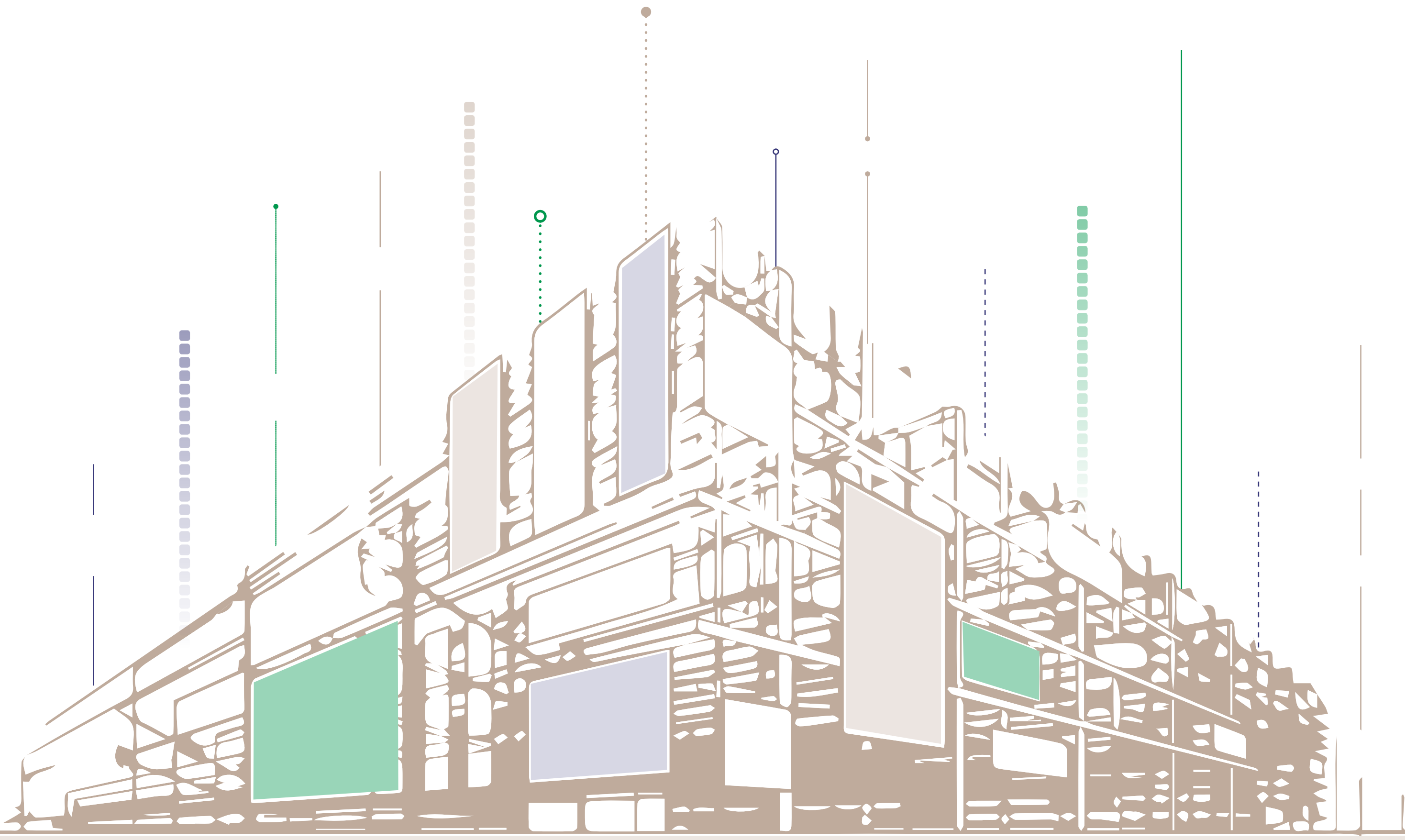
ICED
Infrastructure & Cities
for Economic Development

Digital Innovation in the Built Environment in Low Income Countries:

Diagnostic Report & Implementation Opportunities



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Executive Summary

Digital innovations have been radically transforming the landscape of the Architecture, Engineering and Construction (AEC) sector, however, research tends to focus on digital innovation in the built environment of high income countries (HICs) rather than low incoem countries (LICs). In an urban world, the built environment has a considerable impact on socio-economic development, poverty reduction, environmental protection and resilience. As such the application of digital technologies can support global progress to achieve wider Sustainable Development Goals.

In 2018 the UK Department for International Development (DFID) launched its Digital Strategy 2018-2020, which states: 'digital, data and technology can be an enabler rather than an end goal: the goal is in the material benefits delivered to people, particularly those who are most vulnerable and marginalised'.

DFID commissioned this research to address the knowledge gap on digital innovation in the built environment in LICs and aims to: create a better understanding of the potential economic development and poverty reduction benefits associated with the use of digital innovation in the built environment of LICs; examine the barriers that hinder the introduction of these digital innovations; and identify how digital innovation methods and systems can be most effectively and efficiently adopted in the built environment in LICs.

The research was conducted over a six month period in 2018 and included: a literature review of academic and AEC industry sources; in-depth semi-structured interviews with professionals and researchers working in the built environment in LICs; a survey questionnaire distributed through several communities of practice (e.g. DFID, ALNAP, ICE, UK Shelter Forum); and analysis by the authors based on their extensive experience working in the built environment of LICs.

The nomenclature used for digital innovation in the built environment is vast. This report defines and tries to clarify digital innovation in the built environment as 'tools, techniques, technologies and approaches of the internet age used in the built environment, including infrastructure and building projects, throughout the asset's life-cycle'. This definition moves beyond the hardware and physical aspects of innovations (i.e. tools and technologies), towards addressing the soft skills and competences (i.e. communication and change management) of individuals working and collaborating in the AEC sector.

DFID has an opportunity to influence and improve the enabling environment of digital technology implementation, to overcome the most common constraints: local capacity, professional training, education (with the potential exception of digital communication technologies due to their user-friendliness) and energy/digital infrastructure. However, the success of technology adoption is also dependent on factors requiring consideration such as:

- localised enabling environment;
- different stages of the project cycle where they are applied; and
- local market readiness.

This report focuses on 10 digital innovations which have been selected due to their relevance or potential in the built environment in LICs:

- **Digital communication technology;**
- **Computer Aided Design (CAD) and modelling;**
- **Imagery – Unmanned Aerial Vehicles (UAVs) and satellites;**
- **Management Information Systems (MIS) and tools;**
- **Internet of Things (IoT) and big data;**
- **Modular construction;**
- **3D/4D printing;**
- **Virtual/Augmented Reality (VR/AR);**
- **Distributed Ledgers and Blockchain;**
- **Artificial Intelligence and Machine Learning (AI/ML).**

Each innovation is analysed based on its potential benefits, constraints to adoption, and potential mitigation measures. Following evaluation, the digital innovations identified of most relevance to LICs are 1) digital communication technology; 2) Computer Aided Design (CAD) and modelling; 3) Imagery – Unmanned Aerial Vehicles (UAVs) and satellites; 4) Management Information Systems (MIS) and tools. These innovations exhibit the highest benefits, lowest constraints and are readily available for utilisation within DFID programmes.

Conversely, 3D/4D printing; Virtual/Augmented Reality (VR/AR); Distributed Ledgers and Blockchain; and Artificial Intelligence and Machine Learning (AI/ML) are considered, to be generally, of limited immediate value to DFID programmes at thsi time. This conclusion has been reached as the benefits are these innovations at present are low and these innovations are not immediately market ready. Modular construction exhibits considerable potential benefits to the built environment but also the highest 'barrier to entry' of all the profiled innovations and therefore the market appears least ready for this innovation.

Potential synergies exist where multiple digital innovations can be applied concurrently, for example by applying machine learning to the internet of things. Possible connections between innovations are described within each of the 10 innovation sections. Interdependencies between innovations and infrastructure and between innovations can:

- **Strengthen the built environment** – for example creating further efficiencies, reduction in energy use, connecting people and supporting coordination etc.;
- **Complement the built environment** – examples of this include helping to gather data, analyse information and display information; and
- **Cause new fragilities** – this may include displacement of labour, digital exclusion, exposure of the built environment to cyber threats.

It is recommended that potential synergies be considered in further detail on a case-by-case basis and additional research should be conducted on country specific or regional appications.

Acknowledgements

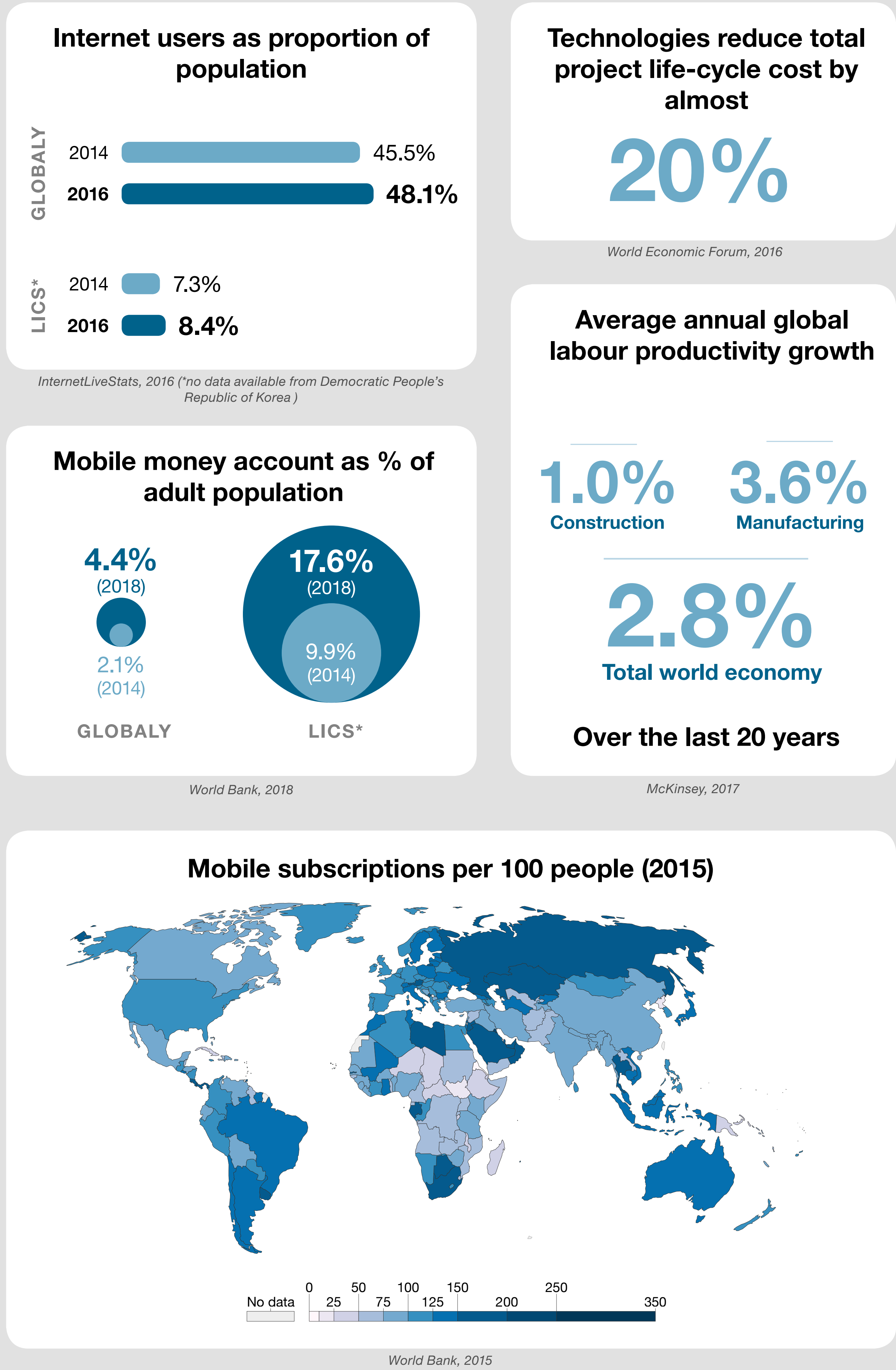
This report, 'Digital Innovation and the Built Environment in Low Income Countries' was commissioned by Hayley Sharp and Rebecca Wooding (both UK Department for International Development – DFID)) through the Infrastructure and Cities for Economic Development (ICED) facility; developed by Andy Kervell, Darren Gill, Eleanor Earl, Ammar Azzouz, Yung Loo and Roman Svidran (all Arup); and supported by Mark Harvey, Jasmine Bourne, Eleanor Bainbridge, Shiraz Shahid (all DFID), Nicholas Miles (Engineers Against Poverty), Adam Molleson, Nina Nasman (both PricewaterhouseCoopers), Kaitlin Shilling, Caroline Ray, Edmore Hove, Fredrick Mukonoweshuro, Brian Kimbui, Purnell Krams, Jamie Ferreira and Siraj Tahir (all Arup). A full list of additional consultations is provided in Annex 3.

Thank you to all those involved. Any additional feedback to inform further iterations will be much appreciated, please direct correspondence to darren.gill@arup.com.

Acronyms

AEC **Architecture, Engineering and Construction**
AI Artificial Intelligence
AR Augmented Reality
BIM Building Information Modelling
CAD Computer Aided Design
CDE Common Data Environment
DFID UK Department for International Development
HICs High Income Countries
ICED Infrastructure and Cities for Economic Development
ICT Information and Communications Technology
IoT Internet of Things
LICs Low Income Countries
MIS Management Information Systems
O&M Operation and Maintenance
UAVs Unmanned Aerial Vehicles
VR Virtual Reality

Figure 1 - Indicative statistics highlighting the digital transformation and potential benefits of technology in society and the built environment



Introduction

Digital innovations have been radically transforming the landscape of the Architecture, Engineering and the Construction (AEC) sector. This is recognised by several governments across the world who have established mandates, targets and taskforces to foster the digital transformation in the built environment for example the European Union's Building Information Modelling (BIM) task group, UK Government's Mandate and BIM Task Group. Professionals widely acknowledge the potential of digitalisation – yet the adoption of innovations in the built environment varies greatly across geographies, organisations and sectors.

Today, a wide range of innovations have been implemented in the AEC sector, these include:

- Digital communication technology
- Computer Aided Design (CAD) and modelling
- Imagery – including drones and Unmanned Aerial Vehicles (UAVs)
- Management Information Systems (MIS) and tools
- Internet of Things (IoT) and big data
- Modular construction
- 3D/4D printing
- Virtual/Augmented Reality (VR/AR)
- Distributed ledgers and blockchain
- Artificial Intelligence and Machine Learning (AI/ML)

The built environment has a considerable impact on socio-economic development, poverty reduction, environmental sustainability and resilience. As stated in DFID's Digital Strategy (2018), DFID will be using digital technology to improve the speed, value for money, reach and impact of its programmes, which will be more flexible and user-centred. Many Low-Income Countries (LICs) are experiencing rapid urbanisation relative to the more urbanised High Income Countries (HICs). An opportunity exists for digital innovation to improve the nature of the built environment as it develops, key statistics illustrating this are highlighted in Figure 1 above. This report, "Digital Innovation and the Built Environment in Low Income Countries", aims to:

- Create a better understanding of the potential economic development and poverty reduction benefits associated with the use of digital innovation in the built environment of LICs;
- Examine the barriers that hinder the introduction digital innovation in the built environment of LICs;
- Identify how digital innovation methods and systems can be most effectively and efficiently adopted in the built environment in LICs; and
- Identify implementation opportunities for DFID programmes to utilise digital innovation in the built environment of LICs.

