcome of collaboration between some members of TG90. The book is structured around two themes: Resources and Processes. The former theme focusses on how information integration can result in more resilient urban environments and projects. The second theme is centred around case studies of projects where information integration has been used to improve different aspects of project delivery. The book concludes with a chapter that discusses the value that information integration would add.

1.2 Appproach and limitations

This research roadmap is based on an extensive desktop study of secondary literature, including publications from relevant CIB task groups and working commissions. It has also been informed by a number of brain-storming sessions between both the editorial team and 42 members of TG90 who represent 14 different countries. Progress on preparing this Roadmap was presented in September 2017 at the International Research Conference 2017: Shaping Tomorrow's Built Environment, which was organised by the University of Salford. Following this presentation, a survey was sent to TG90 Members. This survey was designed to gather data on members' views on why information integration should be achieved and how; and which Global challenges might be addressed through integration. As such, Global coverage and representation have been achieved through the representation in TG90.

Secondary literature on the state-of-the-art in information and knowledge integration in mainstream projects is limited. This limitation was addressed by contributions from members of TG90 who have access to secondary publications in their languages and insight into local practice. It should however be acknowledged that this contribution is confined to the representation that could be achieved within the group.

1.3 Outline

The remainder of this Roadmap is divided into six sections. Section 2 conceptualises the Built Environment (BE) as a key sector in the Global economy that not only contributes to human capital, e.g. by providing employment, but also detracts from the natural environment due its high impact. The Global Challenges that the industry faces are identified in this section. A conceptual framework for integration at organisational, operational, tactical and technological levels across the stages of the project life-cycle is presented in Section 3. The current state of integration is reviewed in Section 4. In Section 5, the future of information integration is explored with a specific focus on meeting global challenges. The two demonstration projects (one from the UK and one from Portugal) that are presented in Section 6 illustrate that integration tends to be technology-centred. The Research Roadmap to achieve the desired levels of integration at all necessary levels is drawn in Section 7.

2 Background

This section will illustrate the significance of the construction sectors globally and identify the challenges that industries face in the developing and developed countries. First, the contribution that construction industries make in countries which will experience the highest levels of growth in this industry is highlighted. Then, the relationships between the built environment and man-made wealth, human capital, quality of life and the natural environment are explored. The challenges which emerge as a result of these interactions are identified. This section concludes by arguing that data, information & knowledge integration would not only help construction industries improve their performance but would also be instrumental in addressing the challenges identified.

2.1 Definitions

The International Standard Industrial Classification (ISIC) of All Economic Activities "is the international reference classification of productive activities" (United Nations, 2008). It provides a framework within which economic activity in different countries and different sectors can be collected and reported. Countries across the Globe either use this classification for their own reporting or data classification purposes or develop their own classifications, which are largely based on ISIC.

Abbott, et al., (2007) argue that the ISIC's definition of the construction industry is very limited because it does not include other value-adding activities upstream, e.g. manufacturing, parallel activities, e.g. architectural and technical consultancy, or downstream, e.g. real estate. The authors acknowledge this limitation, but argue that devising an alternative approach and consistently applying it at the Global scale is beyond the scope of this Roadmap.

Moreover, the authors offer a distinction between the definition of a sector and an industry, which are usually categorised according to ISIC. In our view, Abbott, et al., (2007) posit that the contribution of the Construction **Sector** goes far beyond what is represented in the output figures provided for the Construction **Industry** (Section F, Division 41-43) in ISIC. With this distinction in mind, the ISIC definition of the industry is used alongside other indices to explore the contribution that Construction Industries make to economies and societies of countries where substantial growth of industry is forecast. The authors concur with Abbott, et al., (2007) that the construction sectors make much greater contributions to the relevant economies than the figures cited in this Roadmap.

2.2 Construction industry as drivers for the global economy

Construction is one of the largest industries in the world economy. The construction industries in the developing and developed countries make a big contribution to their GDP. Global Construction 2030 (GCP and OE, 2015) estimates that this contribution will rise to 14.7% of global GDP in 2030 from 12.4% in 2014. It is anticipated that the European construction market will not reach pre-crisis, i.e. pre-2008, levels of spending until at least 2025. The Australian infrastructure market will not recover to its 2012 peak until 2030.

China, US, India, Indonesia, UK, Mexico, Canada and Nigeria are the top eight countries in terms of their contribution to global growth, which amounts to 70% of total growth. The top three will account for 57% of this growth (Global Construction 2030, 2015). In some countries this growth is driven by increased urbanisation, e.g. Nigeria, whereas in others it is driven by long-term under-investment in infrastructure, e.g. the UK.

China, which became the largest construction market in 2010, is expected to increase its global share despite the slowdown from 18% in 2015-16 to 26% in 2025 (PCW, 2017). Indonesia, Vietnam and the Philippines represent a $350 billion construction market growing by more than 6% annually (PCW, 2017). Consequently, we add Vietnam and the Philippines to the countries which will drive growth through their construction industries.

Currently, 50% of global construction companies are in Asia, 30% in Europe and 20% in the Americas (Ingram, 2017). China has the highest number (26) of global companies registered in its jurisdiction, followed by the USA (16 companies), Japan (11 companies), South Korea (10 companies) and Spain (7 companies). Players in China, Korea, and India are increasing their competitive power as they start looking to expand abroad since growth in their home markets has started to ease. These are signs of a shift from the Western World to the Eastern World with regard to leadership growth and delivery in construction.

Having painted the Global picture, we now present detailed data on the structure and output of construction industries in the countries that will drive industry growth to 2030. Unfortunately, this data is only readily available for China, the USA and the UK, and is presented in this section. Some of the structural issues regarding data, information and knowledge integration will be highlighted by evaluating this data. It is assumed that these arguments also apply to other countries.

Table 1 shows the number of companies by employment size as a share of the total number of such companies. It is clear that the vast majority (88% to nearly 98%) of these companies are micro companies that deliver between 1.4-2.9% of the output in China; 21% in the USA and about 30% in the UK (Table 2). Companies which have less than 50 employees make up at least 98.5% of the companies in these countries. These companies tend to be specialists, usually in a particular trade and have overwhelmingly the lowest productivity levels within the sector (MGI, 2017). They characterise the fragmented nature of the industry, which is considered to be one of the key reasons behind its low productivity (The Economist, 2017). If construction productivity caught up with that of the total economy, the industry would add another 2% to the global economy (Barbosa et al., 2017). Hence, it is important to explore what integration means and how it can be achieved in these companies.

Table 1: Number of Companies by Employment Size (Share of Total)

	%	2010	2011	2012	2013	2014	2015	2016
CHINA	Micro (0-7 employees)	N/A	88.1	87.7	90.5	88.8	88.3	88.6
	Extra small (8-19 employees)	N/A	4.2	4.4	3.5	4.1	4.4	4.3
	Small (20-49 employees)	N/A	3	3.1	2.4	2.8	2.9	2.8
	Medium (50-299 employees)	N/A	3.1	3.1	2.4	2.8	2.9	2.8
	Large (300+ employees)	N/A	1.7	1.7	1.3	1.5	1.5	1.5
	Total	N/A	100	100	100	100	100	10
USA	Micro (0-9 employees)	N/A	95.4	95.3	95.1	95.1	95.2	95
	Extra small (10-19 employees)	N/A	2.5	2.5	2.6	2.6	2.4	2.5
	Small (20-99 employees)	N/A	1.8	1.9	2	2	2.1	2.2
	Medium (100-499 employees)	N/A	0.2	0.2	0.2	0.3	0.3	0.2
	Large (500+ employees)	N/A	0.1	0.1	0.1	0.1	0.1	0.1
	Total	N/A	100	100	100	100	100	100
UK	Micro (0-9 employees)	97.3	97.5	97.7	97.6	97.7	97.7	N/A
	Extra small (10-19 employees)	1.7	1.6	1.5	1.6	1.5	1.5	N/A
	Small (20-49 employees)	0.7	0.6	0.6	0.6	0.6	0.6	N/A
	Medium (50-249 employees)	0.2	0.2	0.2	0.2	0.2	0.2	N/A
	Large (250+ employees)	0.03	0.03	0.02	0.03	0.02	0.03	N/A
	Total	100	100	100	100	100	100	N/A

In China, around 75% of the output is delivered by large companies which employ more than 300 people (Table 2). In the USA, large companies are defined as employing 500+ people and delivered around 20% of the output between 2011 and 2016. The definition of a large company in the UK is one that employs more than 250 people. These companies delivered between 29% and 38% of the output in the UK between 2010 and 2015.

The structures of the construction industries in these countries, as judged by the very high percentages of small companies, are similar. However, China, which is still regarded as a developing country, and the USA and the UK, which are developed, are at the opposite ends of the spectrum when the percentage of output delivered by companies of different sizes is considered. It is clear that the bulk of the output is delivered by large companies in China, while most of it (60-80%) is delivered by micro, small-to-midsize companies in the USA and in the UK. This difference might result from the fact that the output is delivered through mega-projects, often incorporating infrastructure delivery, in the rapidly urbanising developing world, and that such projects are usually delivered by large companies.

In the UK and the USA, each group of micro and large companies produce roughly the same amount of output. These contributions are about 30% in the UK and about 20% in the USA. Hence, around 50% of the output in the UK and the USA is generated by companies at either end of the company size scale.

Given this statistic, it is arguable that approaches that are currently advocated for integration and collaboration and that are inherently appropriate for adoption by larger companies in larger projects, e.g. IDDS, BIM, would deliver the necessary outcomes in micro-companies. The authors argue that this brief overview of the structure of construction industries in China, the USA and the UK yields the features of organisations, e.g. size as the first level of conceptualisation so that a framework for integration can be developed that can be consistently applied in different contexts.

Table 2: Production by Employment Size (Share of Total)

	%	2010	2011	2012	2013	2014	2015	2016
CHINA	Micro (0-7 employees)	N/A	1.4	1.7	1.7	2.2	2.6	2.9
	Extra small (8-19 employees)	N/A	2.8	3	3	3.4	3.7	3.8
	Small (20-49 employees)	N/A	4.5	4.6	4.5	4.8	5	5
	Medium (50-299 employees)	N/A	14.8	14.7	14.8	14.6	14.4	14.4
	Large (300+ employees)	N/A	76.5	76	76.1	75	74.2	73.9
	Total	N/A	100	100	100	100	100	100
USA	Micro (0-9 employees)	N/A	21	21.2	21.1	21.1	21	21.1
	Extra small (10-19 employees)	N/A	11.3	11.4	11.5	11.6	11.7	11.2
	Small (20-99 employees)	N/A	28	27.9	28.4	28.8	29.6	29.8
	Medium (100-499 employees)	N/A	17.4	17.1	17.5	18	17.7	17.5
	Large (500+ employees)	N/A	22.3	22.4	21.4	20.4	20	20.4
	Total	N/A	100	100	100	100	100	100
UK	Micro (0-9 employees)	29.8	26.6	29.5	28.6	27.9	30.3	N/A
	Extra small (10-19 employees)	11.9	10.1	10.5	11.2	9.5	10.2	N/A
	Small (20-49 employees)	13.1	10.7	11.9	13.8	11.8	12.4	N/A
	Medium (50-249 employees)	16.1	16.5	14.9	14.4	12.7	13.4	N/A
	Large (250+ employees)	29	36.1	33.2	32	38.1	33.7	N/A
	Total	100	100	100	100	100	100	N/A

2.3 Built environment: contribution & impact

"The term 'built environment' (BE) refers to aspects of our surroundings that are built by humans, i.e. distinguished from the natural environment. It includes not only buildings, but the human-made spaces between buildings, such as parks, and the infrastructure that supports human activity, such as transportation networks, utilities networks, flood defences, telecommunications and so on (Designing Buildings Ltd, 2018)." The BE generates economic and social value in three fundamental ways. First, it generates the economic output and value by delivering services accommodated in the built assets. These assets are part of man-made wealth. Second, the BE generates significant training and employment opportunities, sustaining and developing Human Capital. Third, it constitutes the assets that support the citizens' well-being, health, education and quality of life. These contributions are discussed in the following sections.

2.3.1 The Built Environment & Man-made Wealth

The natural environment provides many of the resources such as breathable air, potable water, food and vitamins for nourishment, in addition to space and shelter for basic human survival. Making most of these resources available at the point they are needed nowadays requires some sort of human intervention in many parts of the world. Such intervention has given rise to the built environment which now exists in relation to the 'non-built' environment or ecosphere (Moffatt and Kohler, 2008). Nonetheless, the built environment does interfere with the system balances existing in the ecosphere creating changes in social, economic and environmental conditions. To a large extent, the growth of the built environment resulting from the increase in man-made wealth[1] implies depletion of the natural environment and therefore needs protection (Twill et al., 2011). Although the protection of the natural environment has long been advocated, it has not inhibited the expansion of man-made wealth, 66-90% of which has been comprised of built assets from the Industrial Revolution to the present day (Lorch, 2003).

The overall wealth of a country as a whole is reflected in the economic measure of her GDP, although the wealth of individuals in and across countries may differ. Globally, 39.6% of the GDP was attributed to buildings and infrastructure in 2016 (ARCADIS, 2016), a small increase from 38.7% in 2014.

[1] Wealth, in this sense, refers to money or property, owned, or accumulated by an individual, partnership, or corporation that can be used or available in the production of additional wealth. Examples include physical infrastructure (buildings, roads, machinery, etc.) used to produce goods and services, including the physical manifestation of information, techniques, and knowledge required to produce goods and services.

Among the 10 countries considered, USA, China, UK, India and Canada had the highest GDP sustained in millions ($US) between 2013 and 2016. However, in terms of per capita GDP, the countries with the highest 'wealth' are USA, Canada and the UK (Figure 1). It is interesting to note that Mexico, which produces a relative GDP of one tenth of China's, has a similar GDP per capita ($8,201.31) as China ($8,123.18) in 2016. Perhaps partly as a result of a population increase from a greater number of more births or by immigration, the GDP per capita for Mexico, Canada, UK and Nigeria, has been falling since 2013, whereas the US has improved its GDP per capita in this period. China, India and Vietnam also improved their GDPs but at a lower and much slower rate.

Indonesia has one of the lower GDP per capita values, but its construction industry makes the highest GVA contribution as a percentage (10.74%) of her GDP. India's construction industry makes the next highest contribution at 7.2%, followed by Canada's at 6.95% and China's at 6.75%. It could thus be argued that the construction industries make a larger contribution to the creation of man-made wealth in the developing countries than they do in the developed countries.

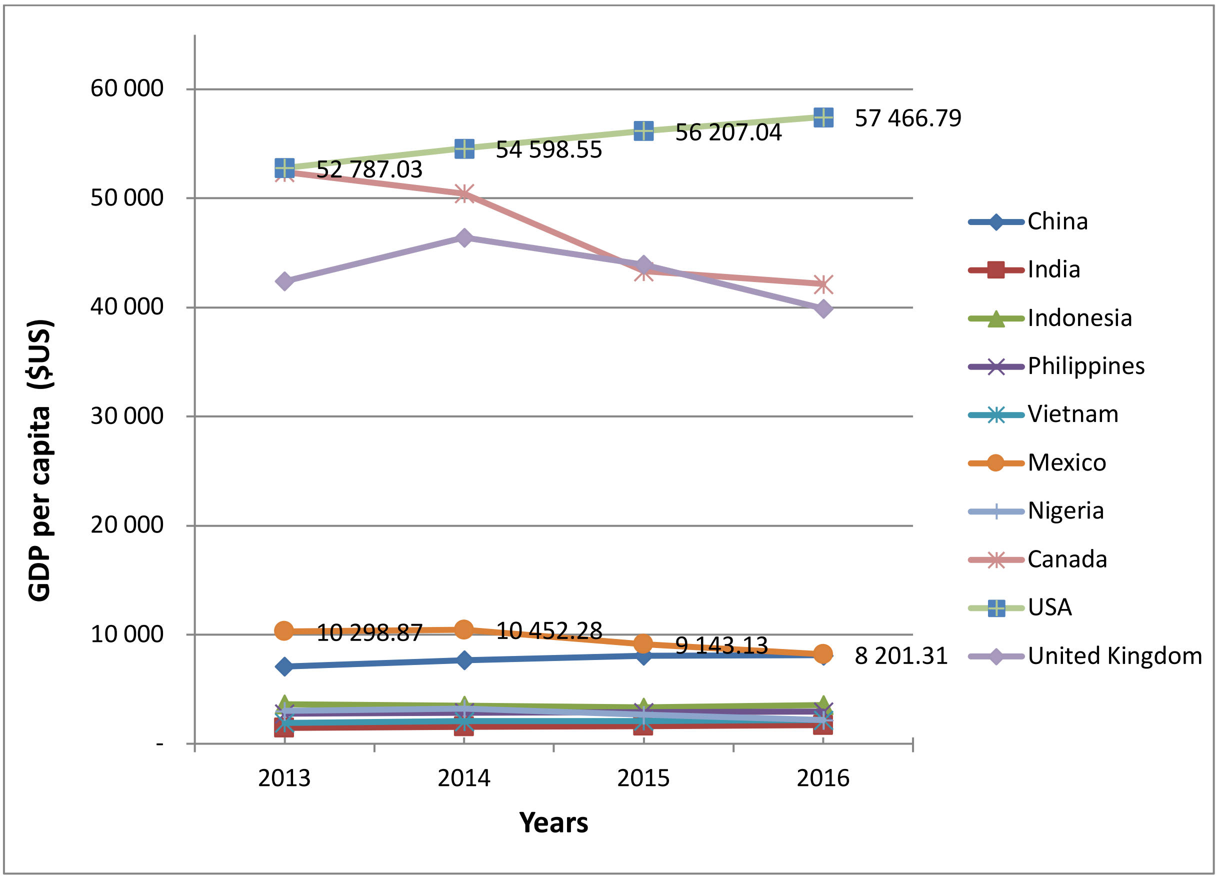


Figure 1. Countries GDP per capita

Once built, these assets contribute to the GDPs of individual countries through their returns on investment. Since 2014, China has surpassed the USA as the country which generates the highest returns from its built assets (Figure 2). Her return on built assets as a share of her GDP stands at 52.9% and is forecast to increase to 70% by 2026. Mexico and the Philippines rely most heavily on the contributions that their built assets make to their respective GDPs, 63.6% and 59.4% respectively. It is forecast that "by 2026, emerging markets will increase their dominance in high performing and sustainable assets" (ARCADIS, 2016).

On the contrary, the contribution of built assets in the UK to the GDP has fallen from 27.2 to 26.3% between 2014 and 2016. The reduction in public and private investment in new assets is considered to be the reason behind this fall. China, the USA, India, Mexico and Indonesia are among the countries which will lead in terms of not only the returns from their built assets but also the growth of their construction industries. Once again, the list is dominated by developing countries.

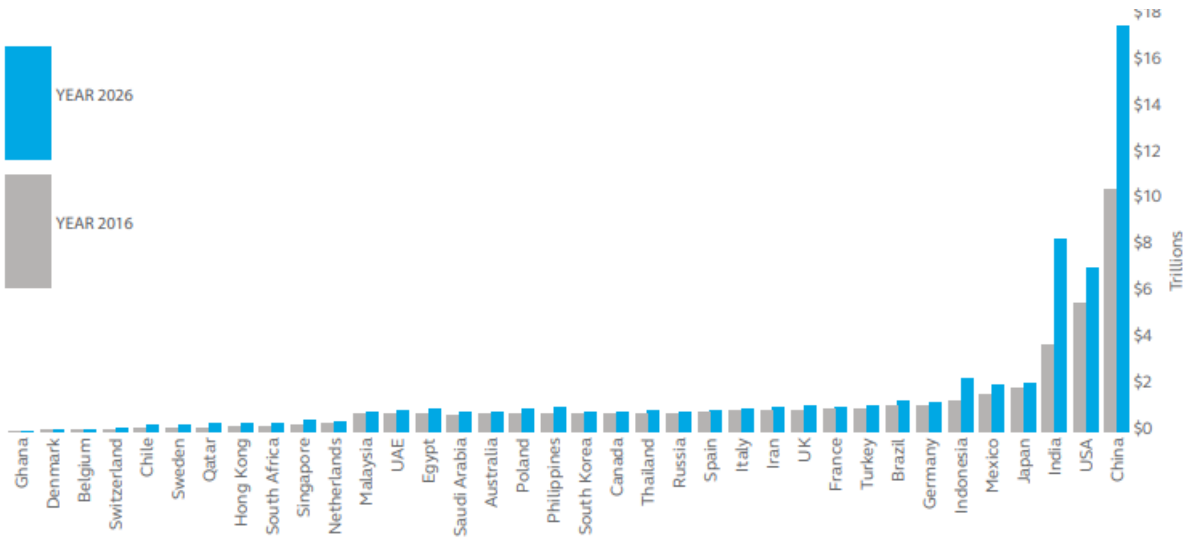


Figure 2. Returns to built assets, 2016 and 2026 (forecast) (ARCADIS, 2016)

2.3.2 Built Environment & Human Capital

Human capital, which is a vital part of the economy, is "the stock of skills that the labour force possesses" (Diebolt and Haupert, 2016). It is generated by investing in people's education, training, health and well-being.

Various combinations of indicators have been proposed by researchers to gauge human capital. One suggestion is labourer's income (Jeong, 2002), another is the combination of overall knowledge, economic resources and physical well-being (De Clercq and Dakhli, 2003). Recognising that skills are key determinants of prosperity and well-being of a country, OECD and the World Bank in collaboration with ETF, ILO and UNESCO used the Human Development Index (HDI) (OECD, 2015). HDI is a composite index of life expectancy, educational attainment and income and emphasizes people and their capabilities as the ultimate criteria for assessing the development of a country. Over a four-year period, 2013-2015 (Figure 3), the HDI has been relatively constant for each of the ten countries. The three countries with the highest HDI (0.9) are the UK, USA and Canada with Nigeria being the lowest (0.5). Mexico stands out among remaining countries with an HDI of 0.8 next to the upper three countries.

Like any industry, there is a regenerative 'dance' between the creation and utilisation of human capital in construction industries. Potential employees are trained and, in some cases, educated to attain the necessary skills and knowledge to create and maintain the built environment. Employment gives the chance of a decent quality of life both for the employee and his/her family. Employees accumulate experience through their professional lifes and thus have the opportunity to increase their income levels. As such, industry also serves to enhance human capital. However, the overall HDI scores in Figure 3 do not show how the construction industries in these countries might have influenced overall HDIs.

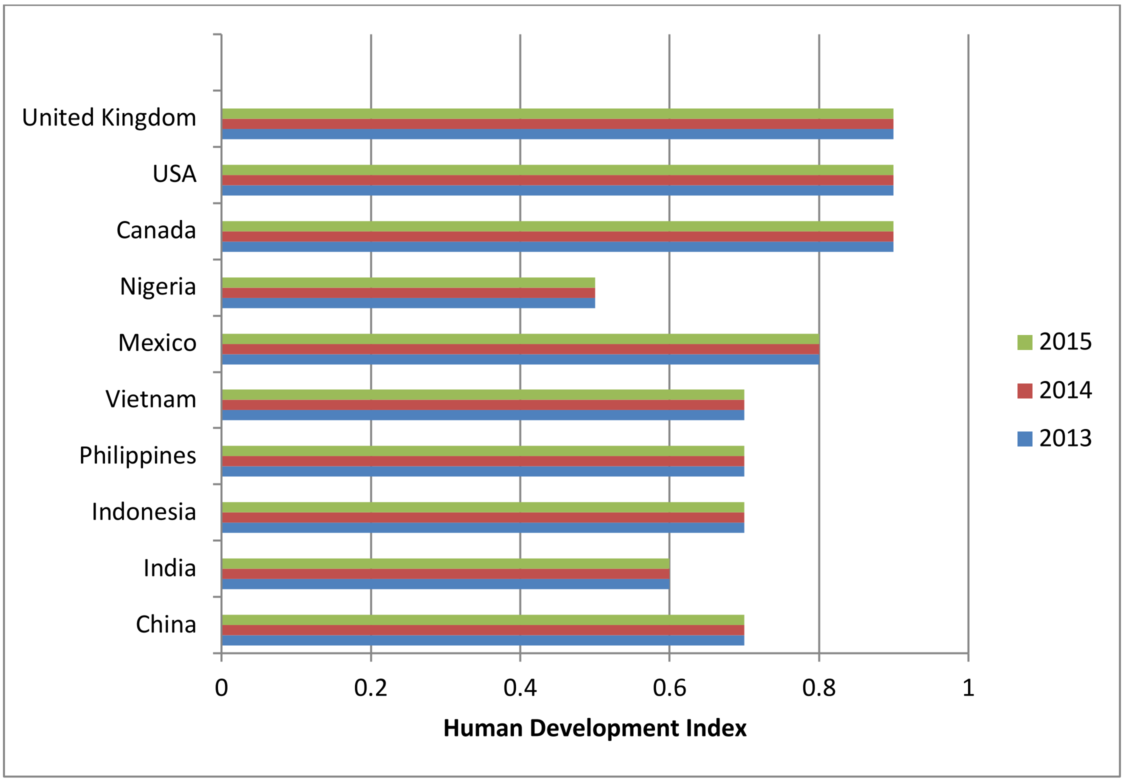


Figure 3. HDI Scores

Table 3 shows the percentage of total employment that construction industries provide in each country. These percentages have been calculated using ILO data. It is clear that construction industries in some of the developing countries provide a sizeable amount of total employment, e.g. 10.74% of the employment in India in 2012.

Table 3: Employment by Construction Industry as a % of total employment

Country	Year	%
India	2012	10.74
Philippines	2016	8.24
Mexico	2016	8.22
Canada	2016	7.66
UK	2016	7.16
USA	2016	7.13
Indonesia	2016	6.56
Vietnam	2016	6.11
Nigeria	2013	2.93

Typically, the educational attainment of the workforce is low. This is partly due to the nature of the industry where on-the-job training is an appropriate route to enhancing the skills of the workforce. Also, globally, the construction industries do not tend to attract young talent due to their image of being low-tech industries which are reluctant to innovate. These issues coupled with fluctuations in the economy and thus available work tend to yield acute skills shortages. Potential entrants to construction and young professionals do not consider this industry to provide opportunities for learning and career development (World Economic Forum, 2018). For site workers, the workplace is far from safe. In developing countries in particular, there are serious health and safety issues. Well-being in the workplace has started to gain attention in the developed world, but again, there are abundant issues with regard to the well-being of construction workers across the globe.

Hence, it can be argued that the construction industries are better at exploiting human capital by relying on labour-intensive processes than they are at developing human capital through investment in education, training and well-being. Their main contribution to human capital is the provision of employment. Technological developments, e.g. off-site manufacturing that rely on high levels of information integration across the supply-chain, have the potential to reverse this trend since they rely on highly skilled workers at the manufacturing end of the supply-chain. Thus, the construction industries could be transformed in such a way that they make substantial contributions to the development of human capital across the globe.

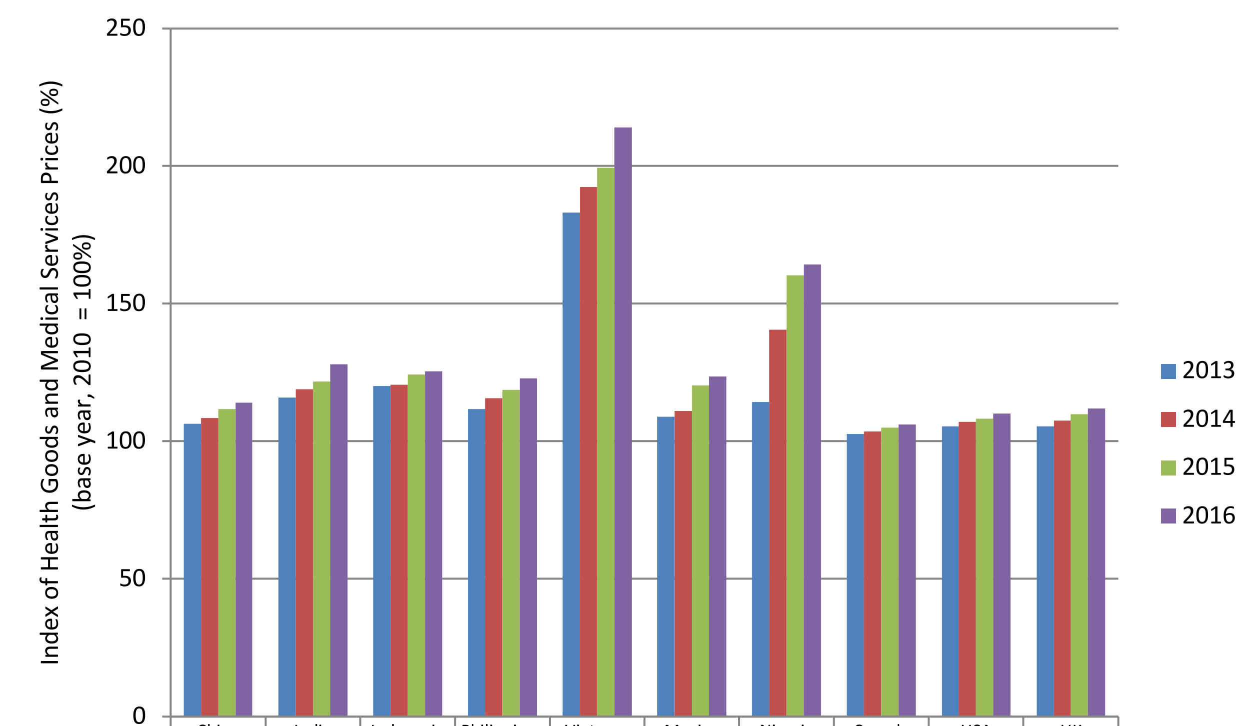
2.3.3 Supporting Quality of Life

Researchers have argued that one of the goals of sustainable development is to support quality of life which is a function of human health and well-being (Northridge et al., 2003; Van Kamp et al., 2003; Mohit, 2013; Sassi, 2016). Similarly, attaining an acceptable quality of life is not unconnected to a comfortable and functional built environment (Sassi, 2016). The built environment creates the capabilities for individuals and communities to explore the potential of growth within the parameters of sustainable living in terms of resource consumption and environmental protection measures. The forseing includes upholding a car-free existence, living in comfortable and healthy buildings, and enjoying walkable neighbourhoods and green spaces. Also, neighbourhood and support networks which characterise the built environment can help develop a sense of identity and provide opportunities for training, education, as well as employment (Sassi, 2006). A better quality of life means being able to live successfully and happily within the environment (Brown and Brown, 2005). In sustainable development terms, such ‘goodness of life’, although subjective to different individuals, should encompass both the present and future generations. It is clear, however, that the economic, environment and social well-being enshrined in the principles of sustainable development are largely inter-dependent and need to be in balance to support an improved quality of life. Quality of life refers to here is the sense of happiness and life satisfaction of individuals from meeting their needs which can be obtained from a combination of the following factors.

- The aesthetic profile of the living environment such as in communities and cities.
- Human health, acceptable social behaviour, cultural identity and civic pride.
- Well-designed infrastructure, education, leisure and entertainment.

While the indicators of quality of life could be objective (e.g. life expectancy, crime rate, poverty rate etc.), subjective (e.g. material possession, sense of safety, happiness) and/or behavioural (e.g. participation in sports, visits to parks, visits to clinic/doctor etc.), they are socially-inclined (Mohit, 2013).

Therefore, we examine the index of health goods and the price of medical service for ten countries (Figure 4) in order to evaluate levels of health delivery as an indicator of access to health and quality of life. The Index of health goods and medical service prices is the weighted average of the index for pharmaceutical products, medical appliances and equipment prices, as well as outpatient service prices and hospital service prices (Euromonitor International, 2018). Using 2010 as the baseline, challenges to securing access to health services appear to be most severe in Vietnam followed by Nigeria. This also implies that the quality of life in these two countries will be lower compared to others. Canada, UK and the USA again show stonger positions in accessing wealth than China, India, Mexico and the Philippines.



	China	India	Indonesia	Philippines	Vietnam	Mexico	Nigeria	Canada	USA	UK
2013	106.4	115.9	120.2	111.7	183.2	108.9	114.2	102.6	105.4	105.4
2014	108.4	118.9	120.6	115.6	192.5	111	140.5	103.6	107	107.6
2015	111.7	121.8	124.4	118.7	199.5	120.3	160.4	105	108.2	109.8
2016	114.1	128.1	125.4	122.8	214	123.5	164.2	106.2	110	111.9

Figure 4: Index of Health Goods and Medical Service Prices for countries

2.3.4 Impact on the Natural Environment

The natural environment has remained the primary source from which human needs can be satisfied which has largely contributed to its transformation over the years. Exhibiting a combination of tangible and less tangible effects of man-made capital, human capital and social capital enshrined in the built environment, environmentalists caution that the growth of the built environment will always be at the expense of the natural environment which must therefore be protected (Twill et al., 2011). Production processes require natural resources. The results affect balances in the ecosystems connected to elements such as climate regulation, flood control and natural habitats. The consequences of material extraction for production and consumption extend beyond national boundaries and feature many environmental, economic and social impacts that transcend generations. The OECD (2015) affirms that the use of natural resources have consequences for:

- The rates of extraction and depletion of renewable and non-renewable natural resource stocks and the extent of harvest and natural productivity of renewable resource stocks.

- The environmental pressures associated with the extraction, processing, transport, use and disposal of materials (e.g. pollution, waste, habitat disruption); and their effects on environmental quality (e.g. air, climate, water, soil, biodiversity, landscape), ecosystem services and human health.
- International trade and market prices of raw materials and other goods, and the productivity and competitiveness of the economy.

Thus, transforming parts of the natural environment into built assets not only confiscates affected areas but, in most cases, requires further extraction of materials from natural reserves located elsewhere. The implications can be dire and require some control and moderation to ensure that resulting conditions maintain an equilibrium between the various components of the environment, economic and social systems. Such progressive policies and appraisal techniques, economic lending approaches, financing and risk assessment methodologies are required to change the financing, profitability, and value determination of innovations in further developing the built environment (Twill et al., 2011). These requirements all point to a need for integration in order to achieve a better balance between the natural and built environments.

2.4 Industry Challenges

The contribution and impact of the built environment on various aspects of the Globe and its inhabitants were discussed in a previous section (Section 2.3). This discussion has painted a picture that the built environment makes a significant contribution to the Global economy and economies of selected countries. However, it also affects the natural environment and human capital. Our discussion complements the many calls from different parts of the world for the construction industries to change and innovate (World Economic Forum, 2018) in order to become more sustainable and rise to the following challenges[2]:

1. Issues shared by developing & developed countries:
    a. Fragmented industries, business models/working in professional silos, multi-disciplinary (NOT inter-disciplinary) approach
    b. Low levels of innovation & productivity despite data/ information integration initiatives
    c. Energy: provision, security, managing demand & supply
        i. Lack of adequate infrastructure and facilities
        ii. Ageing infrastructure in 'old' countries, such as the UK

[2] These challenges were identified through two brain-storming sessions, the first between the authors during a workshop held at Oxford Brookes University, the second between the CIB's Senior Programme Manager and the authors. Bakens (2016) and outcomes of the first session formed the basis for the second discussion.

   d. Data: security, inter-operability, availability and analysis
      i. Security: cyber security,
      ii. Making use of performance knowledge:
         1. Energy performance in buildings
         2. Corrosion, environment, etc in infrastructure
   e. Need to design for life & flexibility
      i. A solution to housing shortages and the need to house an ageing population
      ii. Learning from past experience & integration of users & providers
      iii. Off-site manufacturing / industrialisation
   f. Skills shortages / consequences
      i. Deep specialisation in professional silos becoming a barrier to inter-disciplinary collaboration
      ii. Reluctance to work across disciplinary boundaries
      iii. Changes in desirable skill sets, e.g. factory precision.
      iv. Skill mobility
      v. Life-long learning for an agile workforce
      vi. Companies competing for talent & ageing workforce
2. Issues which specifically concern developing countries:
   a. Issues with stability: governance, politics
   b. Corruption: governance, management of projects
   c. Informal/black economy

2.5 Data, information and knowledge in the built environment

Data, information and knowledge integration can play a significant role in addressing the above challenges. It could be argued that this statement is not new. It is commonly accepted that construction is driven by information and knowledge and that the early-to-mid-2000s witnessed a surge of research and business initiatives for the industry to enhance its knowledge management capabilities, subscribing to Grant's knowledge-based theory of the firm (Grant, 1996).

During this period, the starting point for 'mainstream' approaches to managing knowledge was to categorise it as tacit and explicit knowledge, and to conceptualise data, information, and knowledge across a spectrum. Some scholars took the view that new knowledge is produced through the transformation of existing knowledge from one form into another (Hedlund, 1994; Boisot, 1998; Nonaka and Nishiguchi, 2001). Others presupposed 'designing and installing systems' as the solution to the integration problem (Stacey, 2001:26). Others, e.g. Bresnen et al. (2003), emphasised that "knowledge is often tacit, situated and embedded within particular social groups and situations." Perhaps as a result of the difficulties associated with explicitly capturing tacit knowledge in ways that can consistently be transferred and applied in new contexts, the social aspects of managing knowledge attracted less attention than the mainstream approaches.

By the end of the first decade of the 21st century, the industry's focus had once again shifted towards information as a result of the emphasis on Building Information Modelling (BIM) and its perceived prospect of transforming the industry into a more collaborative and productive entity. We now find ourselves in an environment where data and information reign. Managing building information dominates our efforts to increase the levels of productivity and innovation in construction industries across the globe.

As a result, the important role knowledge plays in improving industries is once again overseen. Knowledge is instrumental in making sense of data and information. Brown and Duguid (2017) warn against focussing too intently on information in our quest to achieve our destination as quickly as possible. They stress the importance of peripheral view, i.e. context, background, common knowledge, social resources. We therefore argue that data, information and knowledge integration should be considered as part of the same spectrum and at the organisational, team, operational and technical levels across the key project phases. Such an approach will enable us to shift the focus from integration at a project level to integration at a strategic level. In the next section, we propose a framework to facilitate this shift.

3 Framework for research on information integration

A framework for the road map and research on information integration are presented in this Section. It sits against the sectorial background which defines the legal, regulatory, social, economic, environmental and political opportunities and constraints which are translated into the framework through the strategic (organisational) level in the framework.

As the integration of information in construction is multi-disciplinary, there is a need for a common base to which all parties can relate. Working with building and infrastructure engineering, the building process is a natural common ground that is present in both infrastructure and building delivery, operations, maintenance and refurbishment. In order to provide a wider perspective on research challenges, a model that categorises research at four levels is proposed: Strategic, Tactical, Operational and Technological. The inter-level-process challenges of research on information integration in construction can be developed and identified within the same framework.

3.1 Building process – RIBA stages

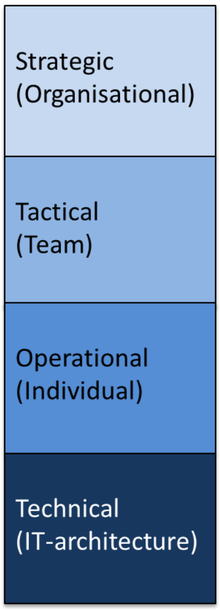
The RIBA Plan of Works is published by the Royal Institute of British Architects (RIBA). The latest version is also endorsed by the Chartered Institute of Architectural Technologists, the Construction Industry Council, the Royal Incorporation of Architects in Scotland, the Royal Society of Architects in Wales and the Royal Society of Ulster Architects. It is also commonly used across the globe.

Split into a number of key project stages, the RIBA Plan of Works provides a shared framework for design and construction that offers both a process map and a management tool. Whereas it has never been clear that architects actually follow the detail of the plan in their day-to-day activities, the work stages have been used as a means of designating stage payments and identifying team member responsibilities when assessing insurance liabilities. These stages also commonly appear in contracts and appointment documents. The latest version reflects increasing requirements for sustainability and Building Information Modelling (BIM) and allows simple, project-specific plans to be created.

In the research road map, the RIBA Plan of Work has been adopted as a framework in order to structure the research road map and define a framework for facilitating a common level of understanding due to the diversity of profession that work within the construction sector.

3.2 Levels of research

To establish a framework for research on information integration in construction, four levels of hierarchy are identified. These levels are interdependent of a successful implementation of information integration.



At the **S**trategic level, the main issues are the benefits and organizational pre-requisites for the integration of information, such as strategies for procurement, project delivery and management strategies.

At the **T**actical level, team composition and team organisation, as well as factors which influence integration and sharing between the different RIBA stages and projects considered.

At the **O**perational level, the professional methodologies and use of technical support are reflected, as well as national building regulations, standardisations and harmonised technical rules. The creation of information and the purpose of its creation are also positioned at this level. The purpose differs between professions. In the pre-construction stages, information is needed for making design and planning decisions. During the construction stage, information is needed for site planning and construction management. In connection with the advancements of Information Technology, machine learning and other artificial intelligence systems, as well as sensor technology are vital, and creation and the exploitation of information (automation, decision-making, etc.) are at the frontier of building information research.

At the last level, the main focus is the technical, supportive architectures that can manage, store, filter, and analyse information in a manner that is seamlessly interoperable and accessible across project teams and individuals.

3.3 Framework

The framework builds on the main stages of the building process and hierarchical levels of research. In Figure 5, these two building blocks are presented in order to show the *inter-level-process relationship.* In addition, the model is intended to underline the need for a broad view of research on information integration.

Research tends to be undertaken from a professional perspective, e.g. procurement strategies, the use of building information in design, production planning or facilities management. Increasingly, focus is shifting towards seamless information flow, but research that deals with both the solutions to technical challenges and the process of implementing these solutions remains limited. Our model highlights the need for an inter-disciplinary approach to research and for truly understanding the interconnections between the different levels and stages in order for the construction sector to benefit from information integration.

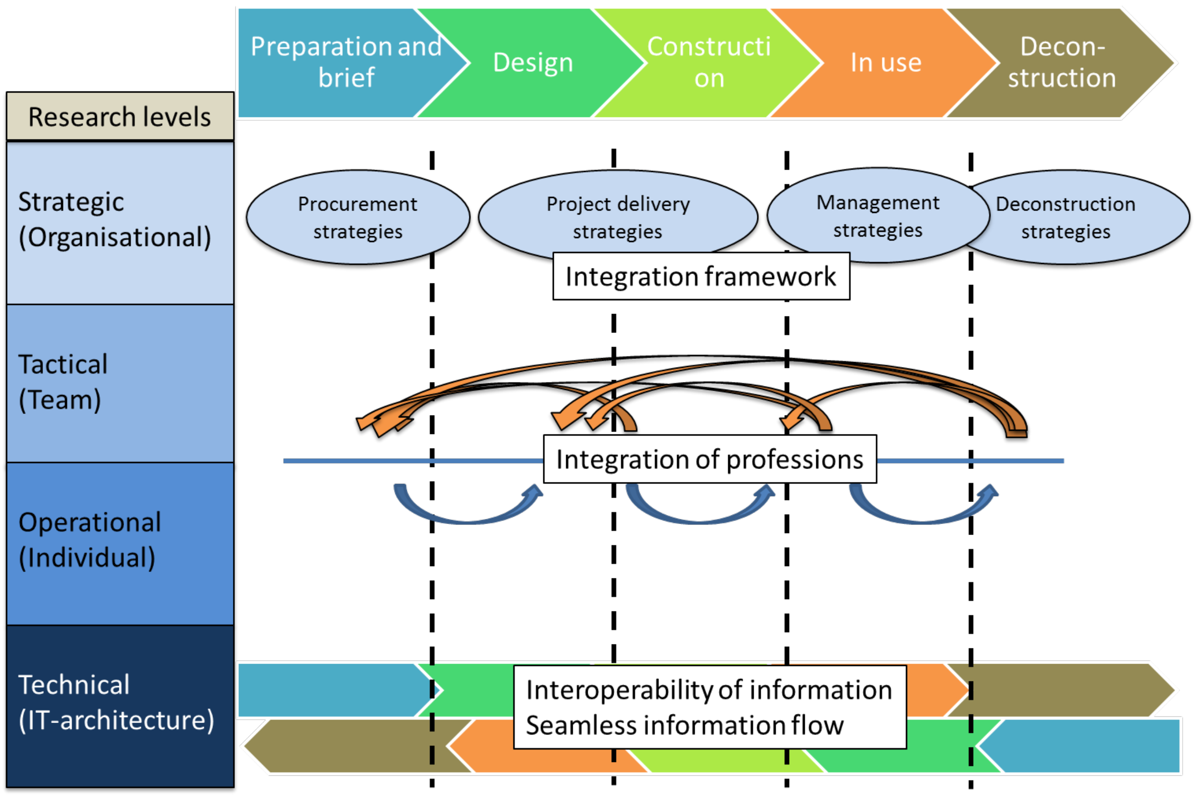


Figure 5: Research framework

3.3.1 Integration mechanisms

It is clear that a strategic mechanism for information integration across the project coalition is needed. This framework can only be put into practice if the client, consultants, contractors and managers are convinced that they will mutually benefit from the integration and sharing of information between their organisations and from one project to the next. An imperative of this is an integration framework which includes all parties and in which each party can identify their gains and positions. Hence, an important area of research for the future is to determine the conditions in which each party would genuinely be willing to integrate their knowledge in small-to-mid-size projects.