OUTCOME OF DIGITAL TRANSFORMATION IN THE BUILT ENVIRONMENT

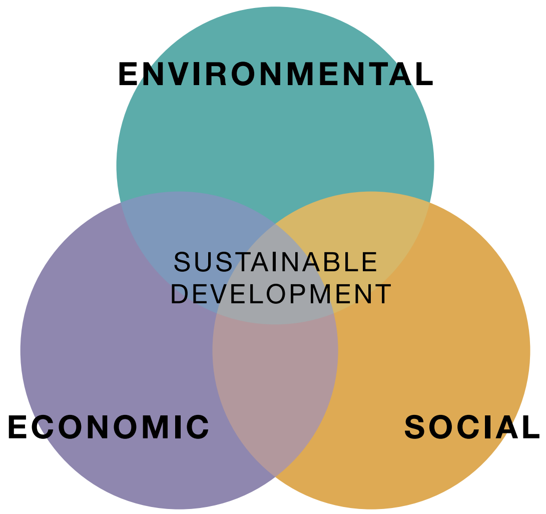
"Ultimately, the outcome of a digitally transformed construction and built environment should enable the improved efficiency and integration of public and private services and infrastructure, ensuring greater return on investment and value for money, enhanced business opportunities, increased resilience for our infrastructure, our environment and our economy. This will lead to a better quality of life for society."

(UK BIM Alliance, 2016)

Research justification

Digital innovation and new technologies are changing rapidly with implications for the architecture, engineering and construction (AEC) industry; the built environment; and society more broadly.

This research is timely as potential benefits of digital innovation in the built environment are vast and widely recognised. Figure 2 categorises the main benefits of digital innovation in the built environment in LICs against social, environmental and economic outcomes which highlights the broad spectrum of benefits that can be achieved through this innovation. These benefits are referred to later in this document in relation to specific technologies.



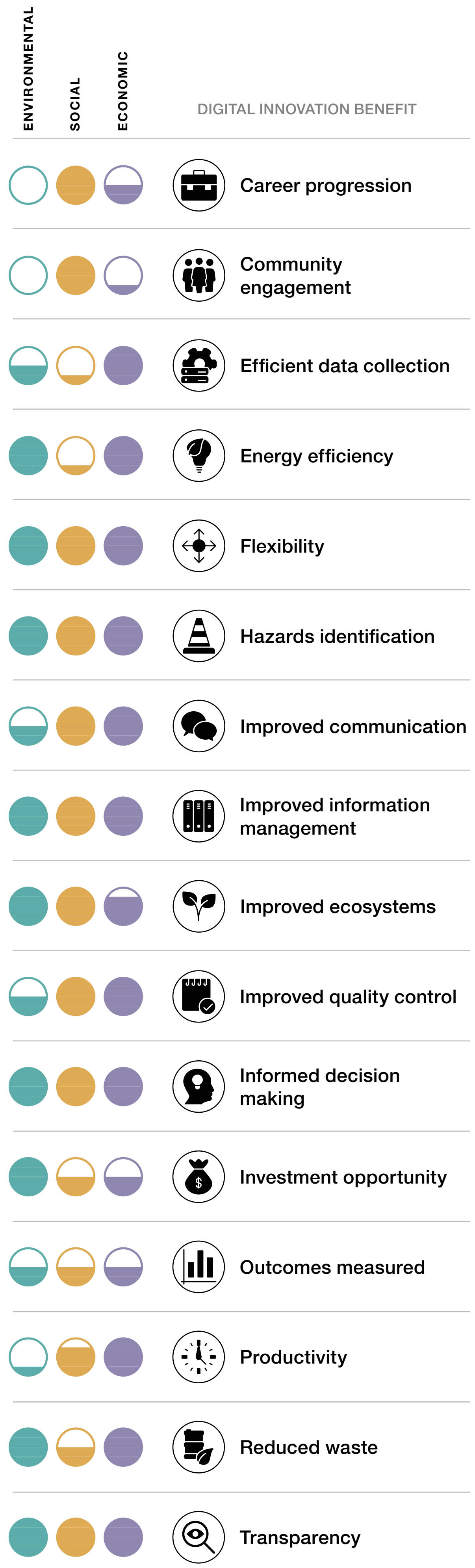


Figure 2 - Variety of benefits of digital innovation in the built environment (Authors)

Slow adoption in AEC industry

The global AEC industry has been slow to adopt digital innovation and according to the World Economic Forum (2016) has never undergone a major digital transformation. As shown in Figure 1 labour productivity growth over the past 20 years is lower compared to the manufacturing sector or total world economy (McKinsey, 2017). In a McKinsey (2016) index of economic sectors, construction was rated just above agriculture and hunting in terms of digitalisation.

The 'fourth industrial revolution' is the development of systems and technologies which join the digital and physical worlds (Figure 3). It could have a greater impact on the built environment, than previous industrial revolutions, as it encourages new types of innovation and creativity rather than enhancing or supporting traditional methods. Despite this slow adoption, the application of digital tools, technologies and processes within the built environment has attracted significant interest and generated considerable expectations from researchers, practitioners and politicians.

Digital inclusion

Despite extensive work carried out on digitalisation in specific regions in the world, there is a lack of knowledge surrounding the emergence, adoption and implementation of digital innovations specifically in the built environment of LICs (Torbaghan et al, 2017). Access to digital innovation tends to be greater for wealthier communities. The contrast between the digitalisation of HICs and LICs is often referred to as the 'global digital divide'. Investigating the potential of these innovations in LICs, including the enablers and barriers of innovation in the built environment of LICs, is of vital importance to better understand the wider agenda of digital innovation in LICs and its impact on societies.

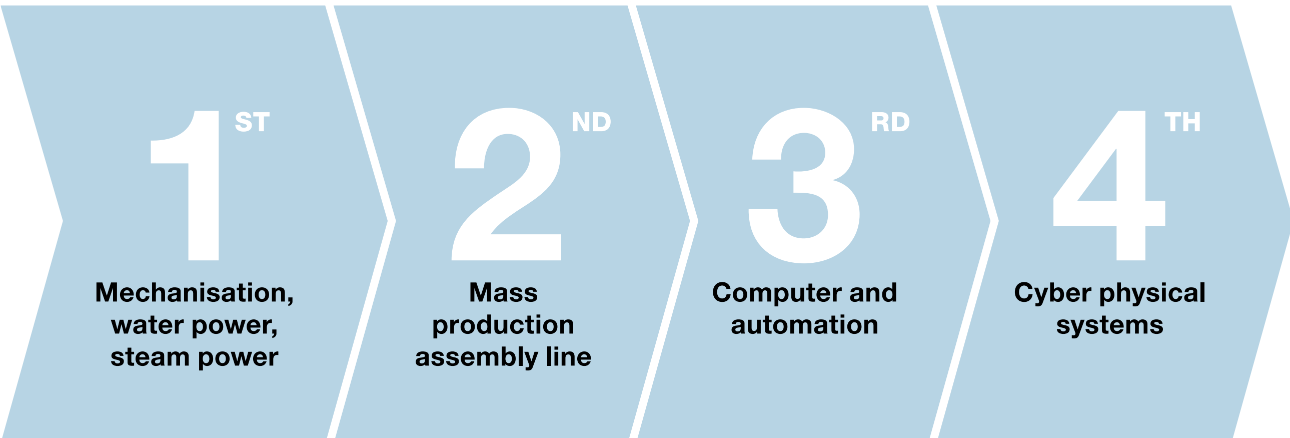


Figure 3 - Transition to the fourth industrial revolution (University of Sydney, 2018)

'Leapfrogging' opportunities

Understanding the digital maturity and future readiness of technologies in LICs is important to help decision-makers choose the most appropriate technology to solve a problem. The use and development of technology is not necessarily a linear process and some contexts may have the appropriate enabling environment for leapfrogging previous stages. A good example of leapfrogging is the development of drawing tools from 2D physical drawing to 3D computer modelling. In many cases, only 2D paper drawing records exist. With improvement in the usability and functionality of 3D digital modelling tools there is an opportunity to leapfrog 2D digital drawing tools. Another example of leapfrogging is the change over the past two decades in methods to collect data, as shown in Figure 4. With digital infrastructure, it is possible to leapfrog earlier methods and gain the efficiencies of more 'cutting edge' technologies (D) without the prior understanding or infrastructure required for previous technologies (i.e. B & C).

New routes to sustainable development

LICs require considerable infrastructure investment to sustainably achieve the desired development outcomes (i.e. the UN Sustainable Development Goals) in terms of sustained positive impact and sustainable resource consumption. The use of digital technologies could play a role in accelerating sustainable infrastructure investment by supporting decision making through improved data collection, availability of digital technology innovations and combinations of technologies. Such changes give LIC's an opportunity to move away from the 'traditional' growth routes in infrastructure, while meeting long-term development objectives. In short, de-coupling economic growth with resource consumption.

For example, China used more cement between 2011 and 2013 than the US consumed in the entire 20th century (Washington Post, 2015). However, if digital innovation had been more robustly available and applied it is possible that more sustainable development pathways could be pursued. As stated by the New Climate Economy, "more compact, connected, and coordinated cities are worth up to US$17 trillion in economic savings by 2050… and could deliver up to 3.7 gigatons per year of CO_2 savings over the next 15 years" (New Climate Economy, 2018).

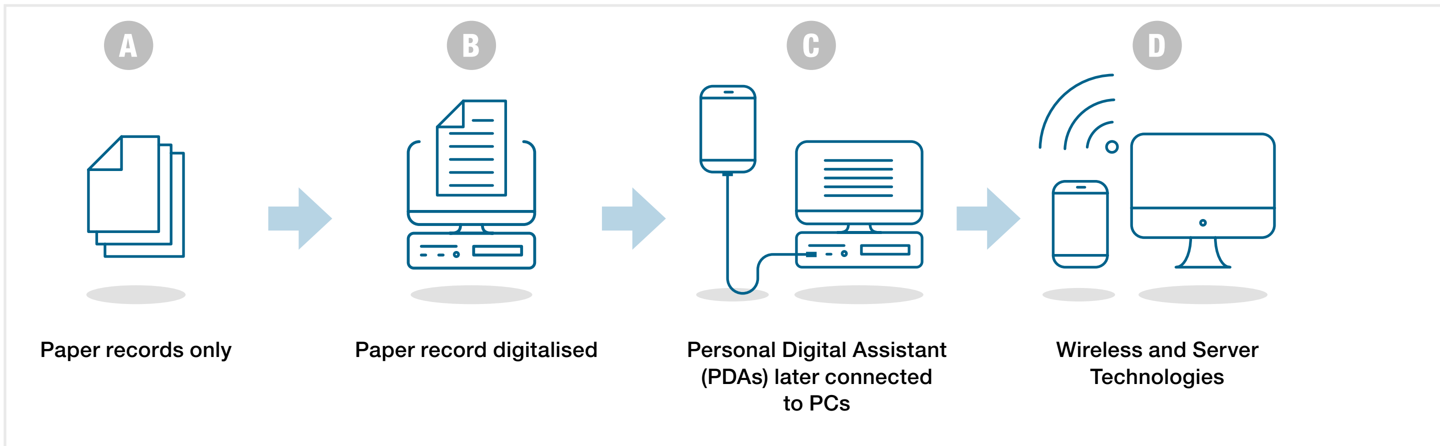


Figure 4 - Example of the digital transformation in data collection

Aims, Objectives & Structure

Research and application of digital innovation in the built environment has concentrated on High Income Countries (HICs) or advanced economies, with few studies on digital innovation and the built environment in LICs. This report contributes to reducing this knowledge gap by exploring the application, potential benefits, enablers and barriers to the use of digital innovation within the built environment of LICs. The report tries to identify potential economic development and poverty reduction benefits of digital technologies in delivering infrastructure. It is hoped the report will be of interest to industry professionals, donors, policy makers, (international) non-governmental organisations, and researchers seeking to improve the socio-economic, cultural and built environments in LICs.

The report is structured as follows:

Introduction

Outlines the aims and objectives of the research project and provides definitions of digital innovations in the built environment. It also identifies the applied research methods and the limitations of the report.

Key Findings

Enabling environment: Several cross-cutting themes have been identified in the report including, professional training and education, energy and digital infrastructure and governance. Without addressing these associated challenges within each of the themes, our research suggests that, limited development in the adoption of digital innovation in the built environment can occur.

Technologies: The report provides an overview of the use of digital innovations across the project life-cycle, implementation opportunities for DFID programmes, and introduces several tools, techniques and technologies that have already been implemented in the AEC sector in LICs – including drones, management information systems and modular construction.

Conclusions and recommendations:

Summarises the project and draws conclusions based on the first two sections. It also highlights many recommendations for future directions for the research and application of digital innovations in LICs.

Methodology

The report was developed using a mixed methods approach to provide insights on digital innovations in LICs as follows:

Literature review from academic and AEC industry sources on LICs, with a specific focus on five LICs including Uganda, Rwanda, Haiti, Afghanistan and Nepal to narrow the research. The search also included Pakistan (not on the list of LICs) but was the country location of one of the DFID programs considered. Key words used to undertake the search included: innovative infrastructure, design and the built environment, construction technology, BIM, and digital construction (see Annex 2 for more information and 'hits' analysis).

Semi-structured interviews with professionals and researchers working in the built environment in LICs were conducted. Qualitative interviews focused on exploring the interviewees' opinions on the status of digital innovations in LICs, the potential benefits and the barriers to their adoption and implementation (see Annex 3 for a list of consulted interviewees).

A survey questionnaire distributed through several communities of practice (e.g. DFID, ALNAP, ICE, UK Shelter Forum, Arup) which has been completed to date by respondents with experience in Uganda, Nepal, Tanzania, Ethiopia, Madagascar, Somalia, Mozambique, Liberia and Zimbabwe. A limited number of responses were received so the available information from the survey was limited.

Drafts of the report were reviewed by; a panel of experts including six Arup staff who are all engaged in digital innovation practice with experience in Afghanistan, Haiti, Indonesia, Kenya, Kyrgyzstan, Liberia, Myanmar, Pakistan, Zimbabwe; and relevant DFID advisors in the Growth and Resilience Department, and Emerging Policy Innovation Capability Department.

Limitations

The report does not attempt to provide a comprehensive catalogue of all digital innovations in the built environment in every LIC; each country needs a considerate and careful focus to better understand the emergence and implementation of digital innovations in a specific region. The report also introduces the range of digital innovations with a focus on those which are in use or might be approaching market readiness. Future research projects could concentrate on a specific tool or technology to examine its full potential. LICs exhibit considerable diversity which restricts the specificity of the findings and recommendations, which are therefore deliberately broad to have relevance across LICs. Examples are identified to illustrate how digital innovation has been applied within specific country contexts. Further research could concentrate on individual countries or regions to ascertain more tailored recommendations.

The work was conducted remotely without direct site access to LICs, or organised focus groups with local architects and engineers working in LICs. Researching digital innovation in the built environment in LICs area is a challenge as there is a lack of reports, case studies and articles published on digital innovations in LICs. The report is reliant on the pre-existing knowledge of the authors, reviewers and research found in the reviewed literature on the built environment in LICs. The authors and reviewers have extensive experience across technology, the built environment, and development in addition to experience working in several current and former LICs including Afghanistan, Cambodia, Haiti, Indonesia, Kenya, Kyrgyzstan, Liberia, Mozambique, Myanmar, Nepal, Pakistan, Rwanda, Tanzania, Sierra Leone, Uganda, and Zimbabwe.

BOX 1: DEFINITIONS OF DIGITAL INNOVATION IN THE BUILT ENVIRONMENT ACCORDING TO VARIOUS INDUSTRY PROFESSIONALS CONSULTED AS PART OF THIS REPORT

"My interpretation of smart construction is the application of automation, parametric design simulation and tools to aid in the process of design and construction of buildings and infrastructure."

"Means to be developed within a long-term vision, in an intelligent and innovative way to have economic financial results."

"The use of locally sourced and produced resources, sustainability & maintainability, environmentally friendly resources, innovative engineering applications, low key skill input, community input, etc."

"Possibly using more technology during the construction process or things like smart meters to measure various parameters in real time."

"Use of digital technology to improve construction efficiencies, accuracies and reduce cost on a construction site."

"Getting the basic design right, so that no retrofitting is required and ensuring the choices related to materials is informed by issues of depletion and long-term sustainability."

"A new type of construction that is more integrated (i.e. different areas speak to one another) than before and leverages the most recent innovative technology."

"Using appropriate technology, material, and adapted local techniques to achieve the highest quality at the best value for money."