3.3.2 Integration of professions

Information sharing at the boundaries between stages will always be challenging. There will probably always be a "hand-over" from one organisation to another, which requires that the sharing of information results in a clear business gain. For example, a building information model can be developed during the design phase by a design consultancy. It is then handed over to the contractor for the construction stage in a way that both the design consultancy and the contractor continue to have access to the model as it is refined during the construction phase. In the same way, facility managers and owners of public infrastructure could generate information that is useful and gives a competitive edge to the design and construction of new buildings and structures. However, the current business model, which relies on short-term contracts, creates a disincentive for sharing information as described above.

Research on project delivery approaches has grown in order to deal with this disincentive. Early Contractor Involvement and Integrated Project Delivery have emerged as delivery strategies that break down parts of this disincentive. However, the complicated situation for the team and individual, referring to the deviation of aims of the "home" organisation and project goals, has not been dealt with. Moreover, these strategies have generally been considered in the context of large, complex projects, without considering whether and how they might be implemented in small-to-mid-size projects.

On a more strategic level, the need for integration between the different stages of a project can be linked to the professional bodies that represent the allied disciplines of the built environment, e.g. architecture, structural engineering. Since they emerged in the 19th Century, these professional bodies have been nurturing their silos. Their influence on education in the professions has continued to strengthen the boundaries between the different RIBA stages. Hence, the time has come to consider the role education and training in professional silos plays on this emerging need for integrations.

3.3.3 Interoperability of information

There are essentially two types of approaches to interoperable information, which has been adopted in such a way that consolidation of data from one set is shoe-horned into the framework used for another set of data. An alternative approach is to build a federation of data where the data resides in its native data set. Here it is important to note that a federation of data does not interfere with the standards of native data sets.

Within the architecture, engineering and construction industries, recent years have seen a shift from vision to realisation in the use of building information models (BIM). Using modern modelling tools, such as Revit Architecture or Tekla Structures, the content produced by architects, designers and engineers has been evolving from traditional 2D drawings, sketches and written specifications to parametric, object-oriented 3D models embedded with information to describe a building or facility in detail.

As a digital representation of the physical and functional characteristics of a building, the purpose of a building information model is to serve as a repository of information to support a multitude of applications along the design and construction processes, including cost-estimation, energy analysis and production planning. Building information models (BIM) aim at eliminating the non-value adding or lower value adding activities to integrate the high value adding but fragmented tasks and improving the automation of processes and project performance in terms of project time, cost, and other relevant parameters, including waste reduction.

However currently, the concept of building information models is often degraded to sharing 3D CAD models for the purpose of clash detection and visualisation. One of the reasons is the information interoperability between different software and information systems which is partly due to the fact that information between the different stages of the design and construction processes is still transferred as independent data files. Although such an approach may utilise the IFC file format, which is considered to be the standard for building information models, the approach puts high demands on the ability of the individual software to prevent loss of information as it is transferred from one stage to another (import-modify-export).

Recent initiatives, such as the BIMserver project, have the potential to enhance the current situation by providing a central storage of information during the life cycle of a building or facility. Such a solution will ensure the persistence of added data, thereby limiting the loss of information between the different stages of design and construction (as compared to a file-based approach). However, seen in a wider context, the BIMServer approach may introduce limitations of its own. Based on the IFC-file format, information is inherently restricted to the physical and functional characteristics of a specific building or facility and does not consolidate the environmental or socio-economic factors surrounding it. For instance, if we consider the planning, design, construction and operation of a new school in the middle of a typical city, it becomes clear that the processes and information surrounding such a project goes beyond those of the IFC-file format. During the planning stage, information regarding population, land use, infrastructure and public transportation becomes essential for a successful outcome. Today, these types of information are often accessible through geographic information systems (GIS) and are used as input in order to form the requirements of the actual design. However, once the project enters the design phase, a gap in the flow of information becomes apparent. Even with the use of a central repository for information, such as the BIMServer, the lack of support for consolidating geographic information system data prevents a successful transfer of information from the previous stage. As a consequence, the idea of consolidating all data (IFC/BIM + GIS + other) into a unified system has been flourishing and the approach has been to shoe horn BIM or 3D-VR data into the GIS system or GIS data to IFC (IFG: IFC for GIS).

For a variety of historical and operational reasons, building data is now, and will continue to be, housed in several independent data sources. Full consolidation of data holds little prospect of a solution and, for the reasons discussed above, would not be desirable. Rather, advances will be required to allow autonomous data sources to interoperate productively, allowing for bespoken integration of data at the point of use. The challenge will be creating collections of data resources that are perceived by users to be functionally integrated, yet with each resource maintaining its autonomy, especially in the basic creation and maintenance of its data resources.

4 State-of-the-art integration

The concept of integration is not novel (Izam Ibrahim et al., 2013) but stands as one important factor that is ever needed in the successive development eras of the Architecture, Engineering and Construction (AEC) Industry. In the efforts to improve industry performance efficiencies, previous reports (Latham, 1994; Egan, 1998) has pointed to integration as a plausible solution. More recent reports (Carbinet Office, 2011) have also emphasised improvement in the levels of integration as a means of moving the industry forward. Integration encompasses elements such as data/information, technologies/systems, people, processes and organisations and can be described as a situation in which project participants work together mutually and effectively. The characteristic features of integration include the merging of different organisations, disciplines, goals and cultures into a cohesive supporting unit (Jaafari and Manivong, 1999; Austin et al., 2002) for the objective of improving team culture and professional attitudes (Howell, 1996; Dainty et al., 2001).

In the AEC industry, effective integration entails the collaboration of multidisciplinary teams involved in the project life cycle, as well as the seamless interaction of associated software systems/tools and information exchange systems used to support the execution of various allocated tasks (Shen et al., 2010). Thus, integration helps to cement together and streamline processes involved in the delivery of projects in the AEC industry which is by their current nature fragmented. Such processes are largely dependent on technologies driven by professionals and other stakeholders whose integration is suggested to have a positive relationship effect on project performance (Kumaraswamy et al., 2005). These and other benefits make integration into an on-going issue of concern in the industry (Baiden et al., 2006; Izam Ibrahim et al., 2013).

4.1 Benefits of integration

An overarching objective of the AEC industry has been to keep project delivery performance at an optimum level at any point in time. However, this objective has been largely elusive due to the fragmentation inherent in traditional procurement approaches which do not encourage effective integration, coordination, communication and collaboration (Love et al., 1998; Walker et al., 2002; Hauck et al., 2004). For instance, Moore and Dainty (1999) demonstrated that no matter the level of structural change adopted under a traditional framework, project teams will always underperform. As such, the general consensus of researchers (Zhai et al., 2009; Lahdenperä, 2012; Aapaoja et al., 2013; Izam Ibrahim et al., 2013) is that the construction sector must move from the traditional adversarial focused behaviour towards more collaborative and integrated strategies/systems to deliver more predictable results to clients while improving project performance. Therefore, it is not surprising that project partnering, project alliancing and integrated project delivery (IPD) have been gaining increasing attention lately. In Figure 6, an illustration of the differnces between traditional and integrated design is given.

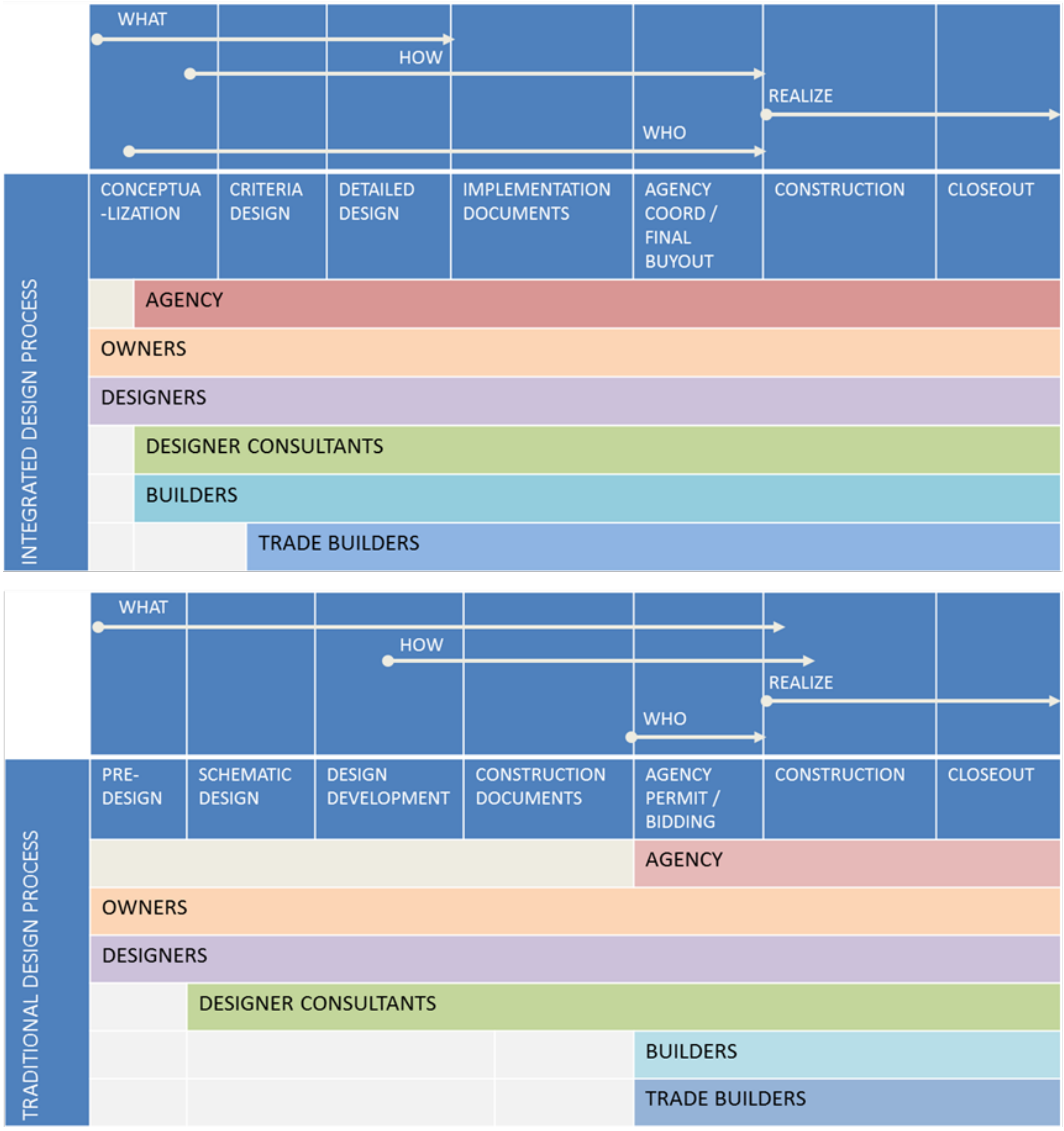


Figure 6: Traditional versus integrated design processes.

Firstly, project partnering is beneficial in situations in which programmes of work need to be delivered. It can be described as a strategic arrangement that enables the concerned contractor to reduce project costs, while also improving efficiency of delivery (Dainty et al., 2001; Harris and McCaffer, 2013). Thus, partnering team members in such arrangements have the opportunity of improving their problem-solving skills and knowledge of the processes involved (Himes, 1995). While the availability of resources and support from top management is a prerequisite for partnering, the ultimate goal is to achieve continuous development through trust, mutual understanding, openness and relationship building (Nyström, 2005).

However Dainty et al. (2001), argue that partnering faces the challenge of being largely restricted to client-contractor linkages, which makes the trickling down of benefits to the construction supply chain difficult. Bridging such flaws to achieve a closer relationship among supply chain members has therefore been in focus in supply chain management. Also, another issue is that gains and losses may not be jointly allocated among partners (Walker et al., 2002). Secondly, in project alliancing, relationships can become more seamless and all-embracing in achieving a unity of purposes between project teams (Walker et al., 2002). Here, project teams are capable of generating new knowledge to solve interrelated problems in a time constrained environment (Davis and Walker, 2009). Suggested as an outgrowth of project partnering (Hauck et al., 2004), profits and risks are jointly based on agreed levels of contributions to a project. The expertise and ability of alliance teams/organisations to meet stringent performance criteria on projects are prerequisites to price considerations and make room for a more confident, trustworthy and committed relationship with a client (Walker et al., 2002). Such relationships tend to become long-lasting and pivotal to value creation (Davis and Walker, 2009). Thirdly, IPD is described as a process characterised by the integration of people, systems, business structures and practices for harnessing talents and insights of all participants in order to achieve optimal results, increased value, reduction of wastes and maximum efficiency throughout a project life cycle (AIA, 2007; Aapaoja et al., 2013). It is built on the foundations of collaborating parties, including the aspects of handling risks and gains (Hall et al., 2014)

Lahdenperä (2012) observed that IPD, project alliancing, and project partnering are often used interchangeably, and even if they have their differences, "early involvement of key parties, transparent financials, shared risk and reward, joint decision-making, and a collaborative multi-party agreement are some of the features incorporated in all the arrangements to a varying degree" (p. 57). Consequently, these models are often based on relational contracting principles (Rahman and Kumaraswamy, 2004a; Rahman and Kumaraswamy, 2004b) incorporating both the formal contract and the relational mechanism for enhancing the collaboration.

Several studies have highlighted that establishing and maintaining collaboration between project members are complex processes and that contractual arrangements and individual attitudes do not always juxtapose (Kadefors, 2004; Kadefors and Bröchner, 2004; Laan et al., 2011; Laan et al., 2011). Behavioural studies have shown that external awards and punishment can undermine or prevent intrinsic motivation (Deci et al., 1999; Frey and Jegen, 2001). In IPD contracts, different economic incentives, such as target costs and forms of pain share / pain gain or risk / award arrangements, are common. Apart from the formal contractual structure, other approaches can be used to stimulate collaboration or team cooperation, including BIM and Lean Construction (e.g. Matthews and Howell, (2005)), and co-location of team members and the use of shared administrative systems.

Dewulf and Kardefors (2012) have shown that the formal (IPD) contract and the informal relation, trust, interact. After having signed the contract, a process starts where the partners gradually start to understand what the relationship means, both in terms of contractual agreements and behavioural aspects. This supports the suggestion made by Cicmil and Marshalls (2005) that structural measures, such as employment contracts, are not sufficient to handle the internal paradox between project performance and outcomes; and the processes for collaboration, cooperation and learning. The basis of Partnering success is the relation between the formal and informal aspects of the relationship (Bresnen and Marshall, (2002).

4.2 The integration of professions

Stakeholders in the AEC industry are numerous but commonly represented by multidisciplinary teams of professionals, including owners, architects, civil and structural engineers, service engineers, project managers, quantity surveyors, land surveyors, builders, facility managers, to name a few. This is owing to the complexity of the industry characterized by projects with multiple life cycle phases (Shen et al., 2010). These phases require different and peculiar tasks to be performed using varying types of materials obtained from distinct design and production/development processes which are often interdependent. The integration of teams of the various professions involved in delivering a project is needed to manage the inherent interdependence associated with characteristic construction processes and systems. These teams can be fragmented, partially integrated or fully integrated (Baiden and Price, 2011), as defined by the extent to which the combined ‘project team’ exhibits the integration characteristics suggested (Aapaoja et al., 2013). According to Baiden et al (2006), a fully integrated team can be characterized by the following:

- A single focus and set of objectives for the project
- Operation without boundaries among organization members
- Working towards mutually beneficial outcomes through support for/from each other and shared achievements;
- The use of collective skills/expertise to accurately predict and realise time and cost estimates by fully utilising the collective skills and expertise of all parties
- Free access to information and sharing among team members of different professions and organisational units
- A flexible member composition and the ability to respond to change over the project duration
- The development of a new identity and co-location in a given common space
- Providing members with equal opportunities to contribute to the delivery process
- An atmosphere in which relationships are equitable and members are respected; and
- A ‘‘no blame’’ culture

The factors that encourage teams to exhibit these characteristics have been the subject of research. Some efforts have been focusing on the improvement of procurement approaches (AIA, 2007), while others have been exploring the optimization of collaboration through the creation of an integrated construction environment via the use of technology tools (Evbuomwan and Anumba, 1998). In seeking to understand the effect of project delivery methods on the level of integration achieved, the early involvement of the contractor is suggested to be vital to the achievement of high levels of integration (Mollaoglu-Korkmaz et al., 2011). This is similar to construction management at risk (CRM) and design & build (DB) approaches. However, researchers (Mollaoglu-Korkmaz et al., 2011) have suggested that early contractor involvement has the potential of encouraging integration even in the traditional procurement approach.

Broader initiatives to foster the integration of teams and other aspects of project delivery exist. An example is the European Construction Technology Platform (ECTP) project aimed at mobilising the entire construction sector to define a clear set of common priorities for stakeholders. The ECTP project is centred on process renewal with the encouragement of New Integrated Processes for the Construction Sector as one of its priorities supporting interoperability and collaboration. Another similar initiative is the Capital Projects Technology Roadmap (CPTR), one of the projects undertaken by the Construction Industry Institute (CII) under the auspices of Fully Integrated and Automated TECHnology (FIATECH). The roadmap is about developing a highly automated project and facility management environment integrated across all phases of a facility life cycle (Shen et al., 2010). Besides the convening of diverse professions in periodic conference gatherings (conferences and congresses), the effort of the CIB (International Council for Research and Innovation in Building and Construction) in the Priority Theme of Integrated Design Solution (IDS) is another international initiative on integration. It promotes the use of collaborative work processes, the promotion of skills and the integration of data and knowledge management to enhance the delivery value across project stages. What is notable is that these initiatives focus on large, complex projects, leaving the small-to-mid-size projects prone to fragmentation.

4.3 The Integration of systems (interoperability of information)

In addition to its reliance on multidisciplinary teams, the execution of AEC projects usually involves the deployment of heterogeneous software and hardware systems/tools used by the various professionals in accomplishing their assigned tasks. Tasks in the project life cycle are highly interdependent in terms of information. The integration among teams and their associated systems/tools is expedient to fostering effective collaboration.

The integration of systems can occur within an organisation or between two or more organisations. The objective is to achieve better performance outputs, upgrades and holistic, robust systems that can engender improved stakeholder collaboration. Shen et al. (2010) assert that systems integration is all about the interoperability of information which entails the ability of diverse software and hardware systems to manage and communicate digitized products and project data seamlessly. Since interoperability concerns the seamless exchange of data, the richness of such data, known as its level of detail (LoD), also transpires as an important factor in AEC integration.

LoD in building specifications refers to information requirements attached to different stages of a building lifecycle. It captures the decomposition of objects and their relationships with regard to the amount of detail included (input) in the model at the various stages of development. This is subtly different from the degree to which information in the model can be reliably extracted (output), known as its level of development (LOD)(BIM Forum, 2015). According to PASS 1192-2:2013 (BSI, 2013), levels of model detail relate to graphical contents of elements which aligns and can be associated with the non-graphical contents, or levels of model information (LOI).

4.3.1 Levels of information interoperability

The ease with which systems communicate information with one another has been expressed in levels (Charalabidis et al., 2004; Charalabidis et al., 2008; van der Veer and Wiles, 2008; Bahar et al., 2013; Rezaei et al., 2014a). These levels reflect the degree to which challenges resulting from the difficulties in reconciling the different information representations approaches and structures have been surmounted by the systems (Visser et al., 2002b).

Bishr (1998) described the levels of information interoperability as a function of systems intelligence broken down into six categories. These levels include (i) network protocols, (ii) hardware and operating systems, (iii) spatial data files, (iv) the data base management system, (v) the data model and (vi) application semantics (See Figure 7). Each level constitutes a wide field of technology that can be improved or advanced to higher levels. The data model and application semantics levels are the most advanced. They are characterized by the transparent and homogenous representation of systems. As such, they are more difficult to achieve. As captured in Figure 7, broader views of the levels of interoperability exist, such as the four levels of aggregations (technical, syntactic, structural and semantic) defined by Visser et al (2002b) and those (technical, syntactic, semantic and organisation) developed by Rezaei et al., (2014b).

The aggregation of interoperability into (1) data and (2) frameworks by Shen et al (2010) is of interest. Data interoperability encompasses syntactic, structural and semantic interoperability aspects and entails the ability of other systems to properly interpret data generated by different systems. This can be achieved through appropriate data modelling involving adapting and reconciling information representation approaches. Data models from such processes can be proprietary or open/neutral. Whereas proprietary models are expressed in native formats and restrictive, neutral formats, such as the IFC, are freely available to all framework interoperability concerns the ability of network protocols, languages, hardware and operating systems to communicate with one another across relatively distributed or remote locations.

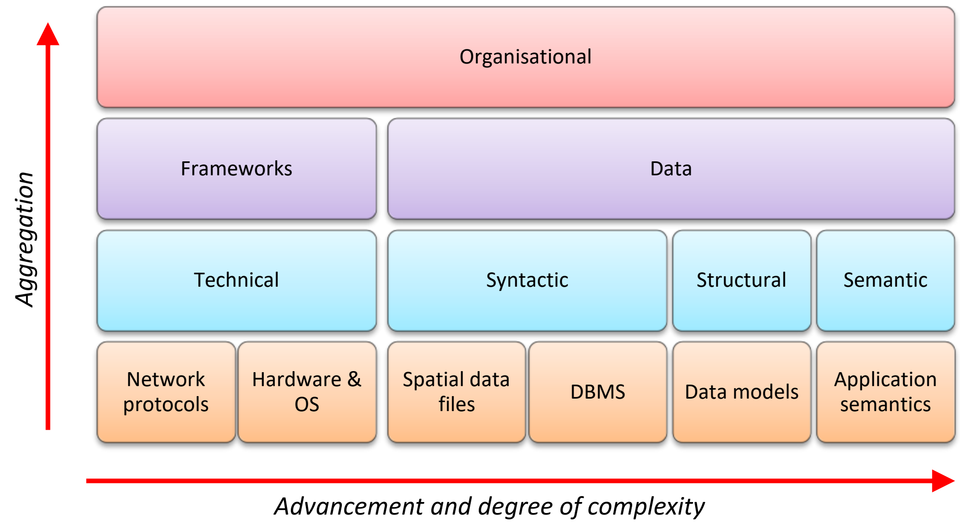


Figure 7: Relationship of levels of interoperability

4.3.2 Approaches to information interoperability

For effective and efficient system integration at the organisational level, interoperability needs to be high at both data and framework levels. This will help in harmonizing communication across proprietary data models/formats and legacy software languages/systems of different platforms. As rightly noted in Shen et al., (2010), achieving such a level of system integration in the AEC industry has been an incessant challenge because software developers have not envisaged the future expectations of working together. Also, focusing on the drive to dominate the available market among competing software systems may have contributed to being a distraction from the consideration of wider interoperability needs and benefits. The various existing platforms can often deal with interoperability challenges that emanate from their own systems, but not those of others. The plausible solution to this challenge now appears to be focused on the development of common models or formats and communication languages and protocols. The currently popular approaches to achieving information integration are Distributed objects/components, Software agents, Web-based applications, Web services and Semantic Web applications (Shen et al., 2010).