BOX 2: TERMINOLOGY AND CONCEPTS USED WITHIN THIS REPORT

Building Information Modelling (BIM): is a process involving the development and management of digital information during the life-cycle of a project.

Built Environment: the human-made surroundings.

Digitalisation: is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business (Gartner, 2018).

Project Life Cycle: is the process undertaken by typical construction project from inception to demolition. This may be a non- linear process where previous stages are repeated to meet the needs of the users.

IoT - a network of embedded sensors and electronics connected to a network enabling widespread collection of real time data remotely and continuously.

Context: which digital innovations and where?

The range of applications, process, tools and technologies that constitute digital innovation in the built environment is contested in industry and as innovation becomes embedded in the industry this list of digital technologies continues to evolve. Various industry professionals consulted as part of this report offered a range of definitions (see Box 1). This highlights the variety of ideas that currently exists in the industry, some focussing on areas and stages during the development of assets in the built environment whilst others present more general descriptions relating to decision-making and use of resources.

The nomenclature used for digital innovation in the built environment is vast. Different terms have been used to reflect these emerging innovations in the AEC industry, e.g. Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Virtual Design and Construction (VDR), Automation in Construction (AiC) and Building Information Modelling (BIM).

This report defines and tries to clarify digital innovation in the built environment as 'new and advanced tools and technologies used in the built environment, including infrastructure and building projects, throughout the asset's life-cycle'. This definition moves beyond the hardware and physical aspects of innovations (i.e. tools and technologies), towards addressing the soft skills and competences (i.e. communication and change management) of individuals working and collaborating in the AEC sector.

This report focuses on LICs as defined by the World Bank which currently include 34 countries.[1] However, the transferability of digital innovation is fluid and examples are also drawn from Lower-Middle Income Countries (LMICs).

(1) For the current 2019 fiscal year, low-income economies are defined as those with a GNI per capita, calculated using the World Bank Atlas method, of $995 or less in 2017. The current 34 countries include: Afghanistan, Benin, Burkina Faso, Burundi, Central African Republic, Chad, Comoros, Congo (Dem. Rep), Democratic People's Republic of Korea (DPRK), Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Liberia, Malawi, Mali, Mozambique, Nepal, Niger, Rwanda, Senegal, Sierra Leone, Somalia, South Sudan, Syrian Arab Republic, Madagascar, Tajikistan, Tanzania, Togo, Uganda, Yemen, Rep., Zimbabwe

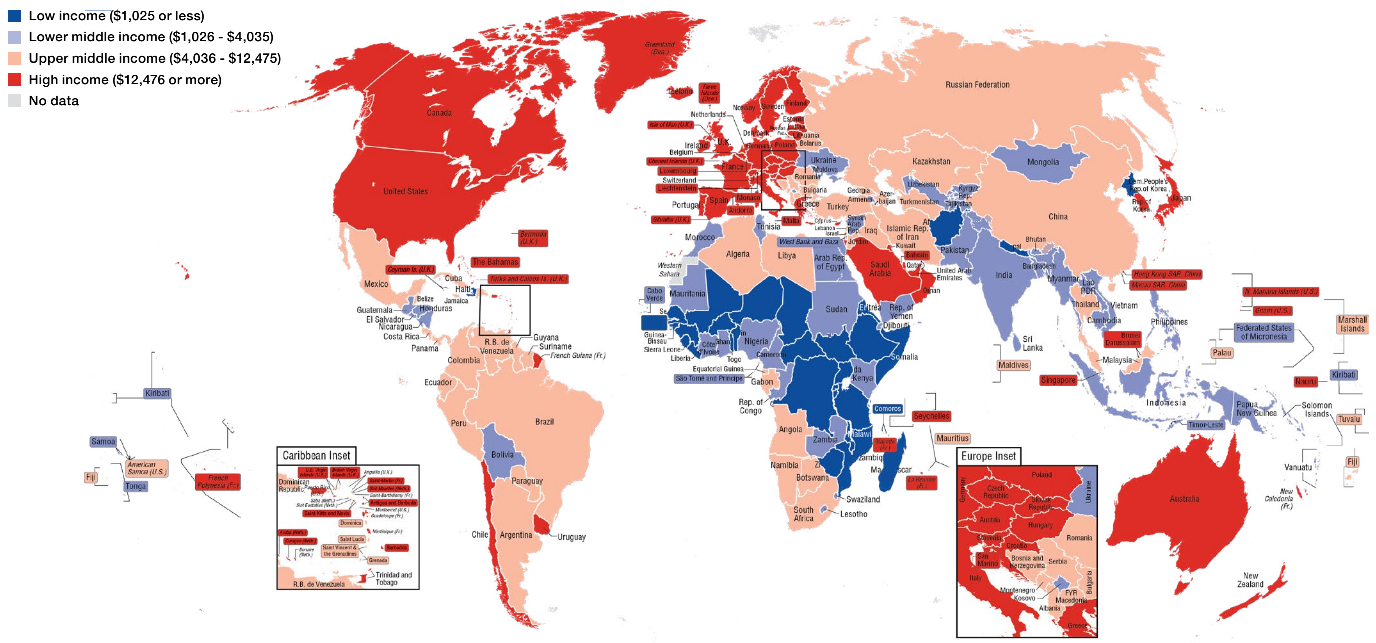


Figure 5 - Map of the world showing the location of LICs in dark blue (World Bank, 2017b) (note Yemen and Syrian Arab Republic are both LICs and Tajikistan is now a LMIC as of 2018)

Enabling environment for digital innovation in the built environment

The research highlights six interrelated enablers needed in the development of most digital technologies in the built environment (Figure 6). Although the research focussed on LICs, these constraints are ubiquitous with digital innovation in other contexts, most likely due to the borderless and rapid nature of the digital transformation. Table 1 summarises the enabling environment needed for any digital innovation in the built environment and the typical readiness of LICs based on project research. Each of these aspects are expanded in subsequent sections. These enablers relate to the Principles for Digital Development (2017), and focus on the initial application of digital innovations rather than the entire lifecycle of a project. DFID endorses the Principles for Digital Development as good practice guidelines for developing programmes to harness digital technologies in LICs.

Before any digital technology is applied to a local built environment project an analysis should be performed to understand the existing enabling environment features and local context challenges. When performing this analysis, it is important to appreciate the interdependencies of the six key enables discussed in Figure 6, as well as the impact of external environments (i.e. financial, political, cultural and energy etc.),. These multiple variables may lead to significantly different local digital innovation implementation opportunities and therefore the readiness to implement digital innovations. It should be noted that these enablers are not solely critical to LICs and many are likely to be required in HICs which could explain why the slow adoption of digital technology in the global construction sector has been present.

A range of possible tools and methodologies exist to assess the enabling environment in a given context. The most relevant methodology identified during this research was the Construction Capacity Framework (ICED, 2018) which provides a structured approach to understanding the strengths and weaknesses of the construction industry in developing countries to help identify areas that could be strengthened to enable more effective infrastructure delivery and development outcomes.

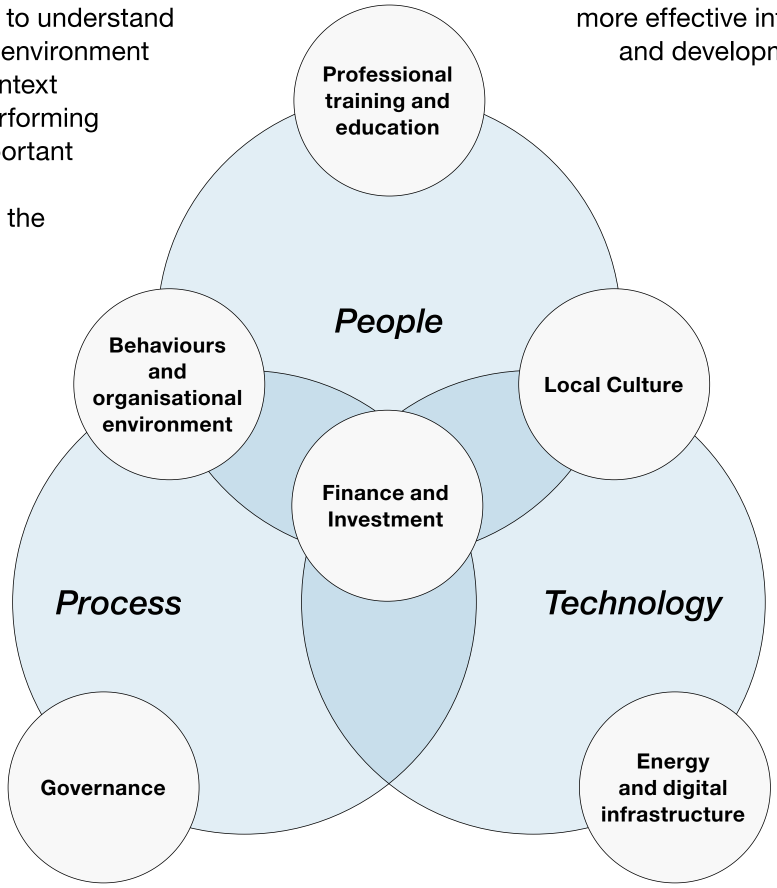


Figure 6 - Key aspects identified that enable digital technologies to thrive in the built environment

Analysis and recommendations for DFID infrastructure programmes

The report presents implementation opportunities for digital innovation in the built environment as they relate (primarily) to DFID infrastructure programmes in LICs. However, many of the findings are also relevant to similar programmes in LICs whether they are led by other development partners, governments, the private sector etc.

For each of the digital technologies discussed in this report, general implementation opportunities are presented and, where appropriate, their application within specific project types (sector), scales, and stages. A range of DFID programme typologies in the built environment have been considered as part of this study:

- Infrastructure programmes delivering tangible assets of multiple small, non-bespoke infrastructure projects, e.g. schools in Pakistan Safer Schools Programme
- Infrastructure programmes delivering tangible large infrastructure programmes (e.g. a road) which are more bespoke, individual and generally expensive, e.g. Nepal Rural Access Programme, Pakistan Economic Corridors Programme
- Infrastructure programmes delivering technical assistance to improve the enabling environment for infrastructure investment and implementation, e.g. Cities and Infrastructure for Growth
- Humanitarian programmes, with remits to provide infrastructure to respond to immediate and potentially temporary/short term needs,
- Sector cross-cutting programmes focused on wider objectives, but with a remit or impact on infrastructure e.g. programmes focused on climate change, disaster risk reduction, health improvements) e.g. Nepal Urban Resilience Programme

Specific implementation opportunities for individual DFID programmes are discussed in more detail in Annex 4. The individual programmes were selected in consultation with relevant DFID advisors both centrally and within country offices based on: relevance to digital innovation in the built environment; the schedule of the programme and therefore opportunity to influence implementation; and ability to access relevant programme documents and personnel. The specific programmes are:

- Nepal Safer Schools Programme (NSSP)
- Nepal Urban Resilience Programme (NURP)
- Cities and Infrastructure for Growth (CIG)

Specific implementation opportunities are not dealt with in uniform detail or application across these three programmes.

Note: Readiness

- Low - Little evidence of development in the 'enabler' in LICs
- Med - Some evidence of the 'enabler' already being achieved in LICs
- High - Widespread adoption of the 'enabler' already in LICs

Table 1 - Enabling environment needed for digital innovation in the built environment (Authors)

INNOVATION ENABLER	DEFINITION	ENABLER READINESS	HOW THIS ENABLES DIGITAL INNOVATION IN LICS?	CONSTRAINTS TO THE INNOVATION ENABLER
Energy and digital infrastructure	The network of energy and digital communications infrastructure needed for use of digital technologies.	**High**	Enables digital technologies to be used. Continuous connection supports productivity. Improving infrastructure can often increase the impact. For example, evidence suggests greater productivity and economic growth can be achieved by substituting basic mobile services with advanced 3G connections (GSMA, 2012).	- **Dependant on geography** - Some LICs may be located close to strategic economic areas (e.g. the 'Digital Silk Road' or strong links to higher income countries for example through intergovernmental and trade organisations like the East African Community). This is reflected in the GSMA Global Connectivity Index (2016) and ITU ICT for Development Index (2017). - **Investment** - Local infrastructure investment needed. - **Requires asset management** - Digital resilience should be considered as the result of combining digital and physical infrastructure which leads to growing interdependence. Consideration of independent energy sources (e.g. solar energy) should be considered.
Governance	Establishment of policies and appropriate authority for managing digital assets.	**Med**	Encourages local innovation. Moving beyond creating short-term visions and establishing projects that empower people in the long-term is needed to enable sustained digital innovation.	- **Dominance of international organisations** - If not carefully managed, the dominance of international organisations in some LICs can undermine governance to develop local innovation in the built environment. - **Governance varies significantly between countries** - Further information on the policies implemented in LICs are discussed in ITU ICT for Development Index (2017). - **Relationship between governments and firms** - According to Fu et al. (2014) although firms in LICs are innovative and government is regarded as important innovation partner, they go largely unsupported. On the one hand firms have scarce knowledge of policy instruments in place, on the other hand innovations are rarely recognised and innovation efforts within the firms are not properly underpinned.
Local culture	Local context and way of life including customs and values.	**n/a**	Communicating with local communities on all levels on how such innovations will impact on their lives may make local people more open to changes, participate in their developments and help adaption of these technologies to local contexts.	- **Satisfaction with the status quo** - Many professionals are satisfied with traditional methods to design their projects and are incredulous of the new functions and advantages (Yan & Damian, 2008). - **Digital divide** - The unequal distribution of who has access in the built environment of digital competences and skills are raising critical questions in LICs. Different levels of access and implementation to new innovations has been seen between i) local and foreign firms and ii) projects based on their scale. - **Perception that it is expensive** – There is a lack of client demand as there is a perception that digital innovation is too costly.
Professional training and education	Skills and training in the built environment	**Med**	Skills and training in digital innovation in the built environment is a key enabler and helps support understanding and enables behaviour and organisational change.	- **Tiered construction industries** - Many LICs run small but tiered construction industries which leads to a wide range of skill and technology. - **Appropriate knowledge materials** – There is a lack of appropriate education materials (Affleck & Freeman, 2010). However, digital knowledge products (e.g. Massive Online Open Courses) could help develop this area. - **Lack of national experience** retention / technology transfer - Evidence of foreign workers / contractors deploying digital innovation with little technology transfer or training. - **Networks for knowledge dissemination** - Need for centres for higher education and local institutions to help disseminate knowledge.
Behaviours and organisational environment	Values and activities possessed and typically undertaken by a group.	**Low**	Willingness to try new tools and processes will help change processes and support adoption of digital innovation.	- **Professionalism** - A lack of professional standards and responsibility in AEC consultancy firms makes innovation difficult to achieve. - **Evidence** - Clear evidence required to educate the benefits to all parties in the production chain. Requires a system that rewards and enables appropriate behaviour to change across industry and client bodies. - **Need for major projects** - Major infrastructure and building projects are more appropriate incubators for developing skills and innovation. At a smaller scale, this might be achieved if similar projects are grouped enabling collaboration to develop skills and innovation to flourish.
Finance and investment	Initial capital and ongoing current finance, funding and revenue streams	**Med**	The application of innovations in the AEC sector will require a large investment capital at the start, despite evidence of long-term savings.	- **Access to capital** - A 'lack of access to credit, as well as market constraints, are the main challenges firms face when adapting knowledge and innovations' (Fu et al. 2014).

Digital Innovation, the Built Environment and the Project Cycle

Applications of digital innovation in the built environment are integrated with the lifecycle of infrastructure and building assets. The lifecycle must be considered when deciding where these technologies might best be used and how multiple technologies can be integrated simultaneously together. Figure 7 below shows the lifecycle of a typical building asset.

The lifecycle of the built environment is often a non-linear process. As more information and understanding is gained about the site or a project, previous stages may be revisited or repeated. As referred to in the 'research justification' section of this report, digital innovation enables new ways of reaching the same outcome (referred to earlier as development pathways). Therefore, it is possible that through these new approaches the entire lifecycle of physical assets in the built environment could change. These new structures are beyond the scope of this document; therefore, the application of digital technologies has been related to the 'traditional' lifecycle of building and infrastructure assets (as shown above).

The potential opportunities of digital innovation in the built environment in LICs, and the constraints to their emergence and dissemination have not been documented collectively in the current literature. However, several academic and AEC professional articles focus on a specific country and document the application of a specific tool or technology. The table below gives an overview of the principle technologies reviewed as part of this report including where these might be used in a building or infrastructure project lifecycle.

The following chapter focuses on the technologies that appear to be most widespread or have greatest benefit to the built environment in LICs. The list of technologies shown in Table 2 is not a comprehensive catalogue, but instead highlights some of the main technologies that our research suggests are having and could have the greatest impact on economic development and poverty reduction. The authors derived this list based on their qualitative assessment of the literature review, insight from consultations, and their experience in the sector (see Annex 1 for further detail). The list would undoubtedly change as innovation continues and these techcnologies are devloped. Many of these technologies are highly connected and may need to be used together to create required outcomes, e.g. imagery and machine learning or MIS and digital communication.

Beyond the enabling environment, as shown in Figure 2, there is considerable variety in the benefits and constraints of specific technologies and therefore the means of mitigation. As Table 2 shows, some technologies may be applied throughout the lifecycle while others are more specific to a stage. The benefits and constraints influence the overall readiness of a technology for its application to the built environment. As explained in the 'Enabling environment for digital innovation in the built environment' section, these benefits, constraints and the consequent readiness of application are not homogeneous and should be assessed carefully in each context.

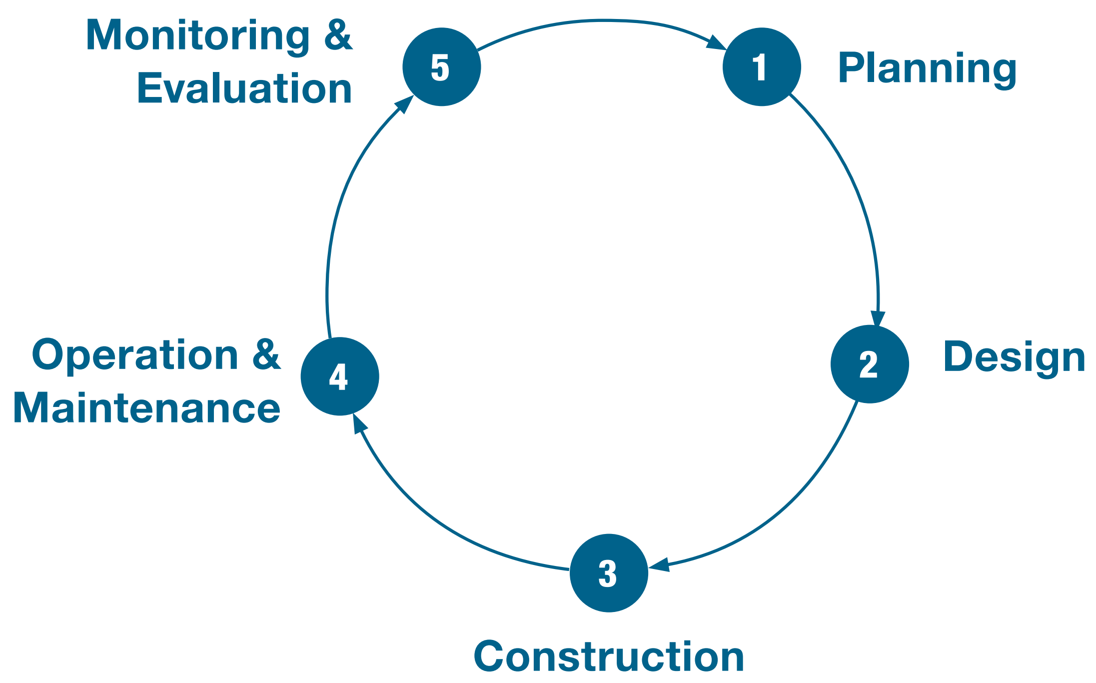


Figure 7 – Typical lifecycle of building and infrastructure assets that digital innovation could be adapted to (adapted from Autodesk, 2009).

1 Planning
The planning stage can help provide transparency and an evidence base for decisions in later stages of the lifecycle. Technologies should be considered which are able to gather data to undertake an economic, spatial and technical analysis; thus informing potential intervention areas/types.

2 Design
Data is gathered in order to inform designs for construction and operations stages. Technologies used at this stage are typically modelling, design tools and some site-based technologies. This stage may involve 3D visualisation, collaborative shared working, scheduling, cost estimation, safety awareness prior to construction.

3 Construction
The construction stage is mostly on-site. Technologies should be considered which support physical construction processes, testing, commissioning, health and safety inspection and resource management.

4 Monitoring & Evaluation
Periodic evaluation of an asset during operation can be used to measure its effectiveness and ability to meet desired needs. This can be linked back to all previous stages. Technologies used here include machine learning, sensors and big data.

5 Operation & Maintenance
The day to day operation and maintenance of the infrastructure consists of scheduled activities to ensure that the asset remains functioning. This often involves processes and tools to monitor assets and ensure that no adverse impact on the system is occurring.

READINESS	TECHNOLOGY	STAGE: 1 Planning, 2 Design, 3 Construction, 4 Operation & Maintenance, 5 Monitoring & Evaluation	BENEFITS	CONSTRAINTS
Immediate	Digital communication technology		Productivity; Community engagement; Improved communication	- Digital technology infrastructure - Cost
	Computer Aided Design (CAD) and modelling		Improved information management; Career progression; Informed decision making; Hazards identification; Productivity	- Training and culture - IT licenses - Interoperability - Digital infrastructure
	Imagery – including Unmanned Aerial Vehicles (UAVs) and satellites		Hazards identification; Informed decision making; Efficient data collection; Cost	- Policy - Initial cost - Training - Digital technology/energy infrastructure
	Internet of Things (IoT) and big data		Informed decision making; Transparency; Reduced waste; Efficient data collection; Energy efficiency	- Data science skills - Digital technology/energy infrastructure - Policy/governance - Processing power
	Management Information Systems (MIS) and tools		Improved information management; Transparency; Reduced waste; Productivity; Improved communication	- Data collection - Digital technology/energy infrastructure - Behavioural/organisational challenge
	Modular construction		Hazards identification; Reduced waste; Productivity; Improved quality control	- Local supply chain - Transport and poor physical environment understanding - Behavioural/organisational challenge - Digital technology/energy infrastructure
	Virtual/ Augmented Reality (VR/AR)		Informed decision making; Hazards identification; Community engagement	- Modelling integration - Equipment
	3D/4D printing		Flexibility; Productivity; Reduced waste; Community engagement; Hazards identification	- Cost - Digital technology/energy infrastructure - Scale of fabrication
	Artificial Intelligence and Machine Learning (AI/ML)		Informed decision making; Improved information management; Hazards identification; Improved quality control; Productivity	- Training - Digital technology/energy infrastructure - Processing power - Policy/governance - Reliable and accurate data
Long term	Blockchain		Transparency; Improved information management; Improved communication; Hazards identification	- Capacity - Cost - Energy-use - Scalability

Relevance to each step in the cycle: HIGH MEDIUM LOW

Key Findings

Applications, benefits and constraints of digital innovation in the built environment in LICS

READINESS

Digital communication infrastructure

Digital communication is the transfer of data through electronic transmission and encompasses a variety of technologies including:

- **Mobile communications** – a network of cellular base stations enabling data to be transferred from mobile devices. Mobile communication includes the 3G, 4G and 5G cellular networks. More recently, drones and balloons have been used to establish temporary base stations.
- **Internet communications** – a global system of computer networks. In this report, we have considered the World Wide Web, social media, instant messaging and email as part of internet communications. This data can be transferred via mobile networks but also fibre optic cables and associated infrastructure for higher bandwidths and speed. This infrastructure has often been limited in certain countries and continents to date.
- **Satellite communications** - a network of orbiting satellites that enables data to be transferred. Often used in remote locations without terrestrial cellular base stations or when mobile communications are working at capacity during a crisis.

This infrastructure forms the basis for nearly all other technologies described as they provide basic data and verbal communication, albeit at different bandwidths. Mobile technology has been increasingly available in LICs leapfrogging the implementation of landlines but can lack speed and reliability at a high relative cost to the user.

As well as underpinning many technologies it is a stand-alone innovation that is transforming the built environment. Digital communication infrastructure is fundamentally changing how we navigate, interact with, design, construct and experience the built environment. In particular:

- **Built environment surveys** – apps like the Nepal Structural Integrity and Damage Assessment (SIDA) and digital versions of Post Disaster Needs Assessments (PDNA) have radically improved the speed, accuracy / consistency, coverage and quality control of building and urban environment surveys
- **Construction oversight** – apps like Field Sight and even basic platforms like WhatsApp have radically improved the viability of remote monitoring and oversight of construction
- **Participation and polling** – digital surveys and questionnaires have significantly decreased the cost (and potentially increased the viability) of community engagement in the planning and design phases to inform the decision making process. Similarly, fault reporting and whistleblowing has been greatly enhanced by digital communication which has the potential to improve transparency, accountability and maintenance within the built environment.
- **Navigation** – apps like Where's My Transport or City Mapper have greatly increased the efficiency and ability for people to move around the city.

BENEFITS

Increases productivity

Reduces time to circulate relevant information and supports collaboration through better communication between remote parties when transport is difficult. Improved internet communication is essential for the BIM approach where a central Common Data Environment (CDE) can be used for collaborative design and modelling.

Community engagement

Particularly with marginalised groups/ people with disabilities through the sharing of information via the web and social media about potential infrastructure projects. Many developments in mobile money transfer have become possible due to mobile communications empowering communities without access to banking systems. Widespread information dissemination such as crop market rates or traffic has empowered users to plan their activities better and maximise any new infrastructure as a result.

Supports integrated information systems

Communication systems can be used for control of systems (see example) and the wider use of sensors and Internet of Things (IoT) devices. These devices often use mobile networks to transfer data and instructions about how infrastructure and buildings are performing and/or controlled.

LIFE-CYCLE STAGE

1 2 3 4 5 **All Stages**

Underpins most technologies and allows an integrated system of data sharing.

CONSTRAINTS

Widely available but lack of communication infrastructure in some locations due to difficult terrain, logistics and reliable power supply.

The cost of using communications technology especially satellite communications can be prohibitive for many users.

Consistent and affordable power supply to charge mobile devices.

MITIGATIONS

Ability to use other technologies (e.g. drones/ balloons) to support improved communication coverage particularly in the short-term.

Use of renewable energy (e.g. solar) power supply for both communication infrastructure and for charging devices.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Digital communication technologies are a key enabler for the use of digital technologies in the built environment. The capacity and possible upgrading of local infrastructure should be assessed early in the project to optimise opportunities during the project lifecycle.

All sectors may benefit from digital communication technologies. It could be argued that digital communication is an enabling technology that cross-cuts most other technologies as it enables connectivity.

Many of the direct implementation opportunities of digital communication technologies are already widely utilised. However, participation in planning and design process could be further exploited by conducting surveys / polls etc. through social media and other channels.

Dissemination of information or open source data is a considerable implementation opportunity. The Nepal Urban Resilience Programme, and other similar initiatives, could utilise digital communication technology to share/disseminate and validate data. The Prepare Pokhara – 2C (Secondary Cities) Project is one example that could inform this implementation opportunity by open sourcing data about public services.

POTENTIAL RISKS OF IMPLEMENTATION

Mobile communications may be used for other purposes that improve business and investment opportunities bringing positive economic benefits.

Communications technology may also be used maliciously for example in cyber scams.

Use of social media has been prolific in the organisation of public demonstrations, such as the Arab Spring, which has had far reaching consequences in recent years.

REMOTE MONITORING OF PRIVATELY-MANAGED RURAL WATER SUPPLIES, UGANDA

The unit allows users to pay for water through a secure payment facility with a "water key". Water keys are purchased by water users and then loaded with credit, transferred either via mobile money or directly from a "credit key" that is held by the Water Agent. Once inserted into the LIFELINK unit, a preset collection fee is deducted from the water key for each litre of water dispensed). The funds transferred and volumes distributed during each transaction are transmitted via GSM and recorded in an online database that can be viewed in real time. Alarms are generated and can be viewed online when satellite connection with the LIFELINK unit has been lost, when the actuated valve, modem or PLC fails and when the water reservoir is empty. The amount of credit remaining on the Water Agent's credit key can also be reviewed remotely. This technology keeps the Water Agent accountable by logging all credit transfers and allowing verification through comparison with both the amount of cash deposited in the specific TradeWater project bank account and with the value of water dispensed during each tapping session. Water Agent Managers are able to make informed decisions regarding water price and promotional activities based on information obtained.

Source: Grundfoss (2018)

HACKATHON DEVELOPS MOBILE PAYMENT FOR TOLL ROADS, CAMEROON

MTN ran a hackathon to encourage innovation in the use of mobile payments. A team from the Faculty of Industrial Engineering of the University of Douala developed a payment system for toll road charges with mobile money during the competition. This approach reduces the time spent by drivers at the toll gates throughout the country, protects revenue and ensures its traceability in real time.

Source: MTN, 2018

Computer Aided Design (CAD) and Building Information Modelling (BIM)

READINESS

CAD and BIM enable a digitally enhanced collaborative design and construction process. They are characterised by the creation and use of geometrically coordinated 3D objects which are linked to additional attribute information (e.g. date of construction) enabling digital models of coordinated physical and digital attributes/characteristics to be developed. The model is typically developed in a 3D software environment and can be used in many forms to represent the infrastructure designed. 2D drawings (typically used on site) can be extracted from the model or enhanced visualisations for public engagement can be created from the same model.

Building Information Modelling (BIM) enables the development of complex models that not only represent the geometric aspects of the assets (such as dimensions and geometry) but also the non-geometric attributes including information-rich models and object-based elements. BIM usually involves a project team working collaboratively using a Common Data Environment (CDE). A CDE is a single source of information used to collect data, manage and disseminate documentation (Designing Buildings, 2018). Appropriate application can create useful structured data which describes brief, design, manufacturing and operational scenarios (Arup 2018). CAD and BIM are widely used in large infrastructure projects, e.g. airports and multimodal transport nodes, where multiple disciplines and project partners can work simultaneously in the same model to reduce the risk of incompatible design components and easing transfer of data throughout the project cycle.

BENEFITS

Improved information management

Cost and schedule certainty though improved coordination and communication within the project team. Improved information management leads to fewer requests for information from the contractor to the designers during construction. Objects being modelled have data attributed to them which can be used within the operational phase.

Career progression

New skills in BIM modelling would be valued by new entrants to the profession as they seek to add value to their work. More widely, CAD may aid economic development in LICs. Modelling tools are now often used directly by the engineers themselves again providing greater skills and opportunities.

Improved decision making

Designers and the wider stakeholders (e.g. government, communities) are informed through better visualisation of the building or infrastructure design in 3D. More collaborative sharing of information enables better change management and interface decisions to be enabled via the CDE. History of change is also recorded within the CDE making decisions more transparent.

Hazard detection

Reduced coordination needed and greater awareness of hazard and clash management clash management. Visualising construction processes and helps risk managers foresee potential hazards to inform risk assessment and mitigation measures, reducing construction accidents and improving safety.

Increased productivity and accuracy

The combination and analysis of federated models (separate discipline based models which are grouped into to a single coordinated model) can prevent and reduce physical clashes between designs. They are potentially developed collaboratively by stakeholders in multiple locations. Clashes are captured in advance of manufacture or construction saving significant amounts time and money. Changes to designs are shared and impacts accounted for by all parties during design, and not on site when it is very costly to resolve.

1 2 3 4 5

LIFE-CYCLE STAGE

1 Planning

Limited use, however there are some benefits with complex infrastructure using low level of detail models at the planning stage. Projects of significant complexity may be less likely in LIC scenarios.

2 Design

The BIM approach is most useful during the design stage to develop a suitable coordinated (3D data rich) model of the project using collaborative methods of working. Change management and coordination is enabled by the approach and CDE, providing a more data rich deliverable for later stages. 2D drawings can be generated from the models with the necessary embellishments required for construction.