Distributed objects/components are products of the Object-oriented programming paradigm. It is a centralized integration approach characterised by the modularity of data structures and code sharing. An example of such application is the integration of commercial software packages (for design, visualization and planning) Simultaneous Prototyping for an Integrated Construction Environment (SPACE) by Faraj and Ashawi (1999). Furthermore, the establishment of three major Distributed Objects standards are attributed to the implementation of Distributed objects/components. These standards are CORBA by the Object Management Group, COM/DCOM by Microsoft and Java RMI by Oracle. Software agents are extended applications of Distributed objects/components directed at tackling challenges with collaboration and integration of teams. The optimization of the structural design process (Bilek and Hartmann, 2006) and construction process using RFID (Atkin et al., 2006) has undergone experimentation with Software agents. The deployment of agents' technology precedes that of Web-based systems and services and has been used for decentralised, changeable, ill-structured and complex industrial applications. Web-based systems are convenient for simple, daily construction project management tasks that can be accomplished though centralised information management systems or databases using web servers which are passive by replying to user request only.

For more advanced tasks, such as geometric and semantic product modelling, design representation and user interaction pro-active applications, such as Web services and Semantic Web, are deployed. In these applications, the software systems are built to support interoperability over the internet through machine-to-machine interaction and extension expressing Web content in natural language and formats readable by software agents (W3C, 2015). More recently, Cloud computing has been gaining ground as improvements in Web services in the AEC industry (Kumar et al., 2010; Beach et al., 2013). Another approach experimented in the AEC industry is wireless networks, such as Radiofrequency Identification (RFID), but lacks wide support from stakeholders (Shen et al., 2010). A main concern of this approach is efficiency of the system regarding energy and aspects of accuracy/consistency as a real time data collection tool to inform real time decision support. However, wireless networks have a great potential for application in the inspection and monitoring of activities in the AEC industry (Shen et al., 2010).

4.3.3 Standards for interoperability

Standards have been instrumental to the level of integration currently achievable in the AEC industry and the description of buildings in digital form. As given in Table 4, one of the first neutral standards developed to guide the transfer of graphical elements between CAD systems is the Initial Graphics Exchange Specification (IGES) around 1980 (Owen and Bloor, 1987; Bloor and Owen, 1991). Shortly thereafter, DWG, the native file format of Autodesk (a leading CAD vendor) became the de facto transfer standard (Björk and Laakso, 2010). In the late 1980s, numerous activities of CAD user groups developed CAD layer standards which were later harmonized as ISO 13567 in 1997. By then, researchers had already begun delving into more advanced representation of building data using the object-oriented paradigm to capture information beyond pure graphics. Driven by the need to solve data exchange challenges among a large number of manufacturing industries, these activities gained momentum around 1985 when the ISO STEP standardisation project started after which tangible outputs began to be realised in the early 1990s.

Table 4: Standards instrumental to integration in the AEC industry (modified after Björk and Laakso (2010))

Standard	Developed period	Use status	Domain
IGES	1978 - 1980	Official, ANSI	CAD graphics
DWG	1982 - 1990	De facto	CAD graphics
ISO 13567	1993 - 1997	Official, ISO	CAD layering
IFCs	1994 – On-going	Industry consortium	Building information model
CIS/2	2003		Structural Steelwork
gbXML	1999 – On-going	Industry supported	Building energy performance simulation
obXML	2010 – On-going		Buildings, Occupants and Behaviours in terms of Seasons and Time of Day
COBie	2007 – On-going	Industry wide	Facility and asset management

The Standard for the Exchange of Product Model Data (STEP) – ISO 10303 was first released in 1994/95 and contributes to providing the foundation for the current level of interoperability inherent in the AEC industry (ISO 10303, 1994). The STEP-file, characterised by the ASCII structure of instance of information per line, has been widely used in the exchange of data because of its clear Text Encoding nature. It has the capability to represent 3D objects in Computer-aided design (CAD) supported formats. As a standard for the representation and exchange of computer-interpretable product manufacturing information, it shares a common technology base with the IFC and CIMsteel Integration Standards (CIS/2) which have been key to the progress in the AEC industry information exchange. The responsibility for developing and maintaining the IFC lies with the buildingSMART International (formally International Alliance for Interoperability). The IFC specification is based on the EXPRESS modelling language and can also be expressed in a parallel XML format (IfcXML). Currently, about 150 software applications in the construction sector are acknowledged to be IFC compliant.

IFC is a neutral BIM data exchange standard with the current version, IFC4, accepted as ISO 16739. This latest version is incorporated with more enhanced definitions for building engineering. Future expansions of IFC4 are looking towards covering other infrastructure, including roads, rails, bridges and tunnels with greater emphasis on semantic web and linked open data applications (buildingSMART, 2016). Also aligned with the aspects of explicit shape representation in STEP is CIS/2, a multi-part industrial standard for the exchange of engineering information for steel-framed buildings. Its first release was in 2003 and now encompasses aspects of analysis, design, detailing and fabrication of structural steel used in buildings. The end product data model of CIS/2 is called the Logical Product Model (LPM). The capabilities of CIS/2 include detailed design of structural steelwork, detailing and manufacturing assembly of component parts and advanced structural analysis (Shen et al., 2010).

4.4 The implementation of integration methods

Inter-disciplinary methods in construction are best exemplified by multi-party contracting practices such as project alliancing, project partnering and integrated project delivery. These contracting methods, referred to as ‘relational’, are based upon the existence of trust between parties with the fair apportioning of responsibilities and benefits (Lahdenperä, 2012; Hall et al., 2014). The relational aspect helps to ameliorate inter-organisational relationships to deal with unforeseen events difficult to capture within the dictates of contract definitions. Thus, it encourages a flexible and speedy response to dealing with the challenges usually associated with a risk event that has not been explicitly spelt out in the contract. Also, such relational understanding enhances partnering organisations’ ability to innovate, access new markets, overcome barriers to local markets and share risks for mutual benefit (Beth Stanek, 2004). These procurement approaches reflect the industry’s quest to stimulate better value for money, and improve its profitability and reliability through closer process and supply chain integration (Simmonds and Clark, 1999; Beach et al., 2005)

Beyond these integrated approaches to project delivery, which mainly transpire at the strategic level, the allied disciplines of the built environment and, consequently, the stages of project delivery, are fragmented. A relational short-term perspective dominates the industry, beyond pockets of collaboration (Anumba et al., 2002). This fragmentation results in several sources of waste and value loss. During construction, value is generated by producing construction works, either in terms of new structures or by improving the already built environment (*Concurrent Engineering in Construction Projects*, no date). Such value generation is highly dependent on the collaboration between numerous suppliers from early design stages up until completion of construction (Oakland and Marosszeky, 2006). This process is not owned by anyone and project progress is achieved by involved participants through continuous negotiations (*ibid*). These negotiations are predominantly undertaken with a focus on discrete processes and/or products, rather than on overall project success. Typically, the impact of decisions made during the project delivery phases on the performance of the building during use is ignored. The process, from early design to completion, looks to be incidental, and yet, it is this process that ultimately determines the key outcomes of the project.

The lack of integration between different professions and trades during this process results in considerable amounts of waste. Here, waste is predominantly considered to be activities and tasks that are performed without adding any value to the customer (Josephson and Björkman, 2010). The lack of co-ordination, the low levels of time predictability, and self-interested parties (Forbes and Ahmed, 2010) are among the factors that result in this type of waste. Some authors (Crowley, 1998; Anumba et al., 2002) have argued that making design and production decisions earlier in the process could result in better integration and thus reduced waste. Others (Oakland and Marosszeky, 2006; Larsson et al., 2014) have focussed on the integration of different trades in the construction industry as a means of increasing the effectiveness of the project delivery process.

4.4.1 Teams in construction

Individuals, who make up the teams that deliver projects, enable or obstruct collaboration and integration. Activities in construction, both during the design stages and on site, are normally performed by individuals with varying skills belonging to different companies, all compounded into multidisciplinary and temporary organisations or groups. Here, these actors need to share information and knowledge for optimum decisions. Management of these activities performed by individuals and groups of individuals within an organisation are then coordinated to ensure a value flow, hence an organised flow in the work schedule. In any organization, to reduce waste and achieve high customer value, it is crucial to gradually change prevailing attitudes and behaviours of individuals within their organization. Only then may customer requirements be fully met (Josephson and Björkman, 2010). Baiden (2006) therefore asserts that teamwork is not an option, but a prerequisite for successful project delivery.

In construction, integration is usually conceived as the introduction of working practices, methods and behaviours that foster efficient and effective collaboration between individuals and organisations (Baiden, 2006). The literature often considers a problem from the perspective of the team. Individual motivations and how they impact on collaboration within a team are largely overlooked. Moreover, approaches to procurement and contractual arrangements dominate the discourse on integrated projects (Kadefors, 2002; AIA, 2007; Mosey, 2009). This limited focus is usually not appropriate for moving from fragmented to integrated design because the roles of the individuals in making integration happen are not considered. Collaborative procurement approaches, e.g. Partnering or Integrated Project Delivery, normally act as a stabilizer by formalizing patterns between the Client and its consultants, suppliers and by improving integrated design team performance. Researchers are mainly concerned with the formal aspects of such procurement methods, rather than the need for changing the relational patterns between parties (Forgues and Koskela, 2008) .

Problems associated with performance of integrated design teams are in general related to the context and not the process itself, i.e. they are not technical but socio-cognitive (Moore and Dainty, 1999; Baiden et al., 2003; Forgues and Koskela, 2008). Also, project teams in construction usually work together for the development of a single project. Consequently, a complete project team rarely works together on more than one project (*Concurrent Engineering in Construction Projects*, no date). Successful teams in manufacturing are those teams which have multiple project experiences and have developed a shared culture and organization of work and design processes. Therefore, due to the short-term perspective, there is always a significant risk that, if not well managed, design coalitions in construction will not perform well or might even be dysfunctional (Sumner et al., 1999; Forgues and Koskela, 2008).

4.4.1.1 Technical support for integration of interdisciplinary teams

Tatum (2005) highlights the importance of technical support for all actors in order to ensure integration and thus, an effective construction process. Integration can take place at three hierarchical project levels: at the macro-, meso- and micro-levels in order to represent different social constructions (Moum, 2010). The information that is communicated among actors and the possibility of integration depend on the level. The macro-level incorporates all participants of a construction project: architects, engineers, contractors and users. This conglomerate of stakeholders with separate interests and expectations is boiled down to a design team that needs to uncover the mutually beneficial expectations of the stakeholders (meso-level). Finally, the micro-level is defined as the collaborative space between the architect and the engineer.Moum's framework has been applied, at the micro- level, to a number of projects in order to study their level of integration, in addition to the impact of information and communication technology (ICT) on the progress of these projects. The non-technical parameters influencing integration were also highlighted. The study concluded that if there was a shared understanding of the aims and intentions, and the team possessed the high-level skills to utilise the ICT, the architects and engineers would collaborated and integrate their activities. In addition, her results highlighted the fact that soft, non- technical parameters, such as an architect's sources of inspiration, are easily disrupted by the introduction of ICT and that these parameters must be better understood in order to attain a successful implementation and use of ICT (Moum, 2010).

Other studies have shown that the introduction and adoption of new technologies can be difficult and slow to manage. (Mitropoulos and Tatum, 2000) consider the strategies for the adoption of new technologies necessary and identify four drivers of new technology adoption: competitive advantage, resolving process problems, technology opportunity and external requirements. In their study, they conclude that if these four factors were dominant, the rate of adoption would increase (Mitropoulos and Tatum, 1999; Mitropoulos and Tatum, 2000). It should be noted that these factors are client and top-management dependent, which may have implications for social integration at the micro-level that are not easily predictable. The potential opportunities for and barriers to such integration have been studied by Rivard et al (2004) using eleven case studies.

Mora et al (2006) concluded that such integration, which facilitates engineering feedback early in the design process, is beneficial for project outcomes. Provision of adequate levels of feedback would require overlapping domains, which traditionally exist between the architecture and engineering professions (Moum, 2010). This overlap constitutes a space in which the engineer can lay out a structural system in an architectural context. In addition, the work of the engineer and its quality is highly dependent on the amount, quality and type of information provided by the architect at this early stage.

The representation of the information into separate domains has beed laid out in two types of entities: functional and physical. Functional entities refer to what the object is intended to accomplish, whereas physical entities make up the structural components providing the function. The architectural domain was concluded to consist of purely functional entities describing the intentions of the architect complemented by the physical entities represented by the structural domain (Mora, Rivard and Bédard, 2006). Consequently, the engineer should have the opportunity to smoothly transition from the physical structural representation to the functional, a transition that would require high quality information (Moum, 2010).

Some authors argue that computer aided design (CAD) does not facilitate this integration, and thus that the bulk of the design process is dedicated to "routine design tasks" (Verhagen et al., 2012) (see Figure 8), typically undertaken in disciplinary isolation. Centralised representation of knowledge (Curran et al., 2010; Bermell-Garcia et al., 2012; Verhagen et al., 2012) offers improved opportunities for overlapping domains that might generate alternative solutions through innovative design. The innovative design process is extended but the overall duration of the design process is reduced as solutions are more quickly agreed as a result of closer collaboration.

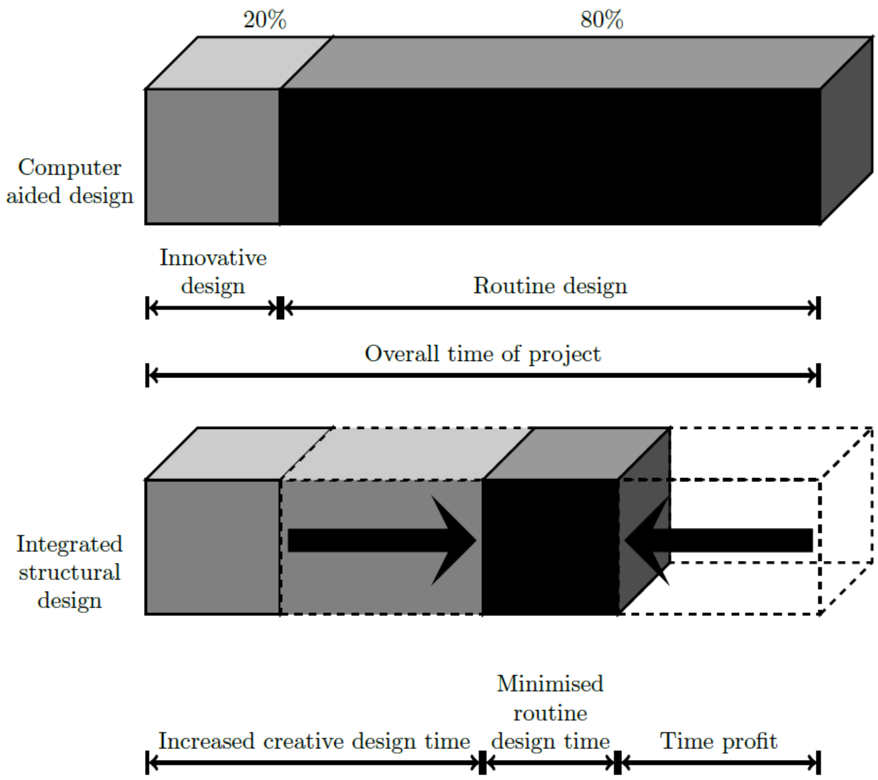


Figure 8: To gain time, all disciplines should strive for an automation of routine tasks, redrawn after Verhagen (2012).

4.4.2 Project partnering

Partnering as a concept has various definitions (CII, 1991; NEDO, 1991; Bennett and Jayes, 1995) which are underpinned by the basic philosophical consensus of a commitment between firms to cooperate (Bresnen and Marshall, 2000). The key is the definition of specific business objectives that are mutual, as well as the methods or arrangements to achieve the agreed upon objectives (Bennett and Jayes, 1995). Beach et al (2005) aggregated the common critical success elements of partnering under commitment, processes, tools and outcome (Figure 9). The management/administration of partnering firms must remain committed to the course. This includes top management to the lowest staff member. Where possible, workshops could be held for education to clarify issues (e.g. share visions and new working cultures) aimed at promoting and cementing partnering relationships. Processes encompassing various aspects of the communication of information, expectations and limitations must be clear and acceptable by partnering organisations. There should be clear understanding of what information can be shared, channels/medium to be used and associated timeliness of information that is to be communicated. Tools including software systems and equipment have been useful in complementing the integrated teams' ability to innovate during design and other phases of project delivery. The overall outcome is the delivery of a successful project. However, the benefits accruing to the project partners should be commiserate with the sacrifice of entering into the partnership when compared to operating otherwise (traditionally). Beyond, monetary profits, the built relationships should create room for more and better business opportunities in the future.

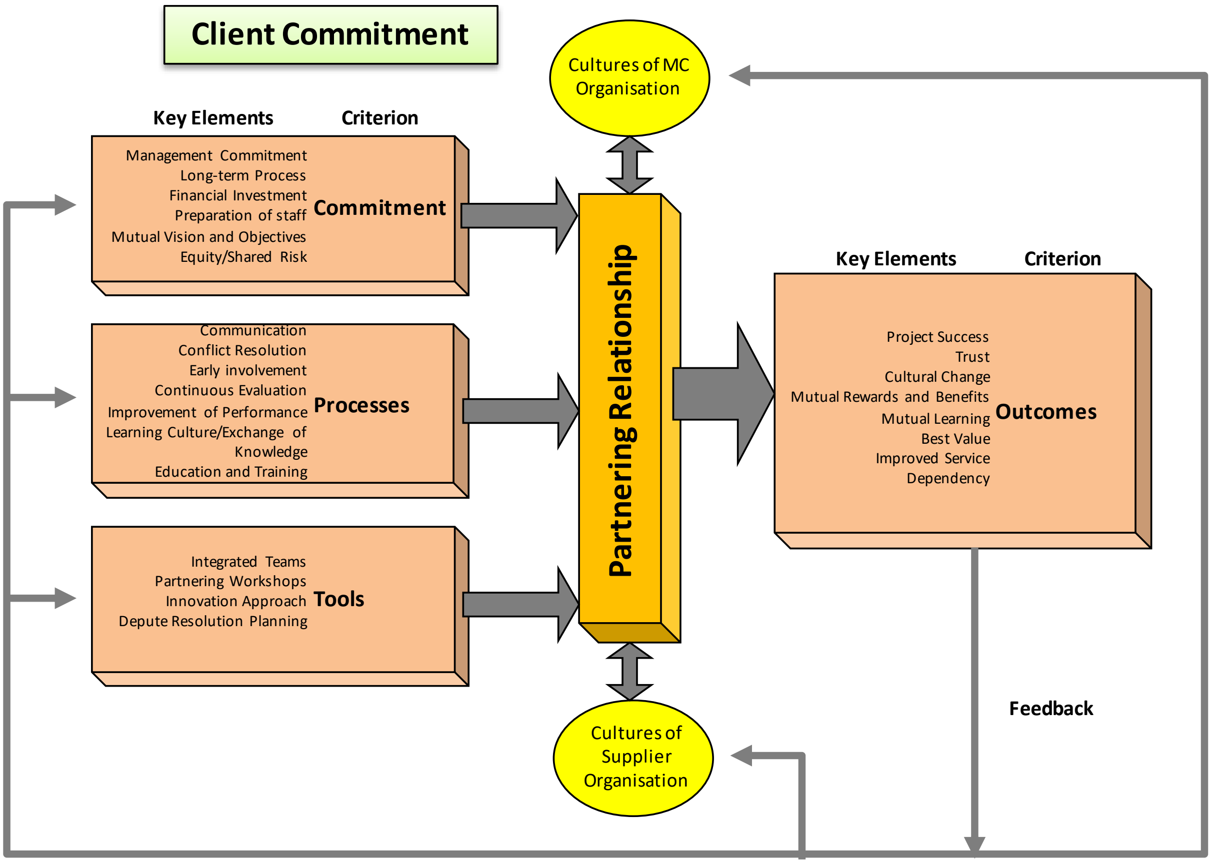


Figure 9: Conceptual framework for partnering (Beach et al., 2005)

4.4.3 Project alliancing

Project alliancing is more all-embracing in achieving unity of purpose between project teams than is obtainable in project partnering (Walker et al., 2002). It entails pooling together the resources of trustworthy, competent and talented professionals to join in with clients in developing a project. Project goals and price targets are established unanimously with a clear stipulation of agreed risks and reward sharing arrangements. A summary of the key features suggested by Walker et al (2002) include:

d. Strong selection criteria (innovation, excellence in performance and relationship management)
e. Substantial design development after forming the alliance
f. Joint commitment to budgets, cost/time unit by senior team members and client
g. Agreement on risks and reward formula including accounting methods
h. Absence of variations from extras as managed by the alliancing team
i. Excellence in communication at both personal and organisation levels

Project alliancing has its roots in the oil and gas sector born out the need for economically more efficient practice commensurate with the high level of risk involved in projects within the sector. The positive experiences from the first launch of project alliancing in the early 1990s by British Petroleum encouraged a spread so that by the late 1990s construction projects were already sharing in the benefits (Lahdenperä, 2012). The projects were more of rail, road and water infrastructure development and a uniquely demanding building (DTF, 2010). Project alliancing practice is thus suited for projects that are highly demanding and risky. The sources of such risks could be the deployment/creation of new technology and uncertainty in deep underground conditions.

4.4.4 Integrated project delivery (IPD)

The IPD approach is relatively more recent than project partnering and project alliancing (Matthews and Howell, 2005; Lahdenperä, 2012). The American Institute of Architects defined IPD as "a project delivery method that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction" (AIA, 2007, p.2).

In practice, five elements have been identified as a minimum to claim that a project is an IPD-project:

j. Continuous involvement of owner, key designers and builders from early design through project completion
k. Business interests aligned through shared risk/reward, including financial gain at risk that is dependent upon project outcomes
l. Joint project control by owner, key designers and builders
m. A multi-party agreement or equal interlocking agreements
n. Limited liability among owner, key designers and builders

The main difference between Integrated Project Delivery and other closely related project delivery schemes (Project Partnering and Project Alliances) is the focus on early planning supported by ICT with the objective of increasing the smoothness and productivity of the process, i.e. seamlessness of the information flow and information availability in general.