3 Construction

The model can be used and updated (as built) during construction. Models can be used for construction planning when linked to a programme and cost estimation if brought into a suitable cost model.

4 Operation

The data which is delivered via the BIM model can be used to update or create an accurate asset register of the building or infrastructure. BIM data is essential for operation and maintenance of the physical asset.

5 Evaluation

Data can be used to evaluate outcomes by comparing the design model with the construction model. More accurate costs and bills of quantities estimated using the model can aid evaluation and construction effectiveness

CONSTRAINTS	MITIGATIONS
Capacity - limited CAD/BIM skills and perceived poor user friendliness and interoperability of current BIM software (although this is improving). Resistance to spending time and money to properly train in multiple software and lack of facilities/courses for training.	Many open-source BIM courses and software are available online reducing the cost of training. The increased availability of BIM object libraries for building/ infrastructure assets, will speed up the use of federated models by multiple designers and contractors in time.
Inertia to change – a model-based method of working is a significant change to traditional 2D drawing methods. CAD requires a change of approach from the whole supply chain including procurement, engineers, manufacturers and modellers alike which is slow and potentially costly.	The consistent approach to sharing model data via a CDE potentially will be standardised across the world with the soon to be published ISO19650 standard suite (an international standard for managing information over the whole life cycle of a built asset using building information modelling).
IT license(s) for BIM tools can have a significant cost and need to be used throughout the whole team typically.	Mandates to use BIM approaches from governments and clients have changed the attitude and behaviours in the sector to adopt CAD/BIM more quickly.
Interoperability of different software is still limited which means that capacity in multiple modelling softwares is required.	Greater use of cloud based hosted CDEs could overcome the need for internal server infrastructure but requires good internet connectivity.
Digital technology infrastructure – data processing and efficient data exchange via the CDE are required for the modelling particularly which requires reliable and large bandwidth connectivity.	Establish BIM forums and task forces (e.g. UK BIM Task Group) in LICs could speed up adoption through cross sector/discipline support and learning.

THE AFRICA DESIGN CENTRE (ADC), RWANDA

In 2016, MASS Design Group launched the African Design Centre (ADC) in Kigali, Rwanda as a fellowship programme to empower and train leaders who will be designing sustainable, just and equitable projects in Africa. Initially, 10 Autodesk members went to Kigali for two 2 weeks to 1) train MASS Design Group staff and ADC fellows on Autodesk tools and human-centred design, 2) to improve the communication methods between MASS Design and local contractors in the construction sector, and 3) to build better connections between local communities and design and construction organisations.

The MASS design team uses the latest software to generate 3D models of their projects. However, once used on site, these models had to be translated again into 2D drawings with the limited use of mobile technology. Field marketing manager, Carrie Raynham of Autodesk (as published on BIM Plus), said that the implementation of BIM is not only about the adoption of technology, but it is also about the processes and the people. According to Carrie, one of the main benefits of this project is to explore how through the ‘processes’ and ‘people’ it could be possible to understand the challenges related to technology adoption.

Source: BIM+ (2016)

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Opportunities to include a requirement for a BIM approach to be adopted should be considered especially once ISO 19650 (an international standard for managing information over the whole life cycle of a built asset using building information modelling) is published. The use of BIM should be based on whether there is capacity within the supply chain and the necessary IT infrastructure to adopt the process.

Where supply-chain limitations exist, discuss the anticipated benefits from modelling with the likely supply-chain. These discussions should focus on how BIM could be used to mitigate any risks on the project, or exploit certain opportunities, and any constraints to achieving BIM’s use. New software is being developed at a fast rate and is increasingly user-friendly and adapted as appropriate. The Nepal Safer Schools Programme (NSSP) could implement CAD/BIM robustly due to the replicable nature of most school designs. In particular, retrofit solutions could be partially automated based on calibrated analytical models that determine the appropriate retrofit solution in response to an assessment of an asset. This could significantly reduce design time from days to hours. Standardised details could also be widely used to reduce the bespoke design and drawing work required for any individual school.

Encourage governments of LICs to consider the adoption of ISO 19650 on their public projects with a time bound mandate, giving the supply chain time to develop their capacity and processes to adopt. Potential pilot projects could be targeted where benefits could be realised with a willing supply chain in place.

Encourage the establishment of regional, national and/or sub-national BIM forums and committees to encourage adoption and share learning across sectors and disciplines. BIM forums have proven to be fruitful in the UK with the BIM Working Group.

CAD/BIM can be particularly useful for larger projects and programs (e.g. highways and railways) that may involve many parties and contracts to support consistency in data management across multiple contracts and disciplines. It can also be useful in infrastructure projects with several interfaces for example a new road which crosses energy and water utilities. The use of a CDE could also increase the efficiency of due diligence and documentation review to ensure appropriate standards are achieved. The Nepal Rural Access Programme (RAPS) could utilise CAD/BIM in conjunction with GIS analysis to plan, design, construct and monitor the range of roads and access routes being considered. This could be adapted into a database for the relevant public authorities to enable more effective asset management in the future, monitor usage and development in the vicinity of the access routes/ roads, and identify improvement / maintenance / repair works.

POTENTIAL RISKS OF IMPLEMENTATION

Dependence on a CDE can put additional pressure on limited bandwidth internet connections

Security of CDEs and the data contained is essential as with any IT system, especially where infrastructure of national importance are being constructed.

Imagery – Unmanned Aerial Vehicles (UAVs) and satellites

READINESS

Imagery, in this report, refers to capturing a snapshot of data of an area or item. The data captured may be more than a ‘photo image’ and can include other measurable characteristics such as: elevations, thermal gradient and noise levels. Typical imagery technologies include:

- Satellite-bourne remote sensors to capture high resolution imagery of earth;
- Fixed wing or rotary aircraft (sometimes drone) captured imagery; and
- LiDAR scanning (which captures point cloud data – a set of data points in space) to produce digital terrain models and surfaces after post processing.

Imagery has already been regularly applied to remote and hazardous environments particularly rural/remote environments with limited road transport infrastructure and local surveying skills; areas with natural hazards (e.g. earthquake-affected areas) or Fragile & Conflict-Affected States and therefore have the potential to have a high impact in LICs.

Although not related to imagery directly, drones and unmanned vehicles can also be used for transportation of light-weight goods and data collection devices via a remotely controlled or autonomous aircraft.

BENEFITS

Hazards and constraints can be identified prior to construction and can be resolved during the planning/design stages through analysis of recently captured imagery, which out of date mapping does not always provide. Detailed topographical terrain models and spatial data can be derived for project planning. During the construction / operation stage, drone and UAV captured imagery can be used to monitor progress and conduct inspections in difficult to access places (e.g. at height, on busy roads etc.) reducing the hazard to the workforce.

Decision-making agility - Provides a rapid evidence base for decision-making. Imagery technologies have also been integrated with machine learning to automate linked processes, there is some evidence of this starting to be achieved in LICs.

Efficient data collection - Fast real-time or retrospective data collection. Can be used in remote areas and over large areas if required. According to an article published by the World Bank (2017c), ‘Tapping the Potential of Drones for Development’, mapping using drones is particularly helpful when designing and implementation of large infrastructure projects that require extensive data collection, detailed mapping and regular inspections.

Cost - Depending on the context, imagery using aircraft could be cheaper than other available means.

LIFE-CYCLE STAGE

1 Planning
Provides an evidence-base of planning decisions, e.g. existing land-use data. The planning stage benefits most as the resolution and data tolerances of remote imagery capture meet most requirements at the planning stage compared to the design, construction, operation and maintenance or monitoring and evaluation which are likely to require a higher resolution image in comparison.

2 Design
Imagery can be extremely valuable for site understanding – gaining topographical data. However often the resolution and data tolerances are not high enough for detailed design. Currently, land based or lower elevation imagery capture survey techniques generally provide higher resolution.

3 Construction
Imagery and drones can be used to monitor progress especially in difficult or unsafe areas to reach by the construction workforce. It may also identify changes to the site including slope/creep identification.

4 Operation
Imagery and drones can be used to monitor and inspect the physical assets and notify users of deterioration, particularly in areas difficult to reach safely by operational workforce.

5 Evaluation
Imagery has been used to see the impact of developments over-time by comparison of past and present imagery, for example the number of buildings, agricultural expansion and/or (unfortunately) deforestation because of new infrastructure.

CONSTRAINTS

National policy/government regulations can restrict the use and capture of imagery.

Cost of equipment and imagery (dependant on type of technology chosen) as well as finding appropriately qualified operators.

Modelling integration can be complicated due to the significant amount of analysis and 'training' required for remotely sensed imagery to be of use.

Capacity - Frequently, case studies showed that digital imagery is coupled with use of Geographical Information Systems (GIS) which provides an environment for viewing, combining, managing & analysing data spatially. Skills are required to analyse the data through these means.

Aerial extent coverage (at a suitable resolution) is sometimes limited by different techniques and flight paths etc.

Manipulation of data requires significant computing power and specialist software which is not always available due to cost and capacity.

Suitable resolution, coverage and frequent enough commercial imagery for analysis may be lacking in certain countries due to the lower market potential for its sale.

MITIGATIONS

Encourage governments to develop policies for the appropriate use of drones/UAVs. For example, Rwanda is set to be the first country to legislate regulation for the commercial use of drones.

Use of online training resources for certain imagery analysis techniques and training of operations.

Drones should be used carefully following local airspace regulations with trained and licenced operators only.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Particularly useful in remote areas where traditional methods of land based topographical survey are challenging. Digital imagery may also have benefit in areas which have poor or out of date mapping available which would benefit from imagery analysis. The Nepal Safer Schools Programme (NSSP) could extensively utilise imagery technologies to conduct physical vulnerability assessments of school locations which would identify landslide, flooding, and other potential local natural hazard risks. In combination with GPS coordinates and GIS, algorithm analysis could rank the vulnerability of schools to natural hazards as part of a qualitative risk assessment. Similarly, the Nepal Urban Resilience Programme (NURP) could utilise imagery technologies to identify sites which are at risk of natural disasters.

Drones, satellites and UAVs may also be combined with other monitoring technologies to gather data other than imaging including weather data. However, again limited information could be found for such UAV monitoring directly relating to LICs.

Satellite imagery has been used to measure the emergence of lighting used during dark hours to assess the economic development in areas compared to the impacts of various events – ranging from road improvement works to climate change. The Cities and Infrastructure for Growth Programme (CIG) could use this extensively as a monitoring and evaluation tool to assess the economic development impact of various programme initiatives. Satellite imagery analysis can be relatively inexpensive compared to primary survey / data collection and can be conducted retrospectively if required which mitigates the risk of differing methodologies (or the absence of) baseline and post intervention survey data.

POTENTIAL RISKS OF IMPLEMENTATION

Drone flights or sightings may provoke anger and uncertainty in contexts where drones have military or government surveillance connotations. The use of drones or UAVs should therefore be completed following community engagement and communication of the purpose. It is also possible that data security may be compromised enabling military forces to gain information on possible targets.

Drones should be used carefully following local airspace regulations with trained and licences operators, failure to do so may result in a criminal offence depending on local law.

Privacy violation concerns and associated negative community reactions also present a risk when using drones.

LANDSLIDE DAMAGE ASSESSMENTS, SIERRA LEONE

Landslide damage in Freetown was assessed through pre- and post-event satellite or drone imagery with the Open Street Map building dataset with available Office of National Security (ONS) data and from field surveys by other consultants with a GPS-linked, GIS-based smartphone survey application.

World Bank, Arup, INTEGEMS (2017). Right: EDA, 2017.

DRONES FOR MAPPING ZANZIBAR, TANZANIA

The Zanzibar Mapping Initiative (ZMI) aims to create a high resolution map of Zanzibar and Pemba Islands using low-cost drones rather than manned planes or satellite images. Drones will also play a significant role in disaster situations for search and damage assessment which usually require labour-intensive helicopter and costly missions. Digitisation, including the use of drones, have been seen by the administration of the Zanzibar Isles as a key to unlock the islands' land value in order to drive investment and growth.

USING DRONES TO SUPPORT PROGRAM MANAGEMENT IN ROAD CONSTRUCTION, PAKISTAN

Drones were used to survey road construction in Pakistan as part of a DFID funded programme. Regular drone flights were used to quantify the extent of construction which could be compared to the schedule of works. Contractor payments were adjudicated based on this evidence as project progress was recorded transparently and efficiently. The data could also be used to inform stakeholders on progress.

Management Information Systems (MIS) and tools

READINESS

A well-structured and managed asset database enables improved planning and coordinating prior to construction in addition to operational monitoring and maintenance regimes. MIS systems can support collaboration between stakeholders as part of the delivery of a built or virtual asset. Examples of MIS systems include dashboards for project and asset management programs.

MIS tools involve the use of computer software/ databases and associated data sets to coordinate, control, analyse information, and ultimately inform decision-making, throughout the lifecycle of an infrastructure asset. This is especially beneficial for the management and maintenance of assets once constructed. Information should be collated and organised during the construction and design process and therefore should be specified as a deliverable to ensure its availability for operational use on commissioning.

In essence MIS gather and interpret data that then can feed into models and systems such as BIM to strengthen the delivery of infrastructure.

BENEFITS

Improved information management.

Physical assets data enable better planning of maintenance and operations.

Transparency

Allows decisions to be tracked in the project and during the operation and maintenance, to ensure budgets are appropriately spent.

Reduces waste

Ability to log the maintenance completed, defects found and therefore improves the life of assets.

Improved productivity

Reduces delays and mistakes to improve efficiency during the operational life as information about the asset, and previous maintenance / enhancements is available to the asset manager.

Communication

Should improve communication between implementation stakeholders as well as the wider community. This could also include marginalised groups.

1 2 3 4 5

LIFE-CYCLE STAGE

1 2 3 4 5 **All stages**

Can be used at all stages to help manage and record progress and decision-making and therefore inform future decisions. Many examples of the use of MIS can be found throughout the AEC industry in LICs throughout the lifecycle of an asset.

CONSTRAINTS

Collection of data and data entry.

Organisational/behaviour challenge. Requires a thorough understanding of the lifecycle of the project to identify what information is needed to make decisions and when, who and how the associated data can be collected.

Digital infrastructure required and needs to be kept up to date to ensure data security from cyber-attack and data corruption.

Capacity to model and establish the sometimes complex data hierarchies of infrastructure is not commonly available in the lower cost construction sector.

MITIGATION

Appropriate training.

Opportunity to enhance local digital infrastructure.

Use of standard/open data models for infrastructure.

Incorporate asset management theory to ensure a line of sight to organisational outcomes to encourage cultural change.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

MIS can create considerable efficiencies within and between programmes and portfolios of programmes throughout the design, construction and monitoring stages. Centralised monitoring of construction progress is being used effectively by DFID's Pakistan Safer Schools Programme (PSSP) and much of this learning could be transferred, for example, to the Nepal Safer Schools Programme (NSSP). In Pakistan, this has reduced payment lags by several weeks which is a considerable advantage in a cash flow sensitive environment as subcontractors can be paid without delay. On-time payments result in debt reductions and ultimately the financial risk of a project.

MIS can contribute significantly to institutionalisation by providing one repository of data that can be shared / transferred to the relevant public authorities. The Nepal Safer Schools Programme could utilise MIS to create a central database of all school attributes. Ideally this database would align with the existing Ministry of Education database and the potential World Bank initiative to catalogue the structural integrity of all schools nationwide.

Data controls and cloud-based hosting are essential to any MIS. DFID programmes should seek to ensure that data entry rules are carefully established with limited free text entry and that data is reliably hosted for longevity and to avoid the risk of data loss.

POTENTIAL RISKS OF IMPLEMENTATION

The increased efficiencies in automated administration, for example invoicing and payments, may lead to a reduced need for traditional administrative/ support positions. If managed incorrectly automated roles may lead to redundancies and negative impacts on the workforce. Employers should proactively seek to upskill or reskill workforce to meet additional challenges of digital technologies.

Any proactive effort to increasse the quality and quantity recodred data must also adapt and adhere to strict data control protocols to ensure personal and/or sensitive data are either not recorded or securely stored.