4.5 Emerging scenarios for frameworks, professions and systems

Like many other industries, AEC is dynamic and characterised by ongoing changes in the form of modifications and development of new frameworks, professions and systems (see Figure 10). Partnering, Alliancing and IPD are relatively recent industry responses to mitigating the inefficiencies allegedly associated with traditional contracting frameworks characterised by low levels of collaborative working practices. These contracting approaches are defined by the level of relational understanding obtainable among stakeholder parties which appear to be successively scaled up in the order of their invention. The latest, IPD, is additionally designed to accommodate contemporary developments in emerging IT systems and professional roles. BIM and related extension applications (Oti and Tizani, 2015; Oti et al., 2016) are at the centre of currently emerging IT systems directed at digitizing building and construction information in the industry. As illustrated in the BIM maturity diagram by Bew and Richards (BIM-IWG, 2011), the industry is working towards the full realisation of Level 2 maturity defined by the federation of inter-disciplinary models that are created in isolation. Looking forward from here is the projection of all professionals working on a single model, the integrated BIM or common model at Level 3 maturity.

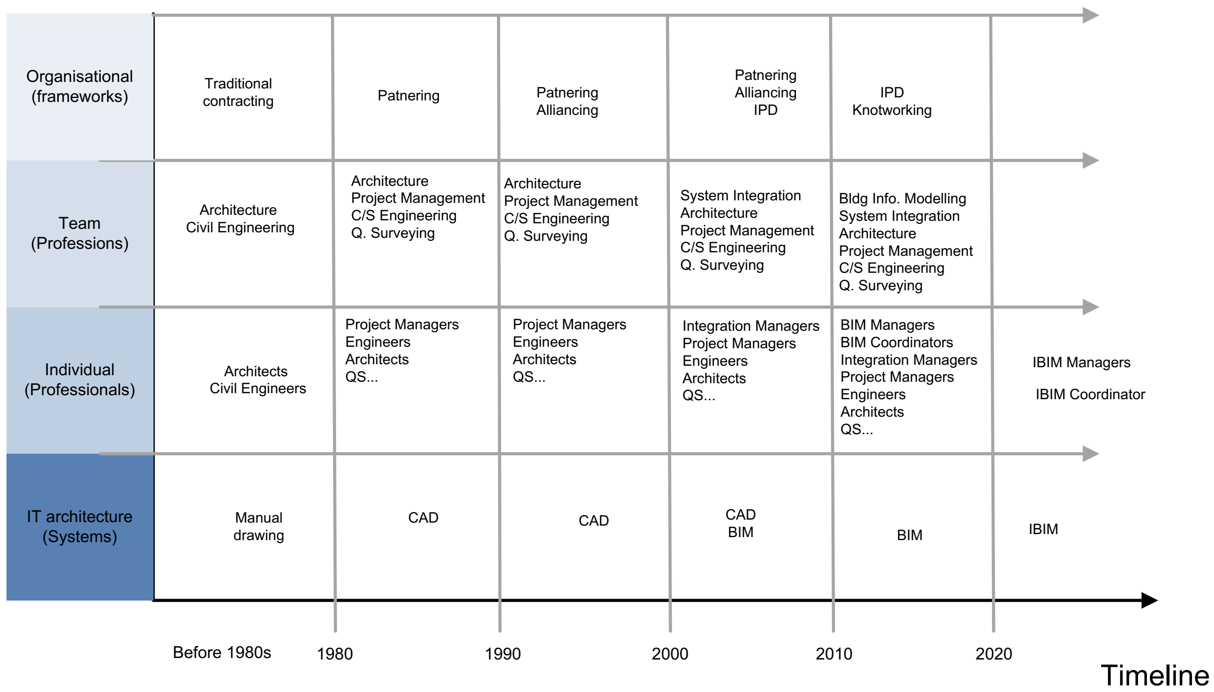


Figure 10: Current and emerging research levels (frameworks, professions and systems)

The advent of BIM does not only call for the amendment of contractual processes and contract documents, but has also generated new professional roles (Bosch-Sijtsema and Henriksson, 2014) such as BIM managers, BIM coordinators and integration managers. The duties of this set of emerging professionals are currently loosely defined and may vary from one organisational set-up to another. As the functions of these roles developed towards standardization, their importance in influencing the institutional change process towards increased digitization of information in the AEC has become more apparent (Bosch-Sijtsema and Gluch, 2016). In line with the suggestion by Jaradat et al. (2013) that new occupational groups involved in managing infrastructural lifecycle data exchange are being formed, the 'Knotworking' approach has been tried at in the Finnish Construction Industry. Knotworking is an emerging practice where co-located 'knots' are organised on a temporary basis to solve specific task/problem in a BIM-based building project (Kerosuo, 2015). While the immediate needs for emerging systems, professions and frameworks may vary, the overall object remains the need to mitigate the challenges fragmentation pose in the industry and to engender high level collaborative working practices for better integration. Thus, the ways in which an optimum level of integration can be achieved in the industry and the associated research activities that would enhance integration definitely extend into the future.

4.6 Demonstration projects

4.6.1 A BIM-enabled collaborative platform for low impact schools: a UK case study

This case study was part of a research project[3], which was championed by a strong multi-disciplinary team comprising of project partners Willmott Dixon (lead), Oxford Brookes University and Scape Group and contributions from the key consultants involved in Sunesis. Sunesis (see Figure 11), is the brand name of a series of pre-designed schools offered in the UK primary school market. It offers extra value added through engaging customers early in the procurement stage and through the use of innovative digital technologies such as Building Information Modelling (BIM). BIM served as a collaboration tool among supply chain members to continuously improve the Sunesis processes and products. This entailed finding innovative data integration solutions to close up the upstream knowledge-feedback-loop between construction and design stages.

[3] This project was partly funded by Innovate UK (formerly known as Technology Strategy Board) under their Rethinking the Build Process Call. It was undertake between April 2013 and March 2016. File no: 101343.Application no. 22136-158169.

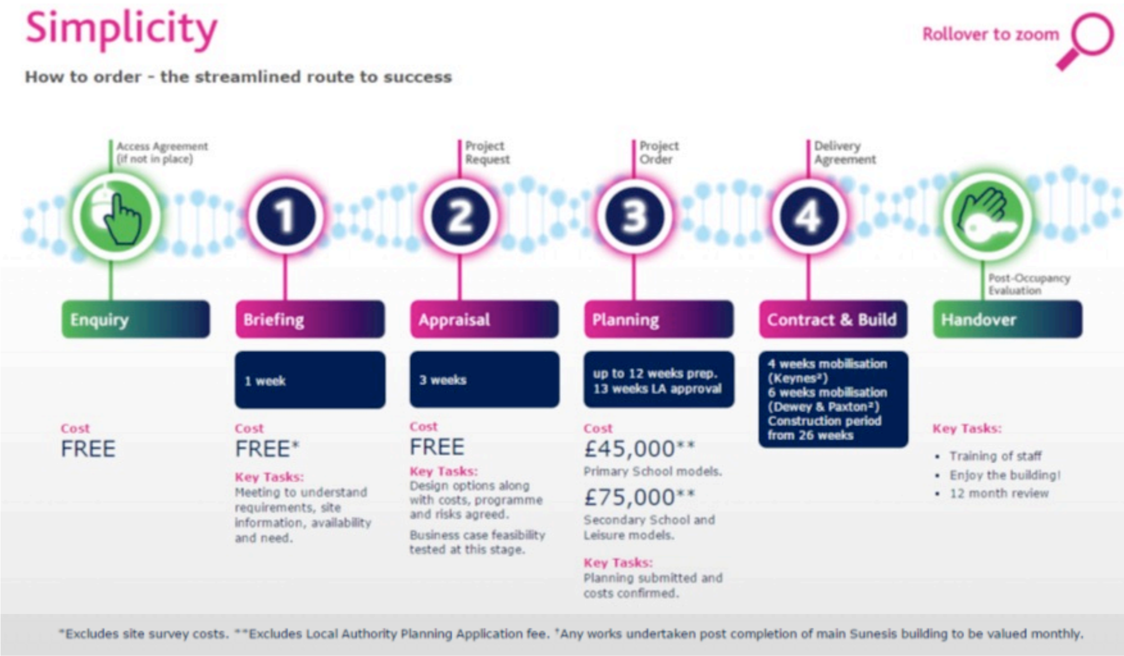


Figure 11: Streamlined process for Sunesis procurement (Willmott Dixon, 2016)

4.6.1.1 Data integration

Data integration was achieved on a number of levels, which are described below.

4.6.1.1.1 Data sharing and reuse

The Autodesk Buzzsaw platform was used to host the Common Data Environment (CDE) to share data and facilitated the collaborative production of the prototype design. This allowed members of the design team to issue models on a weekly basis to the CDE and download the other consultant's models to use as a reference in their own designs.

4.6.1.1.2 Design Review Meetings

BIM was used to aid collaborative design review meetings between project partners, including the contractor, their consultants and members of the supply chain. The aim of these meetings was to continuously improve the 'product'. The research team organised and observed a design review meeting in order to evaluate the use of BIM in this context and gather feedback on BIM-user experiences.

A time-lapse video, a federated BIM and 2D digital drawings were available to meeting attendees. Throughout the meeting, there was a preference towards using 2D information that had been drawn out of the 3D model. In one case, a 2D print out was quicker to make available than its digital version as a pdf file. The time-lapse video was preferred to the construction simulation when visualisation was required.

At the end of the meeting, the participants were invited to take part in an anonymous poll to provide feedback on their experience of the BIM-enabled Design Review Meeting. The results revealed a consensus that 3D visualisation made it easier for participants to share their ideas at the meeting and encouraged them to share these ideas with others. 3D visualisation is not considered to contribute to real-time coordination at the meeting nor to identify programme reduction opportunities or potential conflicts in the design solutions proposed. As such, 3D visualisation facilitated a more effective sharing of ideas but it has not helped with evaluating the implications of incorporating these ideas into the design.

4.6.1.1.3 Feedback from the Operations Phase: Energy performance

A BIM – Energy Consumption Viewer prototype interfacing with Revit was developed in order to display BMS (Building Management System) data in the BIM environment. It was demonstrated that energy performance data could be integrated in BIM to aid future design activities and visualise and evaluate energy performance during use (Figure 12). The latter functionality can be used by facility managers to learn from historic performance records contained in the model to manage future consumption.

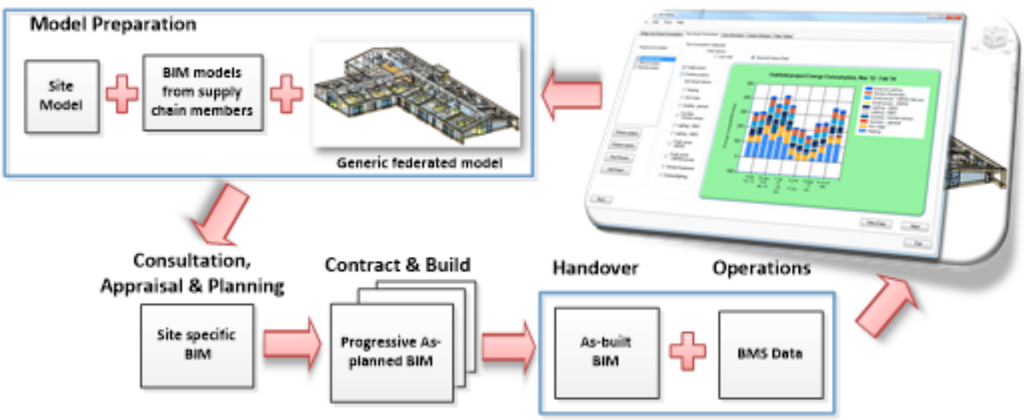


Figure 12: Improving pre-design model through BIM-based feedback of energy use

4.6.1.2 Drivers of integration

The driver for integration on the project is the need to engender continuous improvement of the Sunesis products. As such the Sunesis business model that immensely benefits from the sharing and the reuse of information and data, is the key driver integration. Achieving greater efficiencies in the delivery and operations of the pre-designed schools depends on integration and enables continuous product improvement.

4.6.1.3 Outcome and challenges

Outcomes of the data integration initiatives include:

o. Federating a BIM as part of the design process, and using it as a clash detection tool was beneficial in refining the Sunesis Designs. The challenge was the cost of customising the cloud-based BIM Coordination tools such that data from the construction phase could seamlessly be gathered while complying with the business's internal processes.

p. Issues around 'data life-cycle' have also become apparent during the research project. Data verification, capture and integration to the model at various stages of the project life-cycle remain problematic. For example, it was apparent that detailing the federated BIM beyond 1:50 and updating individual project models to reflect the customised aspects, was not cost-effective. Hence, the BIM was not updated during the construction phase.

q. Sub-contractors still find it difficult to absolutely trust specifications from project documents such as 2D drawings generated from BIM. Sub-contractors often find it more convenient to produce their own 2D drawings to avoid liability for production based on another party's drawings.

r. Changes to 3D model after the 2D drawings have been issued need to be to be handled more efficiently through automatically digitizing the changes rather than manually updating the 2D drawing. This may require the effort of a Document Controller, in the traditional sense.

4.6.1.4 Project Impact

The impact of the project is very significant. First, the knowledge gained and data created in developing a chosen BIM model for the project, either Keynes design model, has been used to develop other Sunesis design models such as Paxman and Dewey. It has significantly reduced the design cost for alternative models and market offering of Sunesis products as a result. Second, the novel processes have been applied for continuous model development. The original goal of the project was to develop Version 2 of Keynes within the project period. The development was completed prior to the scheduled period within the project. The completed Keynes version 2 model was used to develop a version 3 model that addresses the particular need of Education Funding Authority (England) framework. Third, the energy performance plug-in developed will enable the team to evaluate and identify areas for further improvement of the model. It is one area that the team continues to investigate. Finally, the use of the BIM-enabled platform contributed faster construction without any compromise in quality as evident in the projects for Plymouth City Council (e.g. Knowle Primary - Keynes² 2FEN – 30 weeks in lieu of 36 weeks).

4.6.1.5 Conclusion

Based on a commercially successful approach to procure and deliver schools, this project develops a new structure for information exchange on pre-designed school model development. This new structure is facilitated on a common data environment. The project attempted to close the knowledge gap through capturing the lessons-learnt from changes made during construction and developing new asset knowledge from operational data such as those for energy usage. The BIM platform was used in design review meetings to drive the development of collaborative innovative solutions. This benefit is amplified in the Sunesis procurement approach as suppliers are engaged in the continuous product development process. Interestingly, the BIM platform was found useful as a marketing tool. Its use as a learning platform to close the feedback loop between operations and design phase was tested by making BMS data available in the BIM environment but the scope of this initiative was relatively limited.

4.6.2 Information integration across the construction process – Canelas school, Portugal

The present case study[4] addresses to one of the construction projects promoted by the Portuguese government company, Parque Escolar (PE), created in 2007 to manage the secondary school facilities modernization program. This involved more than 300 facilities grouped in several investment stages. The Canelas school project is part of the third stage. This coincided in time with the publication of the new Portuguese Public Procurement Code, based on Directive 2008/18/EC. This legal framework placed a different philosophy for procurement and new requirements. In addition, the experience from previous projects was demanding actions to harmonize processes and project information layers. To support the accomplishment of these requirements Parque Escolar implemented ProNIC – Construction Information Standardization Protocol, which was developed by three institutions, Construction Institute – Porto University, INESC TEC and Civil Engineering National Laboratory as part of a Portuguese government sponsored project.

Canelas School is one of the largest facilities in this programme, with a total ground area of nearly 39 000 m^2 and total construction area of 12 000 m^2, before intervention. It is located near Porto, at Vila Nova de Gaia. The refurbishment project aimed to increase the capacity for 2 000

[4] This case study was provided by Pedro Mêda, Hipólito Sousa and Joaquim Moreira, Construction Institute/CONSTRUCT – GEQUALTEC, Porto University Faculty of Engineering .

students. It involved the renovation of nearly 6 000 m^2 and the construction of a new building with more than 15500 m^2, plus the renovation of all the exterior areas. The estimated construction budget was 20 000 000.00 euros. Construction Institute – Porto University, as part of ProNIC consortium gave support to Parque Escolar and to several agents, in particular the design team from this project.

4.6.2.1 Achieved integration, main reasons:

It should be noted that integration in this context was limited to project/programme level. Traditional design bid build procedures were followed. Specific clauses with regards to the use of ProNIC were included in the contract specifications for the design teams and contractors.

ProNIC was used to minimize "data leakage" between the different stages of project delivery. Construction Institute – Porto University was contracted by PE to support the consultants and contractors to use ProNIC. Some of these consultants and contractors worked on up to three projects which were part of this programme.

One essential aspect is that the implementation of ProNIC was assumed by the PE administration and with the following objectives (framed on the document topics):

s. From the Strategic/Organizational point of view, it was important to ensure a complete project organization, following a common framework set for all the program, ensure the complete fulfillment of the legal requirements, setup links with e-procurement platforms and introduce a new paradigm on information management in order to have cost indicators and tracking;
t. From a Tactical/Operational perspective, and facing the new requirements in terms of design organization (derived from the legal framework), the objectives were placed on ensuring the correct organization of design documents, improve design team coordination and accountability;
u. From the Technical perspective the objective was to define a group of applications for process development, identify where the several tasks would be performed and define integration protocols for multi-application processes;

A common framework for project development from the Design stage until the end of the Construction stage was set in order to deliver these requirements. The development of guidelines for the design disciplines, a database of standard construction works for the definition of bill of quantities, a collaborative and functional environment for the project development and a single information repository constitute the key elements for the achieved information integration.

4.6.2.2 *Achieved integration, main drivers:*

As mentioned, the main driver to achieve high levels of integration is the commitment and vision of the Client. The main objective was to know, at each moment and for all project tasks, the variations and accrual in terms of costs and quantities, and to compare them to estimates presented during procurement. For this, it was essential to have a common platform with functionalities to manage and support all the tasks and associated information. From an operational point of view, it was essential that a training programme was developed. Training supported the different design disciplines during the design stage. Intuitive processes and the intensive training programme to overcome difficulties and deal with resistance to change are the key aspects of delivering integration.

4.6.2.3 *Integration outcomes/benefits/challenges:*

From a Strategic/Organizational point of view it was possible to streamline processes, set a common framework for all the projects so that they could be compared and set a single place where all the information is stored and managed across the construction process. In terms of cost indicators, it was possible to collect data to serve multiple purposes (Figure 13).

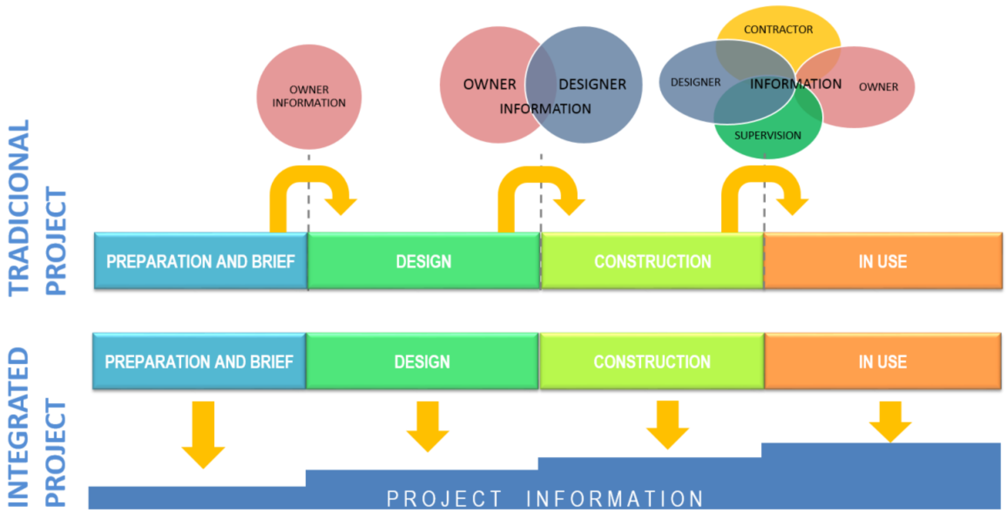


Figure 13: Integration framework for data collection

From a Tactical perspective, both Owner and Design teams benefited from the collaborative environment. It was interesting to observe the evolution in terms of design coordination. Responsibility was also far more "visible", as all designers placed digital signature on their documents. From an Operational/Individual perspective, the experience led to training actions and knowledge acquisition that was unprecedented. This experience was shared by all actors from designers to supervisors. From the Technical perspective, several applications were enabled to work in tandem. They could be utilised to exchange information for the development

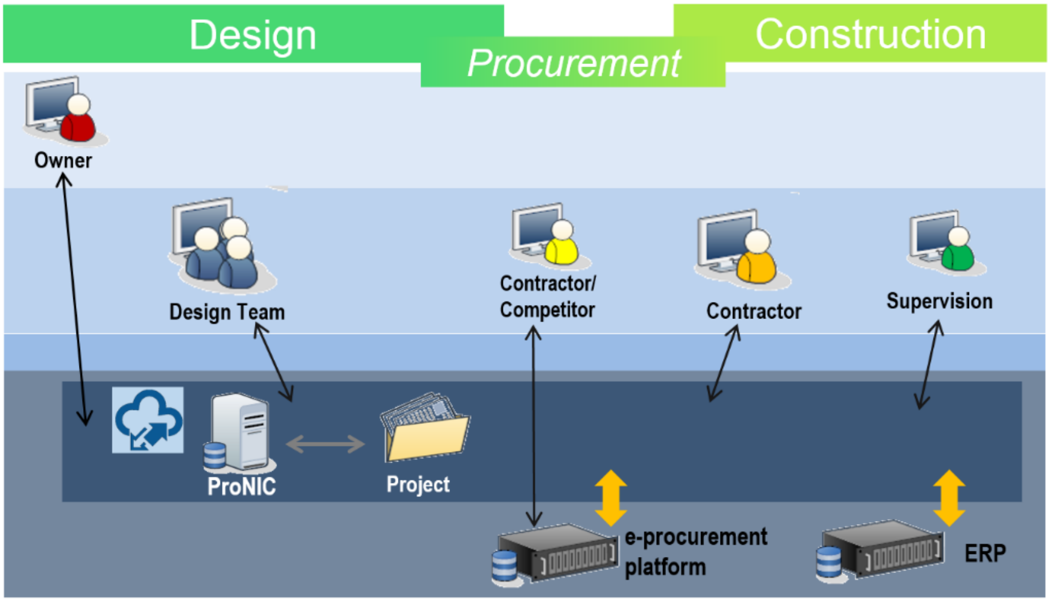


Figure 14: The ProNIC e-procurement platform

of different processes. For examples, the detailed design was sent out for tendering and bids were received on the ProNIC – e-procurement platform (Figure 14). In another case, invoices during the construction phase were processed after considering the monthly measurement reports (ProNIC – ERP – ProNIC).