FIELDSIGHT TOOL

FieldSight is the first humanitarian digital platform designed for project monitoring and infrastructure quality assurance. The tool was designed for Contractors, NGOs, and other implementing partners who had limited technical expertise in construction or project implementation techniques, especially when using new techniques. The FieldSight technology is available free and open source for any organization to use. Organizations with the capacity to develop monitoring content and educational materials can set up an account. The platform is now being used to monitor more than 50,000 houses, WASH sites, schools, police stations, and other infrastructure. Built to work on mobile devices and in remote and difficult-to-access locations, FieldSight creates actionable data and interfaces that help partners deliver higher-quality, lower-risk projects.

Sources: FieldSight, 2018

Internet of Things (IoT) and big data

READINESS

Internet of Things (IoT) and big data have been combined in this section as they are often used in combination to monitor and rapidly evaluate infrastructure or building performance by collecting data which can inform decision-making on an asset.

There is no single universal definition of IoT or big data, in this report we will adopt the following:

- **IoT** is a system of embedded sensors and electronics connected to an IT network. Across this system widespread collection of real time data can be obtained remotely and continuously.
- **Big data** refers to the analysis of large and diverse data sets to infer patterns and trends which can inform decisions or behaviour. Therefore, diverse data sets can be linked and collated informing decision-making at scale with higher precision.

To date, there has been considerable application to transport and energy infrastructure enabling users and decision-makers to monitor infrastructure and optimise its use (e.g. Google Maps for real-time travel durations). Embedded sensors and the subsequent analysis of the data streams resulting can enable the evaluation of infrastructure or buildings performance, in differing conditions to determine if this is occurring as per design expectations.

BENEFITS

Informed decision making

Rapid evidence/monitoring base from the real-time sensors.

Transparency

Decisions can be based and evidenced by the larger quantity data available and its enhanced analysis.

Reduced waste

IoT sensors are often used for building management systems to reduce resources being wasted. Sensors have already been applied to the identification of water pipe leaks and unnecessary use of electricity for heating, however there is no evidence at present of this currently being used in LICs.

Efficient data collection

Large scale, does not require costly and infrequent surveys to be conducted. The use of IoT and/or big data improves data continuity and improves safety by reducing field operative visits. The use of IoT and big data can also be used to gain public opinions and improve community engagement, but community engagement is not necessarily a universal feature.

Energy efficiency

Sensors can help users make better decisions about energy use for example heating, ventilation and cooling systems.

1 2 3 4 5

LIFE-CYCLE STAGE

1 Planning

Provides a clear, transparent evidence base for decision-making on the viability of projects and helps estimate future impacts (but only based on existing infrastructure or available datasets e.g. passenger / traffic).

2 Design

Where data can be obtained from the monitoring of previous buildings/infrastructure, improvements can be made to future designs. Data can also be used to better understand local conditions, for example local flood data, to improve designs.

3 Construction

Sensors can be used to collect data to help evaluate project progress, monitor the impact on existing infrastructure, construction noise levels and pollutants potentially. Limited evidence of use of IoT and big data analysis during the construction phase has been found in LICs.

4 Operation

Large quantities of data can help us understand how well a project is operating. For example, mobile GPS trackers can help us understand travel routes and timings which can help inform maintenance scheduling. IoT sensors embedded into buildings or infrastructure can also be used to monitor the performance or operation of assets once constructed.

5 Evaluation

Data analytics could potentially be used to understand the impact of projects on the local economy, industry or society. For example development resulting from improved transport to an area. Limited long-term studies in LICs have been found, most likely resulting from there being a limited reliable length of dataset available (if at all) in most LICs. It also provides information on who is using the infrastructure, as well as when and how.

CONSTRAINTS

Limited data currently available

Digital technology infrastructure reliant on power source / maintenance and data storage.

Strong data governance is required as significant data sharing and storage is required.

Processing power available for analysis is often significant and costly

Limited data science skills or installation capability.

Standardisation required for larger applications.

MITIGATIONS

Look for opportunities to work with research organisations (e.g. universities) in LICs to develop IoT and data science skills & networks locally initially, including sharing lessons learnt widely to develop best practice for the context.

Use of solar panels for power source and backup battery/generators to enable sensor operation to be maintained at the location.

Use of cloud computing with solar/wind/hydro power can help reduce the impact of resource requirements where data is stored at the centre.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Most likely implementation opportunity is within the planning phase of major programmes; big data rather than IoT is more likely to be of use when planning. IoT would generally require new infrastructure (IoT sensors) to be deployed before tangible results could be ascertained. However, big data may be available through existing sources (e.g. mobile phone usage) and could be used by programmes like Cities and Infrastructure for Growth (CIG) to gauge population distribution, commuting patterns, and congestion to inform efforts that increase urban productivity.

IoT sensors will most likely be restricted to modern building environments or small-scale infrastructure such as new commercial or residential development or specific control structures on a river , electricity generation and distribution, weather stations as they usually need to be included within the design, and costly to retrofit. IoT sensors can have a significant benefit in terms of reducing the operational energy costs of heating / cooling compared to other applications.

Consistent power supply, digital communications and associated maintenance regimes will be required for the maximum effectiveness and to achieve long term benefits of IoT and the analysis of the data. Digital infrastructure is less likely to be available in LICs, and so limits the application of IoT and big data (Miazi et al 2016).

Big data will have limited applications in LICs due to the lack of embedded data capture infrastructure, however there is often a high adoption of mobile phone use (World Bank, 2018), which can be analysed (but usually locational accuracy is limited). There is also a commercial sensitivity and privacy considerations releasing such data by telecom companies, and so its analysis may not be possible.

Longer term consideration of data storage is required as IoT sensors create large quantities of data (Miazi et al 2016).

POTENTIAL RISKS OF IMPLEMENTATION

IoT can have some privacy/security issues. For example, knowing when people are inside/outside of the building.

If data is made open source there is limited control on how the data may be used; this can present privacy violations if private data is accidently shared or mis-used.

BIG DATA FOR TRANSPORT PLANNING AND LAND USE MAPPING USING MOBILE PHONES, HAITI

The mobile network is being used for a big data pilot in Haiti. The study which aims to carry out innovative analysis of call data records to provide valuable inputs for strengthening urban transportation and land use planning. These inputs can help planners unlock the economic potential of Haiti's cities and expand job opportunities. From the call data records, the pilot will identify key intra-city connectivity challenges, producing an employment accessibility analysis for the country's two biggest conurbations, Port-au-Prince and Cap-Haitien. Scenario analyses will be conducted to simulate potential interruptions in mobility between different parts of the cities, including from hazard and disaster events (such as flooding), and their impact on access to jobs. This will help identify key corridors that require resilient strategies to ensure people can reach employment in the event of a disaster.

Source: Monroe (2017)

BIG DATA TO DRIVE PRIVATE WATER INVESTMENT, UGANDA

Waterfund, with IBM acting as calculation agent, will work with the Ugandan Ministry of Water and Environment to calculate the cost of producing water in Uganda through the analysis of unstructured public data text. This work will reflect estimated water production costs measured and be published as part of the Rickards Real Cost Water Index. By calculating the cost of water a more accurate risk and economic assessments of future infrastructure can be made helping to inform investment and reduce uncertainty.

Source: AllAfrica (2013)

IOT FOR FLOOD MODELLING, NEPAL.

In Nepal, researchers from Imperial College London are installing low cost sensors linked together though a large IT network. This IoT system will help to measure flood levels, creating online data platform to involve local people throughout the project life-cycle, and creating a mobile app where local communities can upload pictures of floods in their areas, which will in turn be sent to researchers in London for assessments.

Source: Interviewee

Modular and Prefabrication Construction

READINESS

Modular and prefabrication construction describes pre-built units, usually produced off-site in a factory that are delivered to site and assembled in to larger components. A group of modular units is usually a self-supporting structure, but tall buildings may still require an independent structural frame.

Modular construction is particularly beneficial where low cost multiple, repeated units are required in close proximity. Therefore modular construction is particularly suitable in low-rise building construction; for example redesign of informal settlements, small buildings in rural settings, as discussed later in this report.

While modular construction is more of a construction method, than a digital technology, in recent years the processes involved in delivering modular construction have been ‘digitalised’. Modular construction can be coupled with BIM, robotics and Management Information Systems (MIS) to enable efficient and high-quality delivery of modular units to site. It is this definition that is used throughout this section.

BENEFITS

Reduced hazards

Safer, and potentially healthier, working environment with the controlled and repeatable production of structural elements. Although, there could be an increased hazard risk on-site with larger elements being handled / assembled.

Reduced waste

Offsite construction allows more accurate procurement of materials and manufacturing methods may allow reduced resource use and on time delivery.

Increased productivity and potentially improved safety

Manufacturing a structure offsite in a factory under controlled conditions and thereafter transporting it to be assembled onsite can be more efficient than traditional construction. It also reduces disruption on site and construction should be more rapid.

Improved quality control

Structures and components can be manufactured with precision to the design tolerance in a controlled offsite environment.

LIFE-CYCLE STAGE

2 Design

Modular designs are often more homogenous and therefore cost effective if standard structural modules are being used. Can promote the use of standardised designs rather than bespoke (if conditions allow).

3 Construction

Predominately useful during construction for providing elements of the building/infrastructure.

4 Operation

Structural elements should have similar aging characteristics and so should require similar maintenance regimes/monitoring.

CONSTRAINTS

Local supply chain – significant initial cost required to create the infrastructure for modular/prefabricated structures.

Poor transportation – may be unsuitable in rural environments.

Poor physical environment understanding means that standardised components may not be suitable for a unique physical environment.

Behaviour change – lack of demand and need to meet building regulations in the local context which may be slow to respond to change. Risk of poor utilisation.

Capacity to assemble and handle larger structural elements on site.

Late changes are difficult to accommodate.

MITIGATIONS

Consider modular construction and prefabrication only in areas with good transport logistics available

Build the infrastructure and local workforce capacity for prefabrication during large suitable projects (possibly with foreign investment).

Document and record benefits on pilot test site to encourage acceptance.

Using BIM/CAD may reduce late changes and help accommodate them quickly late in the process.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Could create logistics challenges in remote areas.

Modular construction may offer opportunities for housing programmes like those of the Community Led Infrastructure Finance Facility (CLIFF). However, supply chain constraints, the desire for labour intensive construction, and the incremental nature of housing are all limiting factors. Individual products, like sandwich panels for roofing, may be viable sub-industries worth promoting where existing relatively high cost material products could be refined and improved to address thermal performance or energy consumption in production.

Modular or prefabricated systems continue to provide viable solutions for post disaster / humanitarian shelter programmes – like those currently underway in the Rohingya refugee camps in Cox's Bazaar. In this context, modular construction could be used to reduce waste by standardising the components used.

In remote or insecure areas, modular construction offers advantages due to the potential lack of local materials and speed of construction. Health facilities and schools, for example, can rapidly be deployed with limited on-site construction time. Rapidly deployable and demountable health facilities are one example of where modular construction can be used on a 'temporary' basis and could be utilised by DFID's humanitarian response activities. However, it may require increased and more costly logistics (moving larger parts) and challenges with difficult terrain and inadequate land or water transport routes.

Within larger projects, modular construction methods offer a large potential for improving site health & safety, construction speed and quality with this approach if the logistical and setup costs can be overcome.

POTENTIAL RISKS OF IMPLEMENTATION

Majority of the labour is away from the site location. Therefore, local on-site job creation could be limited during construction phase.

Increased transport on already congested roads, with heavy loads potentially damaging unsuitable infrastructure.

If construction locations are extremely remote or in areas with poor terrain, windy roads, there is a risk large components may not be able to be transported.

SWISS CUBE SYSTEM, RWANDA

The Modern Brick Multiplex System is a standardised structural design for urban low-rise buildings, using RCC-reinforced Rowlock-Bond made of Modern Bricks. In addition a platform offers access to information on various sectors and products in the Great Lakes Region relevant for building material producers, contractors, developers and authorities. Key features include real-time data on brick supply, downloadable demand and supply scenario projection tools.

Source: Made in Great Lakes (2018)

POST-DISASTER HOUSING, HAITI

Housing solutions tailored to specific user and site contexts were provided to shelter the population affected by the 2010 Haiti earthquake using a combined set of rules.

Figure: Rule System Tree Diagram

Source: Benrós et al (2011) and Gunawardena et al (2014)

3D/4D printing

READINESS

3D printing is a process of producing 3D physical object(s) by adding thin layers of material under computer control using a digital file. 4D printing is a similar process to 3D printing but uses materials that change their shape due to a stimulus (e.g. temperature or light). To date use of 3D/4D printing in LICs in the built environment has been limited, but other sectors, such as health, have demonstrated wider uptake and therefore demonstrates potential for use in the built environment. Use of 3D/4D printers within construction are largely still in the research phase but could provide solutions to rapid construction of low cost housing constructed within a few days using this technique. This has the potential application within informal settlements and post disaster to provide appropriate shelter faster than conventional building methods and in harder to reach places.

3D/4D printers can currently print many materials including concrete, glass, ceramics and many types of plastic and metals. Various composite materials have been developed enabling a greater variety of materials to be used including wood. These objects can be printed in any shape depending on the constraints of the printer (e.g. size, flexibility of the material used).

These technologies have been combined in the analysis.

BENEFITS

Flexibility

The variety of materials and forms that can be produced is developing at a fast-pace, as the technology develops, there has been greater flexibility in the type of product that can be created as current constraints are researched and solved. 4D printing allows elements to change as required with time.

Time-to-market

Data files can be produced quickly and given that the manufacturing process is flexible to the form, prototyping and manufacturing processes are accelerated.

Reduced waste

Lean production methods can be used as the object can be designed for a specific purpose. Printers may also be designed to use local materials/waste as the construction material.

Community Engagement

Prototype models can be made to help communicate ideas to community stakeholders.

Increased safety

3D/4D printers have the potential to remove the role of humans in construction from being on site to a quality control and management role. 4D printing enables the material to change due to a stimulus which could be used to increase safety of a structure during extreme events.

1 2 3 4 5

LIFE-CYCLE STAGE

1 Planning
3D/4D printed models can be used to rapidly support decision-making during planning phases as it allows for the ability to create physical scale models.

2 Design
Prototyping using 3D printing can inform decision-making, similar to the planning stage.

3 Construction
Small parts can be printed during the construction process. 3D/4D printing may aid productivity and provide solutions to complex construction problems by providing bespoke parts for a specific application. Buildings and houses have been built using concrete additive techniques with non-standard forms.

4 Operation
Small parts can be printed when required if elements of the infrastructure/building are damaged. 3D/4D printing could enable maintenance to be completed quickly before larger issues occur. This could be particularly helpful in remote locations challenged by logistics and underdeveloped supply chains. As the object can be designed specifically for the application this may be useful in unique retrofit scenarios.

5 Evaluation
Data from the 3D/4D printing can be used to evaluate the building/infrastructure for example the volume of material use, construction time, which elements fail frequently and need to be redesigned etc.

CONSTRAINTS

Cost – the initial expenditure for the equipment. It may also be difficult to obtain or maintain the equipment locally.

Materials – not all construction elements can use additive printing techniques.

Scale of fabrication may be limited.

Digital technology infrastructure reliant on power source / maintenance.

Quality control needs to be maintained by trained individuals during the process.

Standardisation and regulation currently limited.

Educated/trained staff needed for operation.

MITIGATIONS

Look for opportunities to work with research organisations to develop local best practice and capacity building.

Investment opportunity to support initial equipment costs and enable usability between differenct projects in the same area (e.g. that where appropriate a health program and built environment program can both use the same hardware.

3D PRINTED HOMES

NewStory and ICON have designed and built homes for low income communities. They state that this innovation will cost $4,000 per home, take 12-24 hours to print the home and will be better quality. It is planned these will be tested in El Salvador in 2018-2019. Once tested, they plan to democratise the technology to other non-profits and governments to scale around the world.

Source: NewStory, 2018

USING 3D PRINTERS IN HUMANITARIAN CRISES

3D printing has been in humanitarian crises to make small parts for a variety of applications from making toys, medical parts and to fix infrastructure. After the Nepal earthquake, a 3D printer was used to make washers and fittings for pipes. NGOs believe the technology could radically change the speed and cost of humanitarian aid.