4.6.2.4 Integration sequels:

ProNIC was implemented in nearly 70 projects as part of this programme of works. Presently, it is being further developed in order to extend the offer to other Public Clients. As part of this development work, new developments to extend to other stages of the process beyond design and construction are undertaken. New functionalities are defined. The ultimate aim is to develop integration protocols with other tools and to enhance the interoperability of the framework.

4.6.2.5 Reflections

The experience from this process provides very interesting inputs to the subject of integration. As mentioned previously, the commitment of the Client to the process is essential to define the ambitions and targets in terms of information integration. The Client body should also share its main concerns in terms of information integration. A training and support program should be an integral part of this initiative to provide the help all actors will require. Some unexpected factors such as the low levels of experience in Public Procurement Code requirements constrained the delivery of this initiative but they might not surface in the future. From the practical experience, there were very positive aspects and some negative. Further integration can be achieved by placing more stringent requirements on all actors and by building on this experience.

4.6.3 Key Case Study Findings

UK case study is an example where integration enabled a main contractor to deliver projects using a different business model. It should however be highlighted that integration still relied on common forms of contract where the Contractor acted as the Client and employed design consultants, i.e. architectural, structural and M&E. The need and desire to continuously improve the design to provide a better 'product' drove the integration initiatives, which focussed on reducing cost and shortening project programme in the first instance.

Integration in the Portuguese case study is limited to the delivery of a programme of projects. It focussed on access to information held on a common platform and its retrieval by relevant parties. The focus of this integration was the delivery phase, and integration to enhance design solutions was seemingly out of its scope.

The following key findings apply to both case studies:

v. Solutions to integration are mainly technology driven;
w. The focus is on the design or delivery phases;
x. Collaboration & integration during design stage seemingly confined to clash detection;
y. The cases follow the usual multi-disciplinary approach rather than push for an inter-disciplinary approach to facilitate higher level integration; and
z. Integration solutions are mostly about systems and processes, relational aspects of integration are largely overseen.

5 Future scenario

In this chapter, the future of information integration is explored in order to meet the global challenges that were identified earlier (Section 1) in this Roadmap. This exploration is based on the results of the survey that was distributed among TG90 members.

There is no doubt that the construction industry will continue to be driven by information and knowledge. We will see a need for transforming not only our businesses, but also companies´ human capital by adopting skills from adjacent professions, such as data science, social science and computer science. Collaboration across these disciplinary boundaries will be instrumental in creating new knowledge by making sense of existing data and information, thus developing new practices.

5.1 Can future information integration meet global challenges?

One objective of this roadmap is to illustrate the significance of data, information & knowledge integration for the global construction sector. In line with exploring this significance, the roadmap deems it necessary to examine the extent to which future information integration processes/innovations may contribute to overcoming technology-related global challenges. Perceptions of the effects of these challenges and the approaches by which they can be overcome may vary from one organisation or nation to another. This is evident in TG90 – the cross-national CIB Task Group on Information Integration in Construction – responses illustrated in Figure 15. All the individual weights and combined weight of responses for the eleven factors captured indicate a tilt towards the opinion that technology is essential to overcome future global integration challenges. It is noteworthy that tackling the "lack of technical data management ability" is unanimously perceived to be essential in this process. The authors support this view and suggest that technical data management has a significant and positive impact on all other factors. For example, no matter how complex an integration process and procedure can be, the right personal competence in the right environment can provide adequate workable solutions to the problem. This line of reasoning points to the implications of skill shortages, a challenge that transcends generations, and sectoraial and national boundaries that could result in low product quality, a failure to meet deadlines and can impact on company credibility (TEPC, 2011).

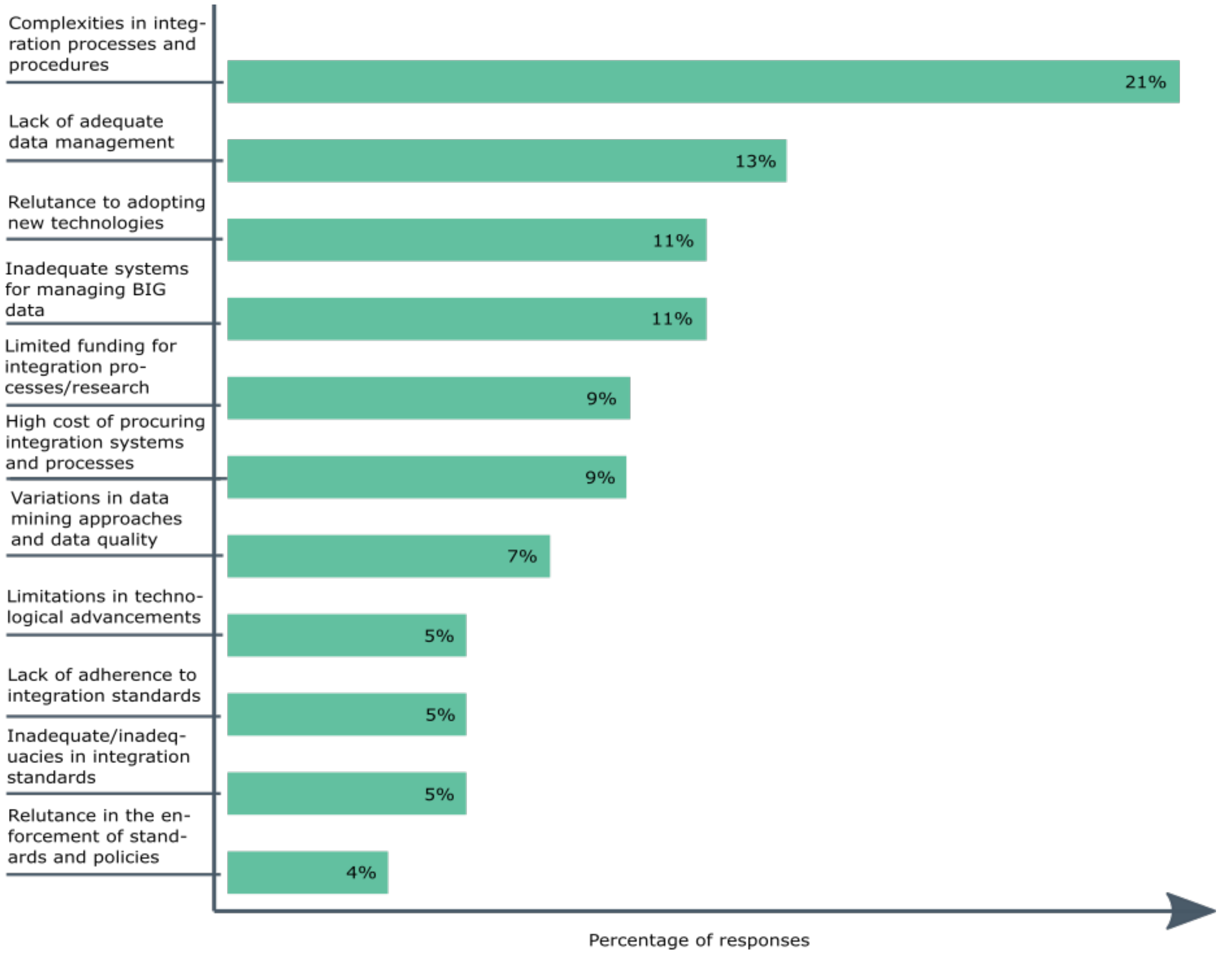


Figure 15: Responses to the question "How well the following - technology-related - global challenges can be addressed by future information integration processes? Responses suggest that information integration will play an important role in meeting this type of challenges.

5.2 Can information integration help overcome cross-sectorial challenges?

On probing down to individual lines of work (Figure 16), responses indicate a general tilt in the spectrum of factors being essential towards overcoming cross-sectorial global challenges. Respondents were either neutral or believe that "adopting technological solutions to information integration" is essential for curbing cross-sectorial integration challenges, such as "fragmented industries working in professional silos".

However, adoption depends on a number of issues. The first is whether the required technologies that can make the desired change already exist in the market or if such technologies need to be developed. Either option depends on the availability of skills and interdisciplinary capabilities of specialists to enable vendors/developers to develop the system. However, there is a second issue about skills. The question in this respect is whether the available levels of skills to operate and manage technological innovations that foster interdisciplinary integration in the construction sector will be adequate and sustainable. The third issue is the financial capability/capacity to manage the process (cost of system procurement, operation, maintenance, training of personnel, etc.) of adopting the requisite technological solutions for information integration. Interestingly, "skill shortages/consequences", is one of the suggested spectra of factors that have not been weighted to a similar level of importance as technology adoption. Perhaps what is needed is a "shared understanding" of the requisite skills and competences (DECC, 2013) needed for the adoption of new technologies and indeed, achieving better interdisciplinary integration of construction information and knowledge. This premise and authors' perception of the implications of skills shortages for integration, is further discussed in the next section.

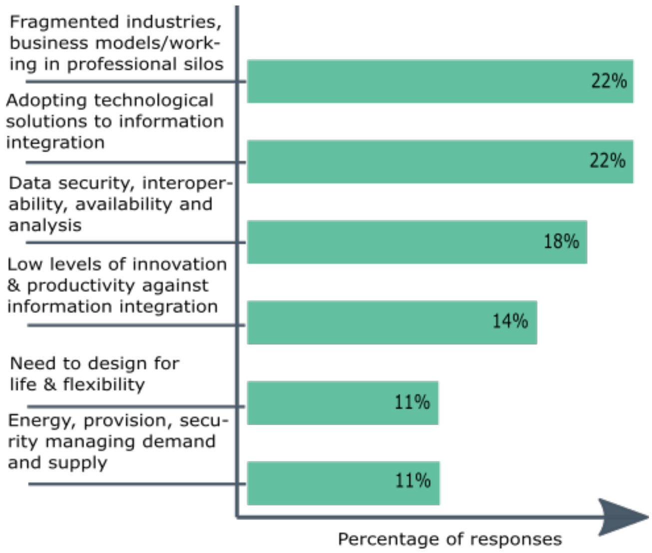


Figure 16: Responses to the question "To what extent would information integration in your line of work help overcome these cross-sectoral global challenges?

5.3 What challenges are there to information integration?

There is consensus in the construction literature that skills are an essential factor influencing productivity and performance (USNREC, 2000; DECC, 2013; BSI, 2019). Rempling et al. (2010) take this argument further by suggesting that interdisciplinary capabilities of specialists also play a significant role. Despite such awareness, the outcry for the need to reduce skill shortages and lack of interdisciplinary capabilities of the work force has gone unabated as the industry, and indeed world economy, is still searching for quick solutions. It is more of a "problem to live-with" as it depends on a number of dynamics, including relatively controllable issues such as the level of education and training to less controllable phenomena such as the rate of procreation – baby boom (BEIS, 2018) and the effects of natural disasters (NPfE, 2019) on population. For the factors considered in the survey conducted for this roadmap, "deep specialisation in professional silos" and "reluctance to work across disciplinary boundaries" are considered to be major challenges to information integration. Opinions appear balanced about the influence of "companies competing for talent & the aging workforce" compared with the impact of "skill mobility" on information and knowledge integration in construction (Figure 17). Nonetheless, the impact of these factors on skill shortages, which is part of a complex process influenced by the external product/service market, organisational policies and regulations designed to react to demand and supply dynamics in labour markets, are interwoven. Green and Owen (2003) suggest that skill shortages could be "new" if warranted by changes in product markets and services or "recurring" in terms absence of personnel to take up sectorial conventional job routines such as in construction trade. In any case, the effect of skill shortages is likely to negatively impinge on economic performance (DECC, 2013).

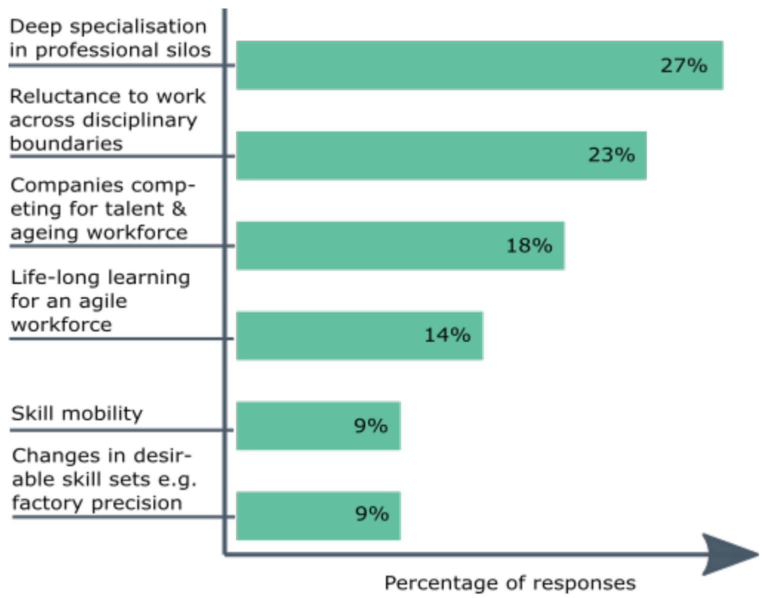


Figure 17: Responses to the question "Which of the following factors are a challenge to information integration?" Responses correspond that the aspects are essential challenges.

5.4 Future trends

In addition, among the spectrum of technologies and methods featured in the survey, respondents seem to have a relatively balanced perception on whether "multi-disciplinary team work" is being phased out or not. This is understandably so, as opinions might be divided between considering a multi-disciplinary team as a physically co-located team or a virtual collaboration using contemporary IT tools as applicable to innovations applied to "Big Room" (Dave et al., 2015). Interestingly, none of the technology or methods is perceived to be completely phased-out. Many technology applications, processes and methods appear to metamorphose into new dimensions on par with innovations and advancements in the industry. This can be attributed to the rigour and high level of R&D characterising the construction industry to keep pace with economic advancements and to maintain its relevance in the global scenery. For such a pace to be maintained, applications of emerging Building Information Modelling do stand out. As evident from Figure 18, "BIM incorporated in facility management" is agreeably an innovation that will most likely drive the future. This expands to encompass aspects of Open and Linked data applications and services, Big Data Analytics of energy consumption and infrastructure systems to smart and future city applications (Bos et al., 2018; Schwerhoff and Sy, 2019).

It is easy for the sector to trust that innovative technologies can solve future challenges. However, the respondents to our survey assess "Deep specialisation in professional silos" to be the major challenge for information integration. This assessment raises the question of whether and how deeply specialised innovative technologies can be integrated for a seamless process. It could be argued that the specialisation era that has been ongoing for a while (the sector is booming with PhDs) has created more professionals digging deeply into their silos without expanding their general skills and developing interactive capabilities to collaborate with other professionals. The sector must not place its trust in technology advancements without paying due attention to the reluctance to work together. As pointed out in the beginning of this roadmap, technology is merely a means or facilitator of the process and the interacting, intervening work is at the core of the building process. Research is needed in both areas:

- research that is interdisciplinary and cross-sectorial; and
- research that develops knowledge and generic skills without losing deep specialisation.

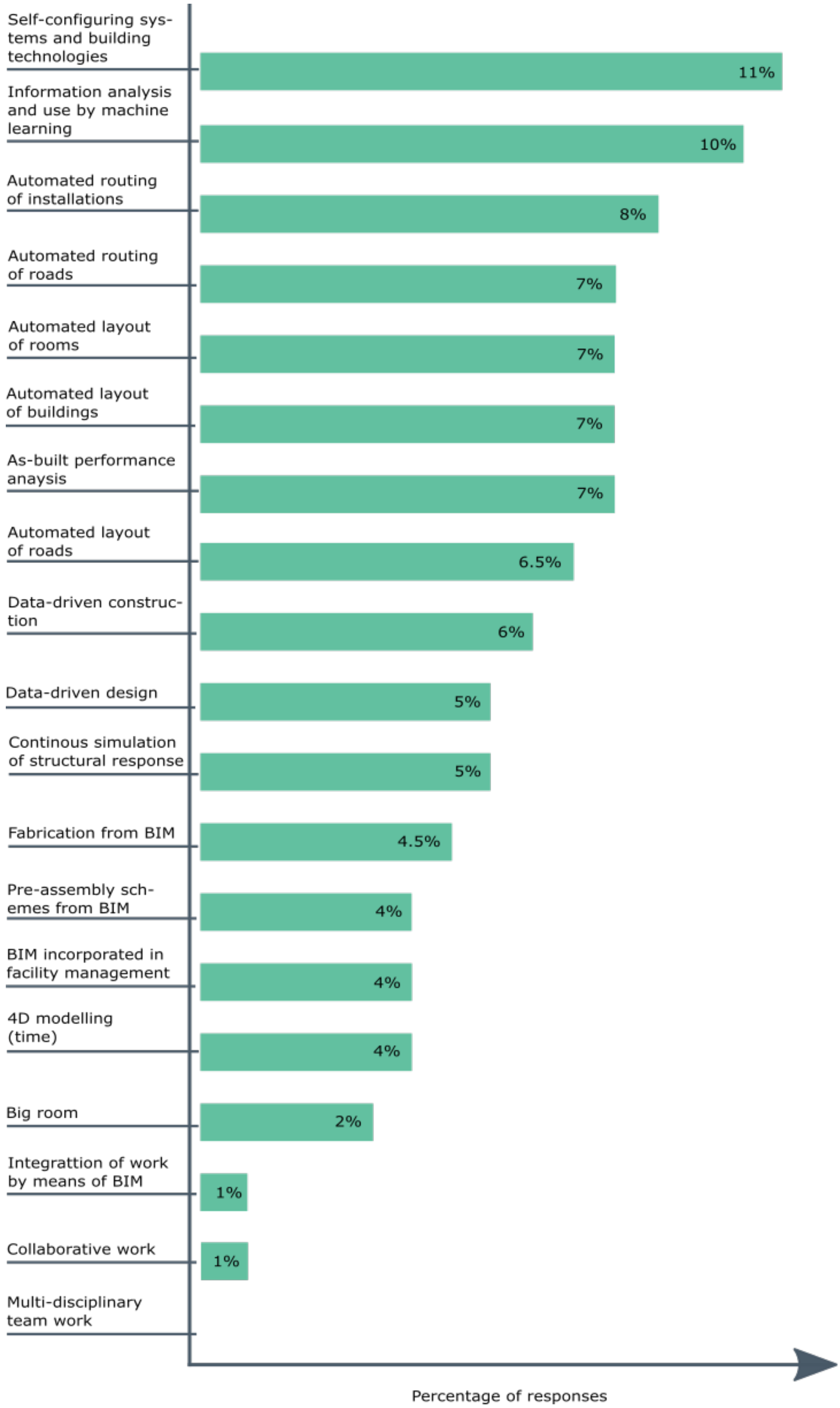


Figure 18: Responses to the question "Indicate which of the following processes, technologies and methods are considered to be future research areas".

5.5 Development strategy

5.5.1 A construction industry driven by information and knowledge

Construction industries will continue to drive global growth. Increasing urbanisation and the need for long-term investment in infrastructure will continue to drive the need for research within the built environment. The growth focussed economies will inevitably result in increases in man-made wealth, and thus the need for further exploitation of the natural environment. There is a definite need to develop sustainable materials and construction methods that minimise the impact of construction on the natural environment. Understanding the performance of these materials and methods during the operating phase of a building's life cycle and their actual impact on the natural environment requires an integrated approach to methods, such as life-cycle analysis. Feedback loops between the different levels and stages of our Research Framework (see Figure 5) need to be established and sustained to use such analyses as an opportunity for continuous improvement and learning from experience.

Financial resources for the development of the built environment will probably increase as costs for sustaining and enhancing the well-being of an ageing population and for dealing with the environmental challenges increase. Researchers are already required to find solutions to reconcile the rising costs with limited resources by coming up with low cost alternatives to current practices. The construction industries globally exhibit low levels of productivity. Hence, research efforts already focus on increasing productivity through innovation.

Effective utilisation and management of data and information throughout the building process has become an important area of research. It is highly likely that research funding and therefore effort will focus on this area. Research on continuous monitoring of building assets and infrastructures, assessing their structural and building performance, will increase and new innovations in technology will make it possible to profit from, use and manage larger volumes of information in the building process. Effective utilisation of data and information across organisational and project boundaries could become the impetus for better integrated businesses. This is a significant research opportunity that has to be exploited.

Today, a lot of digital technologies are available and more are under development. With a systematic approach to digitization, based on its four technology areas (automation, digital interfaces, connectivity and data), there is great potential for streamlining value chains in the construction industry. Sensor networks and embedded systems could be used to register the status of production activities and track movements and positions of personnel, machinery, materials and components on construction sites. Applications can, for example, register strength and moisture content in cast concrete structures monitor work environments. The tracking of RFID tagged components in warehouses or buildings has long been possible. The collected data also forms the basis for (BIG) data analyses with artificial intelligence (AI) methods for adaptive production management to experience rehabilitation of completed construction projects. These and many other technologies will enable a technical revolution in many fields and their development is steady.

5.5.2 Integration of disciplinary knowledge

Johansson (2012) investigated the factors that facilitate and hinder the sharing of knowledge across professional boundaries in the construction field. She pointed out that diverse knowledge and poor information-sharing practices were major hurdles. The former was mainly attributed to diverging perspectives and strategic goals, whereas traditional communication vehicles, such as project meetings and the sharing of documents and drawings, resulted in poor communication practices. The differing perspectives and diverging strategic goals were mainly attributable to organisational tradition and professional orientation. If practitioners were liberated from their organisations and professional mind- sets of "how things should be done", the focus on and willingness to negotiate a solution to common problems would most likely immensely increase.

Ways in which the barriers that Johansson (2012) identified can be overcome need to be explored. Only then can the potential inherent in project teams serving as melting pots for multi-disciplinary knowledge, thus unlocking learning cultures, be exploited (Sense, 2009; Sense, 2011). Team members should be equipped with the skills that enable them to deal with the following dynamics of collaboration:

- diversity of individuals is more important than their ability,
- The optimal collaboration may not feel harmonious, and
- Weak ties and resulting poor networking skills are counter productive to bridging the discrete islands of knowledge and expertise (Harford, 2017).