Source: The Guardian, 2015

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Small products (e.g. pipe connections) can be adapted to the locality and context – therefore the 'one size fits all' approach to current material selection does not have to be used. 3D/4D printers come in many different types and sizes and can be used for a variety of uses. The type of printer should be carefully considered for optimal functionality. Printers may also be used to support innovation in other sectors (e.g. medical, education etc.). This could be applied in humanitarian crises or in remote locations where market/logistic systems are underdeveloped or have been disrupted (see example 2 below). DFID could utilise 3D/4D printing across a range of programmes. The Emergency Preparedness Response Project being implemented by WFP Nepal could consider 3D/4D printers as part of the forward logistic bases to produce (rather than store) a range of products that may be required for disaster response. This is particularly relevant if supply chains are obstructed following a disaster.

3D/4D printing is closely related to automation, robotics and prefabrication and these should be considered in parallel with the use of 3D/4D printing methods.

Quality control and regulation is needed. Trained staff will be needed for monitoring and inspection needed during construction. Currently limited standards for 3D/4D printing and careful consideration of the context would be needed.

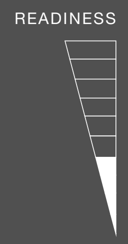
Currently most printing requires polymers which may not be available in the local market and may need to be imported. Production of local polymers and/or development of alternative printing materials (e.g. concrete or rubble) is currently being developed and may make this technology more readily available.

3D/4D printing will most likely be restricted to small elements of modern buildings and infrastructure. However, recently small buildings have been manufactured using 3D printers and the technology is still in development, so there is potential for 3D/4D printing to be used in the built environment if the necessary enabling infrastructure is put in place (BCG, 2018). This could be used for rapid small house construction in informal settlements or as part of providing shelter following disasters (see example 1). DFID's Nepal Safer Schools Programme could utilise 3D/4D printing for small, specialist construction tools or materials but the relative cost of transport may render this poor value for money.

POTENTIAL RISKS OF IMPLEMENTATION

There are several security threats that are well documented. These include: printing objects to avoid international sanctions; to support the exploitation of other technologies for malicious intent - for example making UAVs, weapons and keys (Geneva Centre for Security Policy, 2014)

Virtual/Augmented Reality (VR/AR)



Virtual reality (VR) and augmented reality (AR) relate to enhanced environments between the real and the virtual/digital worlds. The term 'extended reality' (XR), relates to all combinations of real and virtual environments including Mixed Reality (MR), VR and AR. This report only discusses AR and VR, which demonstrate potential for application in LICs, although little evidence was found about their current use. This technology is of relevance to construction, where VR/AR is used in combination with BIM models which form the basis of the digital twin environment used.

- VR immerses users in a fully digital environment; artificially providing sights, sounds and other sensory experiences. While there is currently no evidence in LICs, VR has been used for health and safety training in the built environment particularly for working at height. It is also beneficial for the training of construction workers, so that they are familiar with the planned construction activities in advance of the works.
- AR can allow the user to experience virtual imagery while at the same time seeing a real image. This can be achieved through overlaying images or objects virtually. AR can be used to support decision-making, for example the 'virtual' overlay of services and utilities behind a physical 'real' surface on a site to understand what is hidden behind before conducting any work.
- Mixed reality (MR) relates to the spectrum of reality and involves a mixing of AR and VR providing both artificial sensory stimulation and virtual overlays in a real environment

VR and AR are frequently related to headsets and controllers which are used for experiencing these digital environments. It appears likely, particularly as the cost of equipment is decreasing, that VR/AR could provide a more collaborative 'digital-physical' working environment than the use of monitors/screens that are currently typically used for sharing ideas in digital modelling environments. There is application potential in low income countries for the future for example remote working and training.

BENEFITS

Informed decision making

Improved decision-making as users can see designs/drawings at a more 'human scale'. This is likely to lead to fewer mistakes being made. This technology enables greater stakeholder engagement in a more interactive environment than 2D plans and 3D physical or computer models.

Hazards

Hazards that have previously been missed may be spotted as users experience the design differently.

LIFE-CYCLE STAGE

1 Planning
VR/AR is beginning to be used in the built environment particularly in large infrastructure and bespoke/high-end building projects. VR/AR technology can enhance user consultation with key stakeholders to help identify design issues earlier in the life cycle. This has potential use for designing for people with disabilities and women to experience using an asset before it is built, who may not otherwise be trained in reading engineering drawings. Other benefits include a greater ability to identify hazards and improve safety.

2 Design
Can be used to visualise designs especially by future operators and maintenance managers of the facility, who can advise their suitability, and influence the design at this earlier stage.

3 Construction
Can be used to visualise planned construction activities and potentially support health and safety of workers. Also working in existing facilities with models can use AR to identify potential services behind surfaces.

4 Operation
Can be used to find additional information (e.g. the location of a utility behind a wall using AR). The BIM model can be used in advance of operations for safety or operational training using the VR model.

5 Evaluation
Can be used for validation of construction during commissioning or post occupancy through comparison of design model in VR versus the actual build on site.

CONSTRAINTS

Modelling integration - greatest constraint appears to be due to the limited use of CAD and multi-dimensional modelling which is often used concurrently with VR/AR models.

Equipment needed is usually of high cost and requires specialist knowledge to set up.

MITIGATIONS

Cheaper open-source options becoming available that can be attached to smart devices.

Other tests should always be completed such as use of remote scanning devices (e.g. CAT scans), AR/VR should only augment existing safety procedures before completing work.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

VR/AR appears to be used rarely in LICs due to in part to the cost of equipment, although less sophisticated versions can be attached to smartphones (e.g. Google Cardboard). However, the greatest constraint appears to be due to the limited use of CAD and multi-dimensional modelling which is often used concurrently with VR/AR models. There are limited implementation opportunities currently.

POTENTIAL RISKS OF IMPLEMENTATION

May impact on human behaviour/health if used extensively.

URBAN 95 VR EXPERIENCE

The Urban95 virtual reality experience was born from a desire to help improve, through urban planning, policy, and design, the living conditions of young children and their caregivers living in urban environments. To encourage the new thinking required to transform urban environments into child-friendly cities, Arup in collaboration withe Bernard van Leer Foundation designed a virtual reality (VR) experience to help people with the power to change cities experience what it’s like to be small in a big city.

Source: Arup (2019)

Blockchain and distributed ledgers

READINESS

Blockchain has been termed 'the internet of value, ownership and trust, allowing individuals to have full rights and control over an asset and be able to transfer it without having to rely on a third-party intermediary'. Blockchains are decentralised and public ledgers of transactions which can potentially benefit many sectors and applications (Arup, 2018).

Blockchain has largely been associated with cryptocurrencies such as Bitcoin, to securely store transactions of the digital currency as an alternative to financial institutions. Examples of block chain application in the construction sector are limited, however early systems are being designed to support: land tenure, educational qualifications, material logistics and smart contracts[2].

(2) Smart contracts enable the facilitation, verification/accountability and ultimately enforcement of a contract by embedding the contract in code avoiding the need for third parties. These transactions are irreversible and trackable.

BENEFITS

Transparency

Transparency through trusted, secure and accessible data such as land registries (see example), professional certification, construction material tracking, contracts and other related transactions. There is great potential in time to disrupt the corruption that exists currently in these critical areas of the infrastructure lifecycle through paperless simple authentication.

Improved information management

Blockchain can improve information management expertise due to the interconnectivity and security required.

Improved communication

Information on the ledger can be owned by the user rather than hosted on an external platform or relying on a third party. The user can have greater ownership and access.

Hazards identification

If inconsistencies occur (e.g. due to a cyber-attack) distributed ledgers can support faster recovery.

1 2 3 4 5

LIFE-CYCLE STAGE

1 Planning

Data on assets (e.g. land registrations, utilities etc.) can be held in distributed ledgers providing greater confidence and transparency of data. Smart Contracts may also be stored and upheld through blockchain ledgers.

2 Design

Currently of limited use during the design stage.

3 Construction

Items on a construction site and associated transactions/ certification, approval of testing and construction material logistics (often shipped from overseas into LICs). It may also be liked to automatic payment systems.

4 Operation

Transactional storage of large volume datasets would be stored in the distributed ledgers.

5 Evaluation

Monitoring data is stored in blockchain ledgers would be more accessible and trusted potentially.

CONSTRAINTS

Capacity – with the technology being so early in its evolution there is only limited expertise to set up and write the code for these highly complex distributed networks and their associated security. They run the risk of being easily hacked otherwise.

Energy/Infrastructure – connectivity and the large reliable energy requirements to run the distributed ledgers is a major constraint to their setup in LICs.

Limited scalability currently due to the benefits or application not yet adopted widely outside of cryptocurrencies.

Costs associated with blockchain technology are currently significant as any application would still be an early adopter in addition to the significant infrastructure and energy costs.

MITIGATIONS

Wait until the technology has matured and adopt only the successful application of blockchain technology related to the infrastructure lifecycle.

Typically to be used only in countries with an abundance of low-cost energy (such as hydroelectric, solar or geothermal sources) – potentially attracting blockchain innovators to set up in these countries.

Promote the education of blockchain expertise in LIC institutions as a potential for entrepreneurs in the built environment.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Blockchain technology is too early in its evolution currently. Blockchain should be monitored and benefits established in applications beyond cryptocurrencies, especially land tenure.

POTENTIAL RISKS OF IMPLEMENTATION

Sustainability – currently uses significant internet bandwidth and energy consumption and its associated carbon footprint.

Security – relying on these distributed ledgers, relies on the quality of the code written. Any weakness in the blockchain may result in it being hacked and the trust in the data destroyed and corrupted.

USING BLOCKCHAIN FOR LAND REGISTRY, RWANDA

The first phase of the Rwanda Blockchain project will see the Rwanda Land Registry digitised to ensure control of authenticity. This will use WISeKey's WiseID suite of mobile applications and digitally store necessary land registry data to enable authenticity of identification and the validation of assets.

Source: IAfrican, 2017

Artificial Intelligence and Machine Learning (AI/ML)

READINESS

Machine learning is the use of statistical techniques and algorithms to give computer systems the capability to "learn" with data, without explicit programming (e.g. gradual improvement of performance on a task). Artificial intelligence is a broader field of computer science where computer systems simulate human intelligence.

Application of AI/ML is vast, from language processing (turning words in to actions/outcomes) to robotic control. The development of AI/ML has been fuelled by: increased computational power, significant increase in the availability of data and the development of knowledge through learning from past evidence and automated data collection rather than reliance on rules and scientific reasoning solely. AI/ML can be used for a specific problem (often called 'narrow' AI) or for general reasoning (referred to as general or broad AI).

Research suggests that although AI/ML could have considerable influence in the lifecycle of assets in the built environment, currently its adoption has been very limited in LICs. This is due to a lack of data being available for the systems to process, which in turn is typically due to a lack of internet, skill, finance and often governance. AI/ML can be used in the post processing of remote sensing imagery which can have wide applications in LICs potentially to create land use, vector road networks or building outlines layers for example.

BENEFITS

Higher accuracy in decision-making

Computer systems can process large quantities of data to highlight trends or patterns. AI/ML is likely to increase accuracy as 'real data' is used rather than estimates or 'rule of thumb'.

Integrated information system

AI/ML can support an increasingly integrated technological system helping integrate many technologies together.

Hazard and O&M management

Hazards and maintenance tasks may be identified as data can be compared to data collected during previous events. AI/ML could also be used to improve quality control as defects are observed.

Productivity

ICTs boost productivity and reduces transaction and information costs. They allow new models of collaboration that increase workers' efficiency and flexibility along the supply chain. This is especially true in the post processing of remotely captured imagery analysis which is traditionally laborious.

1 2 3 4 5

LIFE-CYCLE STAGE

1 Planning

AI/ML can be used to understand changes in supply and demand over time and therefore supports decision-making on projects (see IoT and Big Data). It may also be used to test the impacts of planning decisions based on historical data.

2 Design

Designs can be based on data collected from similar infrastructure which have been monitored and operation analysed over time.

3 Construction

AI/ML can be used to alert staff to abnormalities locally. For example, warning staff about potential slope failures of earthworks by using data from pressure sensors.

4 Operation

AI/ML can alert operaters to system failures, / purchase replacement parts and be used to analyse video / imagery for patterns and trends. May be more worthwhile for large infrastructure projects and buildings.

5 Evaluation

Through the analysis of large sets of monitored data e.g. IoT sensors, CCTV video during the life of a piece of infrastructure / building, its effectiveness in operation could be evaluated to lead to performance improvement.

CONSTRAINTS

Education & high-level capacity to train and establish AI/ML systems.

Energy/ digital technology infrastructure.

Processing power needed to perform AI/ML tasks.

Policy/governance needed particularly for use of open data.

Needs reliable and accurate data.

MITIGATIONS

Some open source software already available.

Couples with IoT and big data.

ANALYSIS AND RECOMMENDATIONS FOR DFID INFRASTRUCTURE PROGRAMMES

Implementation opportunities are limited at this at this time due to the early stage of development of the technology. Currently, ML/AI is most likely to be useful to support monitoring systems in the construction and operation phases.

POTENTIAL RISKS OF IMPLEMENTATION

Decisions could be based on unreliable data sets and therefore could lead to unwanted outcomes. Therefore, it is essential that the data is carefully assessed initially, and the trends and patterns identified from the data then analysed.

Digital unconscious biases may also develop, e.g. gendered prescriptions have been studied in the built environment. Machine logic can indiscriminately infer truths from data, which may uncover and embed problematic prejudices at the heart of contemporary society. The artificially intelligent tools that we use daily have been found to amplify and sediment existing gender inequalities.

IMPROVING ROAD CONDITION SURVEYS IN TANZANIA THROUGH ML

To pilot new solutions to development financing and urban planning, Planet and the World Bank leveraged Planet's frequent high-resolution satellite imagery, ground truth data from the community-based initiative Ramani Huria (Swahili for "Open Map"), and advanced deep learning techniques to automatically detect building development in Dar es Salaam as well as measure urban density.

The project was comprised of two applications: one for automatic detection of building footprints and the other for measuring building height. Combined, these two indicators help provide an understanding of Floor Space Index, which governments, NGOs, and international development institutions use to understand how much land is available for development and to determine what is planned and unplanned.

Source: Planet, 2019.

Conclusions and Recommendations

1 Adoption of the innovations chosen in this report and the access to them vary greatly across LICs.

Digital innovation in the built environment in LICs is deeply dependant on the local context; including the proximity to digital commerce, energy and digital infrastructure; and cultural appetite to embrace new technologies.

In some contexts there may be opportunities for traditional infrastructure delivery methods to be replaced by more progressive digital technologies. However, leap frogging opportunities are highly dependent on the context.

Many digital innovations require, or are perceived to require, significant initial investment before the value is gleaned. Prior to technology implementation, analysis can be performed to identify opportunities, barriers and possible mitigating measures to support successful technology adoption. During the analysis implementers should be aware of the potential risks of implementation and unintended consequences; such as exploitation of personal information or data in the case of IoT or security concerns with drones and UAVs. Unintended consequences should be mitigated early on and monitored throughout the lifecycle of the technologies use.

2 Improvements to the enabling environment and tailoring efforts to individual countries (or regions) will allow for broader, faster and more successful adoption of digital innovation in the built environment in LICs.

Where the benefits of technology will add value to the asset and end user outcomes, the focus should be on reducing the barriers to adopting these technologies and adapting them to fit the context of LICs. The most common constraints to all these innovations relate to the enabling environment local culture, professional training, education (with potentially the exception of digital communication technologies due to their user-friendliness) finance, governance and energy/digital infrastructure. Developing energy infrastructure and professional training should be a focus on all projects as they are common barriers to all digital technology application and are fundamental to many other elements of the 'enabling environment' including local culture and behaviours/organisation environment. The relatively young population profile across LICs offers potential to capitalise on 'digital natives'.

3 In all digitalised and non-digitalised built environment projects, the six enabling environment aspects identified should be prioritised.