Moreover, knowledge creation within a project team should link disciplinary knowledge and become an organised project teams. Linked knowledge implies that information and understanding of one's own discipline need to be communicated to other disciplines across the disciplinary boundaries depicted by Moum (2006) (Figure 19). It is co-created by the sender and the recipient. Members of the team need to understand not only the strategic goals and perspectives (personal and organisational), but also identify information that can or cannot be codified or digitised (e.g. reinforcement amount and type versus policy documents). Acknowledging the fact that not all knowledge or information can be codified poses interesting research questions during an era when digitisation and (big) data are considered to be a panacea to the industry's endemic problems.

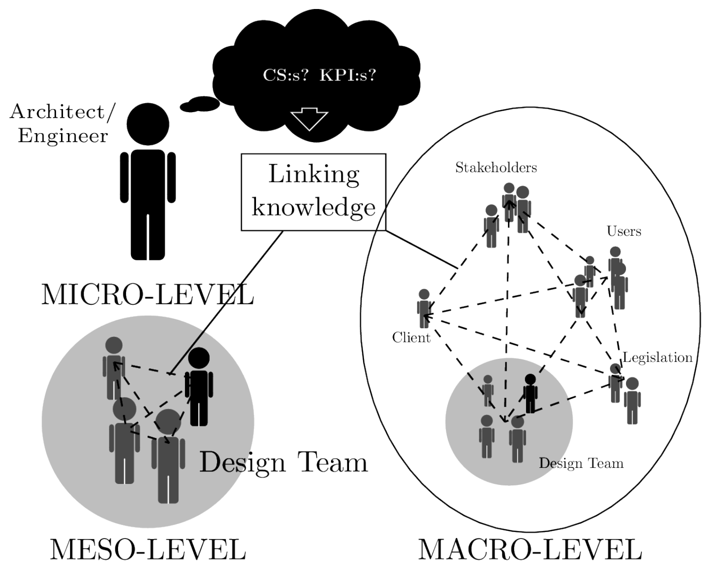


Figure 19: The interdisciplinary professionals, such as the architect and structural engineer need to identify the project specific criteria that form the linking knowledge at meso- and macro-levels. The figure is reproduced from the framework of communication developed by Moun (2006).

5.5.3 Transformation of construction industry business (product and services based on integration of information)

The need for adopting skills from adjacent industries, such as data and social science, goes hand in hand with developing innovative businesses that are based on the integration of information. Traditionally, the construction industry has been poor in developing human capital through investments in education, training and well-being. Technological transformation of the businesses in the construction industry will require extensive training and research programmes to evaluate the benefits of information integration and develop ways in which such integration can be achieved across organisational boundaries.

Foreign companies operating in new market regions need to integrate with local, small-to-mid-size companies by starting partnerships and by promoting new technologies via start-ups and strategic buy-ups. Large share of small companies will, however, remain and with digitalisation, the number may even increase. The major companies will continue to deliver the bulk of the output through forthcoming large infrastructure projects.

The transformation of the natural environment into built assets is the main implication of the

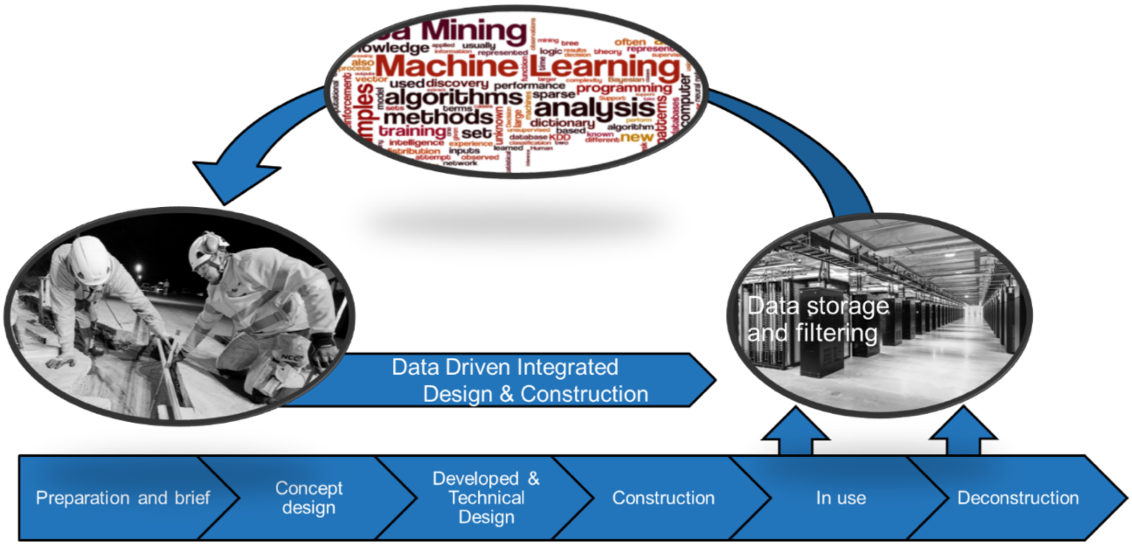


Figure 20: One of the main growing research topics will be data-driven services based on artificial intelligence.

activity in construction industries. To build more, we still need to extract more from natural reserves. The construction industry can play an important role in balancing the various components of the environmental, economic and social systems inherent in the world by investing in research on progressive policies and procurement models, in addition to financing and risk assessment methodologies. Here, key data-driven services (Figure 20) based on artificial intelligence will be one of the main growing research topics.

5.5.4 Integration of adjacent transdisciplinary professions

The transformation of the construction industry into a data-driven business requires the integration of adjacent transdisciplinary professions, such as social and data science. The integration of information and the skill to work in teams will need to be better understood by companies in order to evaluate and re-evaluate their stock of skills. Seamless information flow between professions and stages of the building process is imperative for an integrated, trans-disciplinary workforce. Research to help the development of effective IT-systems can facilitate collaboration of high priority.

The knowledge that an integrated trans-disciplinary workforce possesses is instrumental in making sense of data and information. It is important that data, information and knowledge integration should be considered part of the same spectrum at the organisational, team, operating and technical levels across key project phases. Such a scientific approach will enable us to shift the focus from integration at the technical level to integration at the tactical and strategic levels.

The continuous development of IDDS and BIM will still be needed but based on the proposed framework, research on knowledge integration, data storage and management, as well as data-driven services, becomes fundamental in order to meet future challenges.

Digitalization, especially regarding the construction site, will change the image of an industry that is lagging behind, thereby increasing the attractiveness of the construction sector for younger generations. Fortunately, an understanding of the potential for digitization in the construction industry, as well as particular examples showing how digitization might be implemented, can be realized in practice.

Today, great many digital technologies are available, and more are under development. With a systematic approach to digitization based on its four technology areas (automation, digital interfaces, connectivity and data), there is great potential for streamlining value chains in the construction community.

Sensor networks and embedded systems could be used to register the status of production activities and track movements and positions of personnel, machinery, materials and components on construction sites. Applications can touch, for example, the strength and moisture content in cast concrete structures, monitor the work environment or track RFID tagged components in warehouses or buildings. The collected data also forms the basis for (BIG) data analyses with artificial intelligence (AI) methods for adaptive production management and the rehabilitation of completed construction projects. These and many other technologies will advance a technical revolution in many fields and their development is steady.

As observed, technologies like sensor networks and cloud computing, which were considered to be emerging technologies in 2012, are today a reality, at least in several fields. Other technologies, such as the IoT and augmented reality, have been evolving and are today closer to reach a plateau of productivity. Finally, new emerging technologies such as the concept of a Digital Twin, have been introduced more recently and are still in the early stages of development.

6 Research contribution and agenda

'Research', as used in academic circles, is synonymous with 'research and development (R&D)' in official statistical manuals (Roll-Hansen, 2009). The Frascati Manual describes R&D as comprising three forms of research: basic (theoretical), applied (practical) and experimental development (OECD, 2007). Basic research is fundamental and aims at improving scientific theories for better understanding and the prediction of natural or other phenomena; applied research takes this further by developing techniques to intervene and alter natural or other phenomena. Experimental development is hinged on basic and applied research and entails systematic work directed at producing new materials, products, devices or installing new processes, systems and services, by substantially improving those already produced or installed. The early stages of experimental development can comprise the proof of a concept where applied research advances to validating the analytical feasibility of the various system components in easily manageable small stages/processes. Prototypes have proven useful in engineering and technology fields to convey ideas as proofs of concepts by various institutions.

6.1 Global research investment

Reports on R&D indicate that an increasing number of countries are committing substantial sums to science and engineering research and education (Suresh, 2012; IRI, 2016) to spur stronger economic growth. The collective global research and development expenditure has therefore continued to increase. Global R&D expenditures peaked at 2.082% of GDP in 2001, dropped to 1.956% in 2007 and has been increasing since then to 2.230% in 2015 (World Bank, 2018). The global increase is reported to have slowed in 2017, although not for 12 out of 116 countries that account for 80% of the global R&D spent considered (IRI, 2017). The 12 countries include: USA, China, Japan, Germany, South Korea, India, France, Russia, UK, Brazil, Australia and Canada. Although the USA records the currently highest expenditure on R&D, forecasts indicate a steep increase in R&D funding from China (IRI, 2017). IRI (2017) predicts that China's current rate of growth in R&D expenditure, if consistent, could surpass that of the USA by 2026. The Chienese Government contributes most of the share of China's R&D investment. Obviously, the government is one of a nation's strongest institutions that can drive investments in R&D and while also harnessing the returns from such investments. R&D investment is directly linked to advances in technology and contributes to enhancing the competitive advantage of a firm or nation. Consequently, structures and frameworks for research sponsorships are important for progress, nationally and globally.

While many countries have established national structures that support their various research interests, international alliances have also sprung up to explore common grounds, engender knowledge exchange and utilize requisite areas of expertise. Contemporary global research organisations and networks include European Commission Research (ECR), the European Industrial Research Management Association (EIRMA), European Union Community R&D Information Service (CORDIS), Industrial Research Institute (IRI), Organization for Economic, Cooperation & Development (OECD) and the Global Research Council (GRC). The GRC, for example, is a virtual organisation made up of the heads of science and engineering funding agencies from around the world. GRC is dedicated to promoting the sharing of data and best practices for high-quality collaboration among funding agencies worldwide. The GRC and other organisations alike do not only contribute to driving research progress but are also poised to identify global research needs and defining focus areas that will cascade to regions and nations across the globe. The efforts of organisations such as the CIB are also of paramount importance in defining research themes/ priority areas and developing research roadmaps (Goulding and Arif, 2013; Owen et al., 2013; Bosher et al., 2016; Haugbølle and Boyd, 2016) that will define the future of the construction domain.

6.2 The role of knowledge in the integration of research levels

Three (Organisational (Strategic), Team (Tactical) and Individual (Operation)) of the four research levels of integration identified in this roadmap are people-focused. The remaining (Technical) is IT or system-focused. Knowledge remains central to the integration of these four research levels. Thus, information integration in the construction industry should largely be about the degree to which knowledge is shared, transferred or diffused across these research levels.

Knowledge can be regarded as information with some form of human meaning attached (Bhatt, 2001) or verified through tests of proof (Lee and Bai, 2003). It is possible for knowledge to exist at the individual level or team/organisational level. The knowledge typically embodied in individuals is largely tacit and difficult to codify or articulate, whereas organisational knowledge becomes explicit mainly through documentation and transfer (Venkitachalam and Busch, 2012). Tacit knowledge is viewed as procedural which will usually be required to process by individuals wading through daily tasks and routines in an organisation or construction site (Colonia-Willner, 2004). Such knowledge can become the practical intelligence of an organisation (Sternberg et al., 1995) thus becomes an asset difficult to dispense with.

Managing organisational knowledge entails the management of knowledge about the activities (staff, operations, competitors, customers and suppliers) of a company (Siemieniuch and Sinclair, 2004). The contribution of staff makes up a major part of organisational knowledge cascading up to teams or the entire organisation. Congruent with this, Johnson (2007) argues that tacit knowledge serves as a means to creating and sharing know-how that generates organisational knowledge. The crux of the matter therefore becomes how to balance the development or deployment of an individual and that of the team to which they belongas well as the firm in which they are employed. While transferring best practices inter-firm may be important to a firm's learning and competitive advantage (Szulanski, 1996), it may become a disadvantage to another firm depending on the means of achievement. For example, the employment of a migrating individual with 'practical intelligence', as Sternberg et al. (1995) put it, implies that another firm may be losing out on the services of the individual especially if the skills have not been sufficiently transferred to other staff in the original firm. Such an awkward and sometimes unhealthy competition may be mitigated through organisational integration.

Even concerning integration at all the four research levels, the management of tacit knowledge is important. In readiness preparation for such integration, the challenge is establishing how tacit know-how can be transferred and used, collectively and collaboratively, in organisations and communities of practice (Venkitachalam and Busch, 2012). It is therefore important to identify focal areas in terms of desired research development in science and technology, strategize on the sequences of time lines and examine developing networks/collaborations and alliances between domains/sectors within/across nations geared towards effective globalisation in the industry.

6.3 Developing research areas

The above discussion on the research levels should be considered against the background that collaborative work and multi-disciplinary team work are at the bottom of the list of future trends for research (Figure 18). Our survey respondents think that the technology tools and methods will continue to lead the way into seamless integration. An exception is the Big Room, which may be in the process of being phased out. Admittedly, the concept of Big Room is not new in the construction industry but has tendencies to transform with and through time. Essentially a large facility supporting the co-location of an entire project team, the tools and facilities used to enhance the functions of a Big Room can always be upgraded to keep up with advances in technology. The proposal of a Virtual Big Room by Dave et al (2015) is an example of such deployment of contemporary digital technologies. It is such application of digital technologies with which to integrate construction processes that the emerging building information modelling (BIM) is hinged on. With the industry striving to push the operation at Level 2 BIM maturity to the maximum, documents such as the PAS 1192 series are intended to provide technical guidance and consistent methodology for the definition, creation, management and sharing of product information throughout the life cycle of an asset. Recent studies propose the inclusion of social dimensions in BIM maturity levels, having captured aspects of data security (BSI, 2015) and health & safety (BSI, 2018). The recent output of the transition process from the PAS 1192 family series of documents to BS EN ISO (BS EN ISO 19650-1 and BS EN ISO 19650-2) is an indication that the industry is already thinking of formalising the standardisation of information management requirements for BIM-based processes on projects at the international level (BSI, 2019). Further, the industry is looking towards BIM Level 3 as the future in managing assets, project data, seamless information exchange and collaboration of professional platforms in a more integrative dimension. Characterised by integrated modelling of information across professional platforms, BIM Level 3 is expected to be synchronised with other digital advances, including building management systems, Big Data Analytics, Open and linked data, smart city applications and the Internet of Things (IoT).

The interest in blockchains has recently been gaining ground in IoT applications to support data security. Blockchains supports distributed peer-to-peer networks which allow non-trusting members to interact with each other without the need for the intervention of any trusted intermediary. It is capable of facilitating the sharing of services and resources leading to the creation of a digital marketplace and automatic cryptographic verification tasks. Christidis and Devetsikiotis, (2016) argue that the blockchain-IoT combination will be a powerful tool with which to enhance significant transformations across several industries attracting the evolution of new business models and distributed applications. Construction is suggested as one such sector to benefit from blockchains in providing trustworthy infrastructure (Turk and Klinc, 2017), especially with the emergence of the digital transformation of projects as advocated in BIM methodology. Thus, a robust synchronisation of BIM methodology with IoT holds a promising future for the construction Industry. In the Manufacturing domain, the introduction of IoT applications has instigated visions of businesses becoming global networks incorporated with machinery, warehousing systems and production facilities as Cyber-Physical Systems (CPS) (Lee, 2008; Peniak and Franekova, 2015). Known as Industry4, a combination of IoT and advances in IT applications, is envisaged as the fourth (in addition to: steam, electricity and automation) major disruptive change in the history of industrial revolutions (Kumar and Kumar, 2013). The usage of smart materials, smart communication protocols and the ability to embed intelligence in information all contribute to making the transformation change. The future is therefore set to give birth to research and innovations on advances in IT applications, such as IoT, smart systems, and Open and Linked Data.

It is imperative that the research community do not become too focussed on technology-inspired research. Research funding already focusses on this sphere. Although people and processes are regarded to be integral aspects of technological transformation, there is little cutting-edge research in these areas. Some signposts for this kind of research to develop are provided in the next section.

7 Final remarks and conclusion

This Roadmap has demonstrated that integration at organisational/strategic level has already been considered in terms of utilising solutions such as Project Partnering, Project Alliancing and IPD. It has also been argued that integration at this level through strategic mechanisms does not automatically translate into integration amongst the project teams at the technical and tactical levels. There is a lack of research on integration at this level even when projects are procured using IPD, alliancing, etc. This research gap becomes significant when the findings of our survey, where deep specialisation in professional silos and a reluctance to work across professional boundaries emerged as the top barriers to integration, are considered. Hence, it is obvious that finding innovative solutions to overcoming these barriers should become an integral part of future research. Another important omission at this level of integration is the integration of SMEs and how innovative approaches from a procurement perspective, e.g. Partnering, impacts on the capability of SMEs' to secure work unless they happen to be part of these frameworks.

There is limited research on understanding the real dynamics of integration at the team level. Studies on integrative project delivery, including partnering and alliancing, tend to focus on the strategic and organisational aspects of these arrangements. It is implied that integration at the team level will come about as a result of these arrangements. Whether and how the relational patterns between parties are (re)shaped as a result of these arrangements are largely overlooked. The drivers and enabling mechanisms for collaboration at the individual and team levels, and how they can be fostered in different project contexts, should be identified. An important aspect of this research is to establish how the benefits of approaches such as IPD, e.g. risk sharing, can be translated into benefits at the individual and team levels so that individuals are motivated to collaborate. In other words, is there a gap between the individuals' and teams' motivations for collaboration and the motivation of an organisation to collaborate? Perhaps there is less need for this research an SMEs because the benefits of collaboration at the project level are more likely to trickle down to the individual, thanks to the flatness of the organisational structure. Motivations of individuals and teams may be more aligned in SMEs because they can build trust and shared risk. Shared gain scenarios driven by procurement can be accrued by the individual more readily in SMEs than it can in larger organisations.

Against this background, we propose the following research questions that are relevant to information integration in construction. It should be noted that eliminating the reluctance to work across boundaries underlines the questions proposed below:

- What are the business models that would facilitate integration in projects of different scale, e.g. from the mega-project to the small-project?
- To what extent does integration at the strategic/organisational level fostered by approaches such as IPD translate into integration amongst the project team at the technical and tactical levels? Do the advantages these approaches offer, e.g. risk sharing at the organisational level translate into advantages at the individual level? What are the real dynamics of integration at the team level?
- What are the features of collaboration that foster open, timely and reliable information sharing and integration at individual and team levels?
- How will the technology level assist SMEs to integrate in the future? Or will technology become a barrier to integration unless it can be demonstrated that integration would increase the productivity of these companies?
- How does the local context differ from the global in terms of information integration and the demands for such information integration?
- What lessons can be learnt from large companies/organisations, which make up a relatively small proportion of the companies by size of employment but deliver a high proportion of the output? What role does integration play in delivering such high levels of output?

Ultimately from this road map, we resolve that the individual's willingness to collaborate is critical to high levels of integration. Our survey did identify "Reluctance to work across professional boundaries" as a major barrier to integration. Hence, we conclude that research on integration should pay due attention to the individual.

References

Aapaoja, A., Herrala, M., Pekuri, A. and Haapasalo, H. (2013). "The characteristics of and cornerstones for creating integrated teams." *International Journal of Managing Projects in Business* **6**(4): 695-713.

Abbott, C., Barrett, P., Ruddock, L. and Sexton, M. (2007). Hidden innovation in the construction and property sectors. *RICS Research paper series*. London, RICS

AIA (2007). "Integrated Project Delivery: A Guide. ." Retrieved 04 November 2016, from http://www.aia.org/groups/aia/documents/pdf/aiab083423.pdf.

Anumba, C. J., Baugh, C. and Khalfan, M. M. (2002). "Organisational structures to support concurrent engineering in construction." *Industrial management & data systems* **102**(5): 260-270.

ARCADIS (2016). "Global Built Asset Performance Index 2016 - Doing more with less: Buildings and infrastructure as drivers of economic performance." Retrieved December, 2017, from https://www.arcadis.com/media/7/A/F/%7B7AFA3768-5208-4320-A4E5-9FAAF82AD588%7DAG1029_GBAPI%202016_GLOBAL_FINAL%2022_11%20.pdf.

Atkin, B., Leiringer, R. and Wing, R. (2006). "RFID applications in construction and facilities management."

Austin, S. A., Baldwin, A. N. and Steele, J. L. (2002). "Improving building design through integrated planning and control." *Engineering Construction and Architectural Management* **9**(3): 249-258.

Bahar, Y. N., Pere, C., Landrieu, J. and Nicolle, C. (2013). "A thermal simulation tool for building and its interoperability through the Building Information Modeling (BIM) platform." *Buildings* **3**(2): 380-398.

Baiden, B. K. (2006). Framework for the integration of the project delivery team, Loughborough University, Ph.D. Thesis, © Bernard Kofi Baiden.

Baiden, B. K. and Price, A. D. (2011). "The effect of integration on project delivery team effectiveness." *International Journal of Project Management* **29**(2): 129-136.

Baiden, B. K., Price, A. D. and Dainty, A. R. (2003). "Looking beyond process: human factors in team integration."

Baiden, B. K., Price, A. D. F. and Dainty, A. R. J. (2006). "The extent of team integration within construction projects." *International Journal of Project Management* **24**(1): 13-23.

Barbosa, F., Mischke, J. and Parsons, M. (2017). "Improving construction productivity." Retrieved November, 2017, from https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/improving-construction-productivity.

Beach, R., Webster, M. and Campbell, K. M. (2005). "An evaluation of partnership development in the construction industry." *International Journal of Project Management* **23**(8): 611-621.

Beach, T. H., Rana, O. F., Rezgui, Y. and Parashar, M. (2013). "Cloud computing for the architecture, engineering & construction sector: requirements, prototype & experience." *Journal of Cloud Computing: Advances, Systems and Applications* **2**(1): 1.

BEIS (2018). Industrial Strategy: Nuclear Sector Deal. Business Energy and Industrial Strategy. London, HM Government.

Bennett, J. and Jayes, S. (1995). *Trusting the team: the best practice guide to partnering in construction*, Thomas Telford.

Bermell-Garcia, P., Verhagen, W. J., Astwood, S., Krishnamurthy, K., Johnson, J. L., Ruiz, D., Scott, G. and Curran, R. (2012). "A framework for management of Knowledge-Based Engineering applications as software services: Enabling personalization and codification." *Advanced Engineering Informatics* **26**(2): 219-230.

Beth Stanek, M. (2004). "Measuring alliance value and risk: a model approach to prioritizing alliance projects." *Management decision* **42**(2): 182-204.

Bilek, J. and Hartmann, D. (2006). *Agent-based collaborative work environment for concurrent structural design processes*. Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Citeseer.

BIM-IWG (2011). BIM Management for value, cost and carbon improvement. *A report for the Government Construction Client Group, BIM Working Party Strategy Paper*, BIM Industry Working Group (BIM-IWG).

BIM Forum (2015). Level of Development Specification, BIMForum.

Bishr, Y. (1998). "Overcoming the semantic and other barriers to GIS interoperability." *International journal of geographical information science* **12**(4): 299-314.

Björk, B.-C. and Laakso, M. (2010). "CAD standardisation in the construction industry—A process view." *Automation in Construction* **19**(4): 398-406.

Bloor, M. S. and Owen, J. (1991). "CAD/CAM product-data exchange: the next step." *Computer-Aided Design* **23**(4): 237-243.

Boisot, M. H. (1998). *Knowledge assets: Securing competitive advantage in the information economy*, OUP Oxford.

Bos, K., Chaplin, D. and Mamun, A. (2018). "Benefits and challenges of expanding grid electricity in Africa: A review of rigorous evidence on household impacts in developing countries." *Energy for sustainable development* **44**: 64-77.

Bosch-Sijtsema, P. M. and Gluch, P. (2016). *Interrelation of emerging professionals and institutional processes in project based environments: An institutional work perspective*. EGOS 2016 conference, Naples, 5-7 July 2016.

Bosch-Sijtsema, P. M. and Henriksson, L.-H. (2014). "Managing projects with distributed and embedded knowledge through interactions." *International Journal of Project Management* **32**(8): 1432-1444.

Bosher, L. S., Von Meding, J., Johnson, C., Farnaz Arefian, F., Chmutina, K. and Chang-Richards, Y. A. (2016). "Disasters and the built environment. Research roadmap."

Bresnen, M., Edelman, L., Newell, S., Scarbrough, H. and Swan, J. (2003). "Social practices and the management of knowledge in project environments." *International Journal of Project Management* **21**(3): 157-166.

Bresnen, M. and Marshall, N. (2000). "Partnering in construction: a critical review of issues, problems and dilemmas." *Construction Management & Economics* **18**(2): 229-237.

Bresnen, M. and Marshall, N. (2002). "The engineering or evolution of co-operation? A tale of two partnering projects." *International Journal of Project Management* **20**(7): 497-505.

Brown, J. S. and Duguid, P. (2017). *The Social Life of Information: Updated, with a New Preface*, Harvard Business Review Press.

Brown, R. and Brown, I. (2005). "The application of quality of life." *Journal of Intellectual Disability Research* **49**(10): 718-727.

BSI (2013). PAS 1192-2:2013 - Specification for information management for the capita/delivery phase of construction projects using building information modelling, British Standards Institute. **PAS 1192-2:2013**.

BSI (2015). PAS 1192-5:2015 - Specification for security-minded building information modelling, digital built environments and smart asset management British Standards Institute. **PAS 1192-5:2015**.

BSI (2018). PAS 1192-6:2018 - Specification for collaborative sharing and use of structured Health and Safety information using BIM, British Standards Institute. **PAS 1192-6:2018**.

BSI (2019). Transition guidance to BS EN ISO 19650 British Standards Institute. PD 19650-0:2019, British Standards Institution 2019, British Standards Institute. **BS EN ISO 19650**.

buildingSMART (2016). "Home/Future." Retrieved 28 March, 2016, from http://www.buildingsmart-tech.org/future.

Carbinet Office (2011). Government Construction Strategy, Carbinet Office.

Charalabidis, Y., Panetto, H., Loukis, E. and Mertins, K. (2008). "Interoperability approaches for enterprises and administrations worldwide." *The electronic journal for e-commerce tools and applications (eJeta)* **2**(3): 1-10.

Charalabidis, Y., Pantelopoulos, S. and Koussos, Y. (2004). *Enabling interoperability of transactional enterprise applications*. Workshop on Interoperability of Enterprise Systems, 18th European Conference on Object-Oriented Programming (ECOOP), Oslo.

Christidis, K. and Devetsikiotis, M. (2016). "Blockchains and smart contracts for the internet of things." *IEEE Access* **4**: 2292-2303.

Cicmil, S. and Marshall, D. (2005). "Insights into collaboration at the project level: complexity, social interaction and procurement mechanisms." *Building Research & Information* **33**(6): 523-535.

CII (1991). In Search of Partnering Excellence, Special Publi- cation 17–1, Construction Industry Institute, Austin, TX.

Crowley, A. (1998). "Construction as a manufacturing process: Lessons from the automotive industry." *Computers & Structures* **67**(5): 389-400.

Curran, R., Verhagen, W. J., Van Tooren, M. J. and van der Laan, T. H. (2010). "A multidisciplinary implementation methodology for knowledge based engineering: KNOMAD." *Expert Systems with Applications* **37**(11): 7336-7350.

Dainty, A. R., Millett, S. J. and Briscoe, G. H. (2001). "New perspectives on construction supply chain integration." *Supply Chain Management: An International Journal* **6**(4): 163-173.

Dave, B., Pikas, E., Kerosuo, H. and Mäki, T. (2015). "ViBR–conceptualising a virtual big room through the framework of people, processes and technology." *Procedia Economics and Finance* **21**: 586-593.

Davis, P. and Walker, D. (2009). "Building capability in construction projects: a relationship-based approach." *Engineering, Construction and Architectural Management* **16**(5): 475-489.

De Clercq, D. and Dakhli, M. (2003). *Human capital, social capital, and innovation: a multi-country study*, Vlerick Leuven Gent Management School.

DECC (2013). The United Kingdom's Sixth National Report on Compliance with the Convention on Nuclear Safety Obligations. Department of Energy and Climate Change, Crown

Deci, E. L., Koestner, R. and Ryan, R. M. (1999). "A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation." *Psychological bulletin* **125**(6): 627.

Designing Buildings Ltd (2018). "Built environment." Retrieved October, 2017, from https://www.designingbuildings.co.uk/wiki/Built_environment.

Dewulf, G. and Kadefors, A. (2012). "Collaboration in public construction—contractual incentives, partnering schemes and trust." *Engineering project organization journal* **2**(4): 240-250.

Diebolt, C. and Haupert, M. (2016). *Handbook of cliometrics*, Springer.

DTF (2010). The Practitioner's Guide to Alliance Contracting. Melbourne, Department of Treasury and Finance, Victoria.

Egan, S., J. (1998). Rethinking Construction. *Construction Task Force Scope for Improving the Quality and Efficiency of the Construction Industry*, Department of Environment, Transport and the Regions (DETR), London, UK.

Euromonitor International (2018). "Passport database." Retrieved March, 2018, from http://go.euromonitor.com/passport.html.

Evbuomwan, N. and Anumba, C. (1998). "An integrated framework for concurrent life-cycle design and construction." *Advances in engineering software* **29**(7): 587-597.

Faraj, I. and Alshawi, M. (1999). "A modularised integrated computer environment for the construction industry: SPACE." *Electronic Journal of Information Technology in Construction* **4**: p37-52.

Forbes, L. H. and Ahmed, S. M. (2010). *Modern construction: lean project delivery and integrated practices*, CRC press.

Forgues, D. and Koskela, L. (2008). "Can procurement affect design performance?" *Journal of Construction Procurement* **14**(2): 130-141.

Frey, B. S. and Jegen, R. (2001). "Motivation crowding theory." *Journal of economic surveys* **15**(5): 589-611.

GCP and OE (2015). "Global construction 2030: a global forecast for the construction industry to 2030." *Global Construction Perspectives (GCP) and Oxford Economics (OE), London, UK*.

Goulding, J. and Arif, M. (2013). "Offsite production and manufacturing–research roadmap report." *International Council for Research and Innovation in Building and Construction (CIB)*.

Grant, R. M. (1996). "Toward a knowledge-based theory of the firm." *Strategic management journal* **17**(S2): 109-122.

Hall, D., Lehtinen, T., Levitt, R., Li, C. and Padachuri, P. (2014). The Role of Integrated Project Delivery Elements in Adoption of Integral Innovations. *EPOC 2014*. P. Chan and R. Leicht. Winter Park, Colorado, USA

Harford, T. (2017). *Messy: The power of disorder to transform our lives*, Penguin.

Harris, F. and McCaffer, R. (2013). *Modern construction management*, John Wiley & Sons.

Hauck, A. J., Walker, D. H., Hampson, K. D. and Peters, R. J. (2004). "Project alliancing at National Museum of Australia-collaborative process." *Journal of Construction Engineering and Management* **130**(1): 143-152.

Haugbølle, K. and Boyd, D. (2016). "Clients and Users in Construction: Research Roadmap Summary."

Hedlund, G. (1994). "A model of knowledge management and the N-form corporation." *Strategic management journal* **15**(S2): 73-90.

Himes, P. E. (1995). "Partnering in the construction process: the method for the 1990s and beyond." *Facilities* **13**(6): 13-15.

Howell, I. (1996). "The need for interoperability in the construction industry." *INCIT 96 Proceedings: Bridging the Gap*: 43.

Ingram, K. (2017). "The Digital Evolution of the Construction Industry, a Keynote Speech to the COMIT 2017 Conference: Mobilising Digital Assets.". Retrieved 2 May, 2018, from http://www.comit.org.uk/copy-of-comit2017-day1.

ISO 10303 (1994). Standard for the Exchange of Product Model Data **International Standardization Organization, ISO 10303 -1:1994.**

Izam Ibrahim, K., Costello, S. B. and Wilkinson, S. (2013). "Key practice indicators of team integration in construction projects: a review." *Team Performance Management: An International Journal* **19**(3/4): 132-152.

Jaafari, A. and Manivong, K. (1999). "The need for life-cycle integration of project processes." *Engineering Construction and Architectural Management* **6**(3): 235-255.

Jaradat, S., Whyte, J. and Luck, R. (2013). "Professionalism in digitally mediated project work." *Building Research & Information* **41**(1): 51-59.

Jeong, B. (2002). "Measurement of human capital input across countries: a method based on the laborer's income." *Journal of Development Economics* **67**(2): 333-349.

Johansson, K. (2012). "Knowledge Sharing Across Professional Boundaries in Construction: Facilitators and Hindrances."

Josephson, P.-E. and Björkman, L. (2010). *31 recommendations for increased profit-reducing waste*, Chalmers University of Technology.

Kadefors, A. (2002). *Förtroende och samverkan i byggprocessen: förutsättningar och erfarenheter*, Chalmers tekniska högsk.

Kadefors, A. (2004). "Trust in project relationships—inside the black box." *International Journal of Project Management* **22**(3): 175-182.

Kadefors, A. and Bröchner, J. (2004). "Building users, owners and service providers: new relations and their effects." *Facilities* **22**(11/12): 278-283.

Kerosuo, H. (2015). "BIM-based Collaboration Across Organizational and Disciplinary Boundaries Through Knotworking." *Procedia Economics and Finance* **21**: 201-208.

Kumar, B., Cheng, J. C. and McGibbney, L. (2010). *Cloud computing and its implications for construction IT*. Computing in Civil and Building Engineering, Proceedings of the International Conference.

Kumar, N. and Kumar, J. (2013). "A Framework for Human Efficiency Measurement in Advanced Manufacturing: HCI in INDUSTRY4. 0." *Guwahati, India*.

Kumaraswamy, M. M., Ling, F. Y., Rahman, M. M. and Phng, S. T. (2005). "Constructing relationally integrated teams." *Journal of Construction Engineering and Management* **131**(10): 1076-1086.

Laan, A., Noorderhaven, N., Voordijk, H. and Dewulf, G. (2011). "Building trust in construction partnering projects: An exploratory case-study." *Journal of Purchasing and Supply Management* **17**(2): 98-108.

Laan, A., Voordijk, H., Noorderhaven, N. and Dewulf, G. (2011). "Levels of interorganizational trust in construction projects: Empirical evidence." *Journal of Construction Engineering and Management* **138**(7): 821-831.

Lahdenperä, P. (2012). "Making sense of the multi-party contractual arrangements of project partnering, project alliancing and integrated project delivery." *Construction Management and Economics* **30**(1): 57-79.

Larsson, J., Eriksson, P. E., Olofsson, T. and Simonsson, P. (2014). "Industrialized construction in the Swedish infrastructure sector: core elements and barriers." *Construction Management and Economics* **32**(1-2): 83-96.

Latham, S. M. (1994). *Constructing the team*, HM Stationery Office.

Lee, E. A. (2008). *Cyber physical systems: Design challenges*. Object oriented real-time distributed computing (isorc), 2008 11th ieee international symposium on, IEEE.

Lorch, R. (2003). A research strategy for the built environment? Paper to nCRISP Workshop on What Kind of Research and Innovation Strategy does the UK Construction Industry Need, London: nCRISP.

Love, P., Gunasekaran, A. and Li, H. (1998). "Concurrent engineering: a strategy for procuring construction projects." *International Journal of Project Management* **16**(6): 375-383.

Matthews, O. and Howell, G. A. (2005). "Integrated project delivery an example of relational contracting." *Lean Construction Journal* **2**(1): 46-61.

MGI (2017). Reinventing construction: a route to higher productivity Mckinsey Global Institute (MGI), Research Insight Impact.

Mitropoulos, P. and Tatum, C. (1999). "Technology adoption decisions in construction organizations." *Journal of Construction Engineering and Management* **125**(5): 330-338.

Mitropoulos, P. and Tatum, C. B. (2000). "Forces driving adoption of new information technologies." *Journal of Construction Engineering and Management* **126**(5): 340-348.

Moffatt, S. and Kohler, N. (2008). "Conceptualizing the built environment as a social–ecological system." *Building Research & Information* **36**(3): 248-268.

Mohit, M. A. (2013). "Quality of life in natural and built environment–an introductory analysis." *Procedia-Social and Behavioral Sciences* **101**: 33-43.

Mollaoglu-Korkmaz, S., Swarup, L. and Riley, D. (2011). "Delivering sustainable, high-performance buildings: Influence of project delivery methods on integration and project outcomes." *Journal of Management in Engineering* **29**(1): 71-78.

Moore, D. R. and Dainty, A. R. (1999). "Integrated project teams' performance in managing unexpected change events." *Team Performance Management: An International Journal* **5**(7): 212-222.

Mora, R., Rivard, H. and Bédard, C. (2006). "Computer representation to support conceptual structural design within a building architectural context." *Journal of Computing in Civil Engineering* **20**(2): 76-87.

Mosey, D. (2009). *Early contractor involvement in building procurement: contracts, partnering and project management*, John Wiley & Sons.

Moum, A. (2006). "A framework for exploring the ICT impact on the architectural design process." *Journal of Information Technology in Construction (ITcon)* **11**(30): 409-425.

Moum, A. (2010). "Design team stories: Exploring interdisciplinary use of 3D object models in practice." *Automation in Construction* **19**(5): 554-569.

NEDO (1991). Partnering: contracting without conflict. London, National Economic Development Office, HMSO.

Nonaka, I. and Nishiguchi, T. (2001). *Knowledge emergence: Social, technical, and evolutionary dimensions of knowledge creation*, Oxford University Press.

Northridge, M. E., Sclar, E. D. and Biswas, P. (2003). "Sorting out the connections between the built environment and health: a conceptual framework for navigating pathways and planning healthy cities." *Journal of Urban Health* **80**(4): 556-568.

NPfE (2019). "Nuclear Power Plant, Nuclear Power for Everybody (NPfE) ". Retrieved January, 2019, from https://www.nuclear-power.net/nuclear-power-plant/.

Nyström, J. (2005). "The definition of partnering as a Wittgenstein family-resemblance concept." *Construction Management and Economics* **23**(5): 473-481.

Oakland, J. S. and Marosszeky, M. (2006). *Total quality in the construction supply chain*, Routledge.

OECD (2015). *Material Resources, Productivity and the Environment*, OECD Publishing, Paris.

Office of Rail and Road (2018). "Periodic review 2013: consultants and reporters' studies." Retrieved January, 2018, from http://orr.gov.uk/rail/economic-regulation/regulation-of-network-rail/price-controls/periodic-review-2013/pr13-publications/pr13-consultants-reports.

Oti, A. H. and Tizani, W. (2015). "BIM extension for the sustainability appraisal of conceptual steel design." *Advanced Engineering Informatics* **29**(1): 28-46.

Oti, A. H., Tizani, W., Abanda, F., Jaly-Zada, A. and Tah, J. (2016). "Structural sustainability appraisal in BIM." *Automation in Construction* **69**: 44-58.

Owen, J. and Bloor, M. S. (1987). "Neutral formats for product data exchange: the current situation." *Computer-Aided Design* **19**(8): 436-443.

Owen, R. L., Amor, R., Dickinson, J., Prins, M. and Kiviniemi, A. (2013). "Research roadmap report: Integrated Design and Delivery Solutions (IDDS)."

PCW (2017). "Engineering & construction." Retrieved August, 2017, from https://www.pwc.com/gx/en/industries/engineering-construction.html.

Peniak, P. and Franekova, M. (2015). *Open communication protocols for integration of embedded systems within Industry 4*. Applied Electronics (AE), 2015 International Conference on, IEEE.

Rahman, M. M. and Kumaraswamy, M. M. (2004a). "Contracting relationship trends and transitions." *Journal of Management in Engineering* **20**(4): 147-161.

Rahman, M. M. and Kumaraswamy, M. M. (2004b). "Potential for implementing relational contracting and joint risk management." *Journal of Management in Engineering* **20**(4): 178-189.

Rezaei, R., Chiew, T. K., Lee, S. P. and Aliee, Z. S. (2014a). "A semantic interoperability framework for software as a service systems in cloud computing environments." *Expert Systems with Applications* **41**(13): 5751-5770.

Rezaei, R., Chiew, T. K., Lee, S. P. and Aliee, Z. S. (2014b). "Interoperability evaluation models: A systematic review." *Computers in industry* **65**(1): 1-23.

Rivard, H., Froese, T., Waugh, L. M., El-Diraby, T., Mora, R., Torres, H., Gill, S. M. and Reilly, T. O. (2004). "Case studies on the use of information technology in the Canadian construction industry." *Journal of Information Technology in Construction (ITcon)* **9**(2): 19-34.

Sanchez, A. X., Hampson, K. and London, G. (2017). *Integrating Information in Built Environments*, Routledge.

Sassi, P. (2006). *Strategies for sustainable architecture*, Taylor & Francis.

Sassi, P. (2016). Built Environment Sustainability and Quality of Life (BESQoL) Assessment Methodology. *Engaging stakeholders in education for sustainable development at university level*, Springer**:** 21-32.

Schwerhoff, G. and Sy, M. (2019). "Developing Africa's energy mix." *Climate policy* **19**(1): 108-124.

Sense, A. J. (2009). *Knowledge creation spaces: The power of project teams*. International Conference on Knowledge Science, Engineering and Management, Springer.

Sense, A. J. (2011). "The project workplace for organizational learning development." *International Journal of Project Management* **29**(8): 986-993.

Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., Thomas, R., Pardasani, A. and Xue, H. (2010). "Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review." *Advanced Engineering Informatics* **24**(2): 196-207.

Simmonds, P. and Clark, J. (1999). "UK Construction 2010-Future Trends and Issues: Briefing paper." *CIRIA Funders Report CP/65). London: CIRIA*.

Sumner, T., Domingue, J., Zdrahal, Z., Millican, A. and Murray, J. (1999). *Moving from on-the-job training towards organisational learning*. Proceedings of the 12th Banff Knowledge Acquisition Workshop, Banff, Alberta.

Tatum, C. (2005). "Building better: technical support for construction." *Journal of Construction Engineering and Management* **131**(1): 23-32.

TEPC (2011). Fukushima Nuclear Accident Investigation Report (Interim Report – Supplementary Volume), The Tokyo Electric Power Company (TEPC), Inc.

The Economist (2017). "The construction industry's productivity problem." Retrieved November, 2017, from https://www.economist.com/news/leaders/21726693-and-how-governments-can-catalyse-change-construction-industrys-productivity-problem.

Turk, Ž. and Klinc, R. (2017). "Potentials of Blockchain Technology for Construction Management." *Procedia Engineering* **196**: 638-645.

Twill, J., Batker, D., Cowan, S. and Wright Chappell, T. (2011). "The Economics of Change: Catalyzing the Investment Shift Toward a Restorative Built Environment." *Earth Economics, Tacoma WA.*

United Nations (2008). International Standards on Industrial Classification of All Economic Activities. New York, Department of Economic and Social Affairs Statistics Division, United Nations.

USNREC (2000). Decommissioning of nuclear power reactors, Regulatory Guide 1.184. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission (USNREC),.

van der Veer, H. and Wiles, A. (2008). "Achieving technical interoperability." *European Telecommunications Standards Institute*.

Van Kamp, I., Leidelmeijer, K., Marsman, G. and De Hollander, A. (2003). "Urban environmental quality and human well-being: towards a conceptual framework and demarcation of concepts; a literature study." *Landscape and urban planning* **65**(1): 5-18.

Verhagen, W. J., Bermell-Garcia, P., van Dijk, R. E. and Curran, R. (2012). "A critical review of Knowledge-Based Engineering: An identification of research challenges." *Advanced Engineering Informatics* **26**(1): 5-15.

Visser, U., Stuckenschmidt, H., Schuster, G. and Vögele, T. (2002b). "Ontologies for geographic information processing." *Computers & Geosciences* **28**(1): 103-117.

W3C (2015). "Semantic Web." Retrieved March, 2016, from https://www.w3.org/standards/semanticweb/.

Walker, D. H., Hampson, K. and Peters, R. (2002). "Project alliancing vs project partnering: a case study of the Australian National Museum Project." *Supply Chain Management: An International Journal* **7**(2): 83-91.

Willmott Dixon (2016). "Sunesis." Retrieved January, 2016, from https://www.sunesisbuild.co.uk.

World Economic Forum (2018). "8 ways the construction industry can rebuild itself for the 21st century." Retrieved March, 2018, from https://www.weforum.org/agenda/2017/05/construction-industry-recruit-talent/.

Zhai, D., Goodrum, P. M., Haas, C. T. and Caldas, C. H. (2009). "Relationship between automation and integration of construction information systems and labor productivity." *Journal of Construction Engineering and Management* **135**(8): 746-753.

CIB General Secretariat
Van der Burgh weg 1
2628 CD Delft
The Netherlands
E-mail: secretariat@cibworld.nl
www.cibworld.nl

CIB Publication 417 / ISBN 978-90-6363-09-66