Despite the enabling environment being a considerable barrier in many contexts, improving the enabling environment will allow the later uptake of the digital innovations identified in this study and potentially unlock other new technologies. All these aspects would also develop the digital capabilities of the local context both within the built environment and beyond.

4 Technologies which exhibit high benefits, high readiness and comparatively low constraints will be more easily and successfully adopted.

Of the technologies addressed in this report, four technologies have been identified with good potential for success in LICs, including: 1) Computer Aided Design (CAD) and modelling, 2) Digital communication technology, 3) Imagery – including Unmanned Aerial Vehicles (UAVs) and Satellites, and 4) Management Information Systems (MIS) and tools.

5 The extensive benefits of these technologies encompass social, environmental and economic spheres which can contribute to inclusive economic development and poverty alleviation.

Adoption of digital innovation in the built environment of LICS is an opportunity to: increase productivity and therefore the rate of economic growth in LICs; to bridge the digital divide between HICS and LICS, to reduce inequality and leave no-one behind; to leap frog stages of development and encourage development efficiencies; and avoid path dependency mistakes of energy and resource intensive development models.

6 The consequences of introducing technologies too early in development could have considerable negative impacts to local behaviours, culture and future adoption so it is important that well tested technologies are used in LICs.

The four digital innovations with good potential for success are well tested in many different contexts and lessons learnt are well recorded. Some of the other technologies covered in this document are very early in their development, for example blockchain and artificial intelligence. Digital innovations in the built environment should be applied in a sensitive way, considering local needs and challenges, making use of contemporary design approaches to introduce the innovation in an iterative and adaptive way, maximising learning and minimising any negative effects (see Principles of Digital Development, 2017).

7 Conversely, technologies which demonstrate limited benefits currently may not be prioritised but in a rapidly changing digital world new and emerging innovations should be constantly evaluated and their progressed monitored and supported for appropriate application to development challenges.

These include 3D/4D printing; Artificial Intelligence and Machine Learning (AI/ML); Blockchain; and Virtual/ Augmented Reality (VR/AR).

8 Modular construction has, potentially, the greatest 'ecosystem' constraint to all the technologies identified above.

The scale of project that modular construction technology is applied to will be critical to its uptake as considerable investment in the enabling environment is required, including the supply chain, processes and training.

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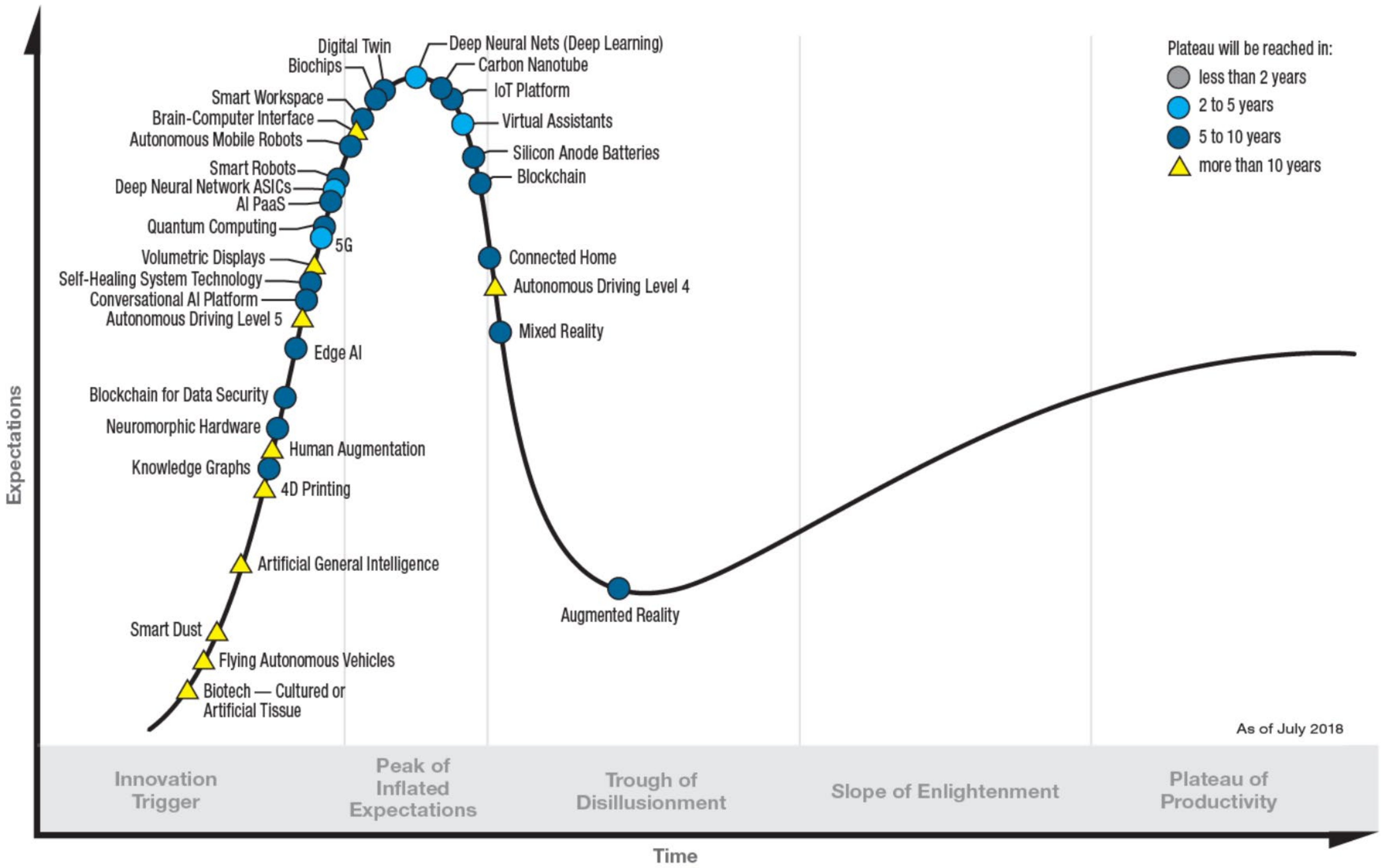
Annex 1: List of technologies

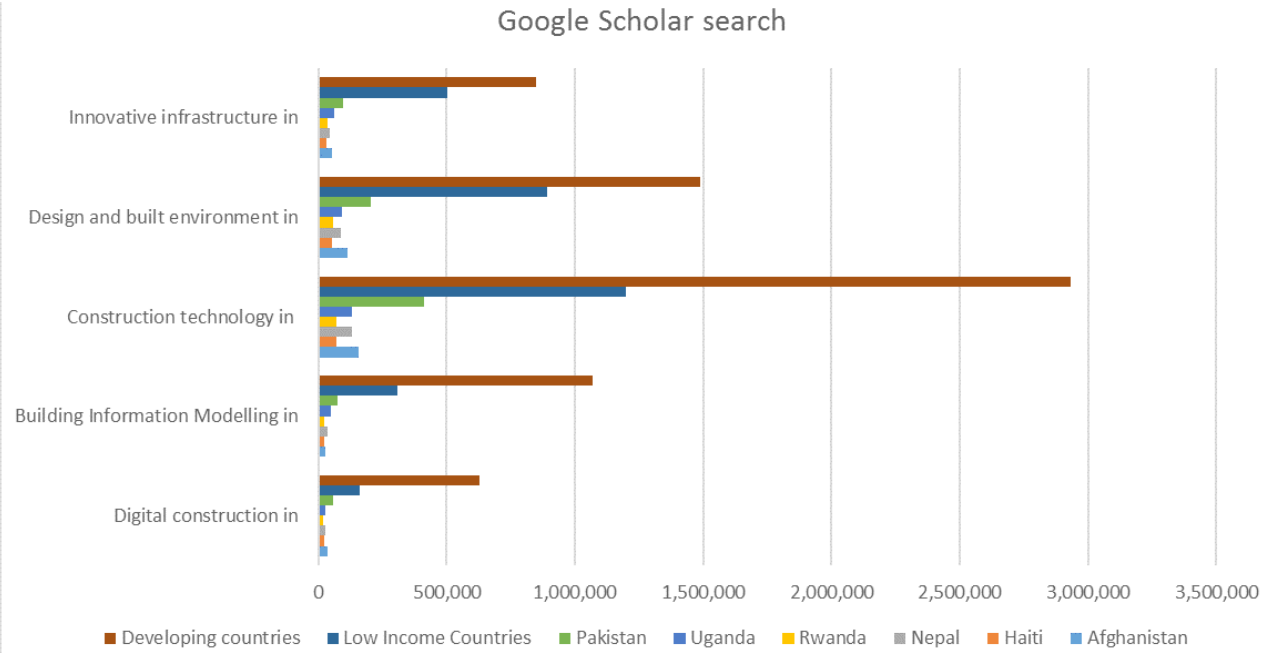
List of technologies and relevant analysis here (incl. Gartner hype cycle)

THEME	TECHNOLOGY SECTION
Biotech	Not covered – limited applicability currently in the built environment
Flying Autonomous Vehicles	Imagery – including drones and Unmanned Aerial Vehicles (UAVs)
Smart Dust	Internet of Things (IoT) and big data
Artificial General Intelligence	Artificial Intelligence and Machine Learning (AI/ML)
4D Printing	3D/4D printing
Knowledge graphs	Artificial Intelligence and Machine Learning (AI/ML)
Human Augmentation	Not covered – limited applicability currently in the built environment
Neuromorphic Hardware	Not covered – limited applicability currently in the built environment
Blockchain for Data Security	Blockchain and distributed legends
Edge AI	Artificial Intelligence and Machine Learning (AI/ML)
Autonomous driving	Not covered – limited applicability currently in the built environment
Conversational AI platform	Artificial Intelligence and Machine Learning (AI/ML)
Self-healing system technology	Links to Internet of Things (IoT) and big data
Volumetric displays	Not covered – limited applicability currently in the built environment
Quantum computing	Not covered – limited applicability currently in the built environment
5G	Digital communication technology
AI PaaS	Artificial Intelligence and Machine Learning (AI/ML)
Deep Neural network ASICs	Not covered – limited applicability currently in the built environment
Smart robots	Linked to modular construction.
Autonomous mobile robots	Linked to modular construction.
Brain-computer interface	Not covered – limited applicability currently in the built environment
Smart workspace	Links to Internet of Things (IoT) and big data
Biochips	Not covered – limited applicability currently in the built environment
Digital Twin	Relates to artificial intelligence, machine learning, IoT, MIS and associated analytics.
Deep Neural Nets	Artificial Intelligence and Machine Learning (AI/ML)
Carbon Nanotube	Applicable to the built environment but related to material science not digital technologies.
IoT Platform	Internet of Things (IoT) and big data
Virtual Assistants	Linked to Digital Communication.
Silicon anode batteries	Not covered – limited applicability currently in the built environment.
Blockchain	Blockchain and distributed legends
Connected home	Internet of Things (IoT) and big data
Autonomous Diving Level 4	Not covered – limited applicability currently in the built environment
Mixed Reality	Virtual/ Augmented Reality (VR/AR)
Augmented Reality	Virtual/ Augmented Reality (VR/AR)

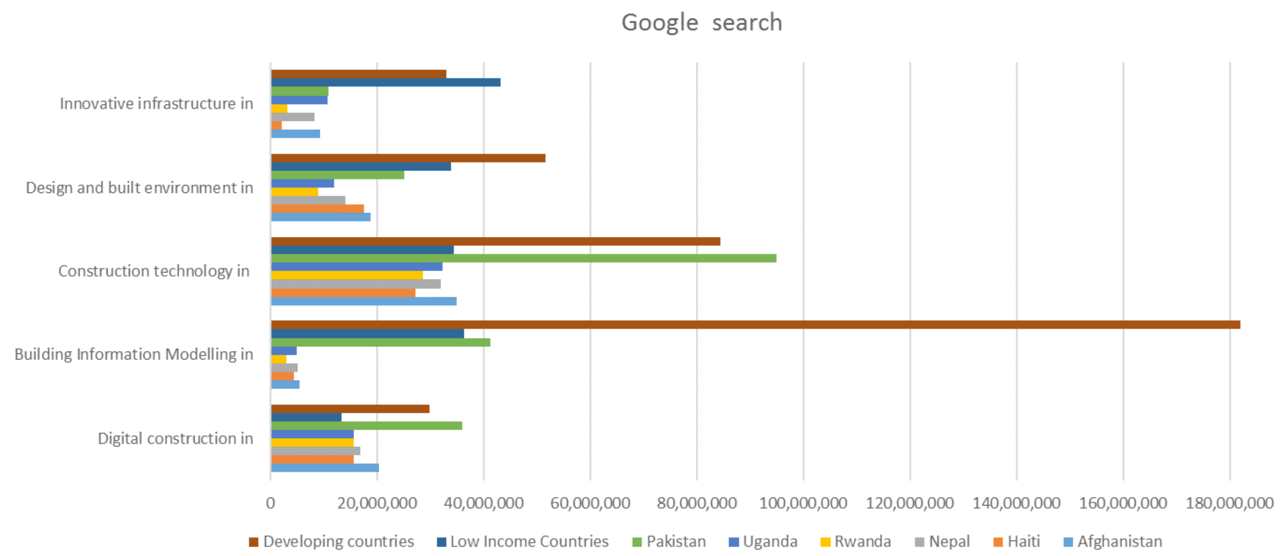
Hype cycle for emerging technologies



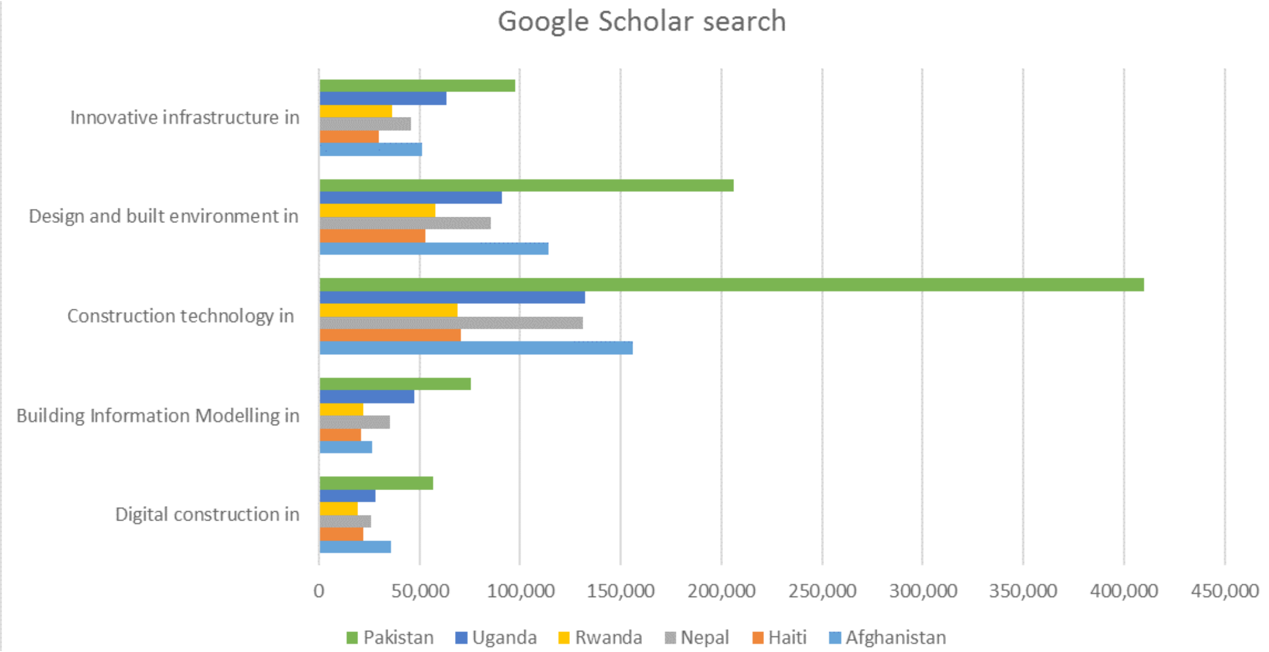
Annex 2: Literature Review Overview



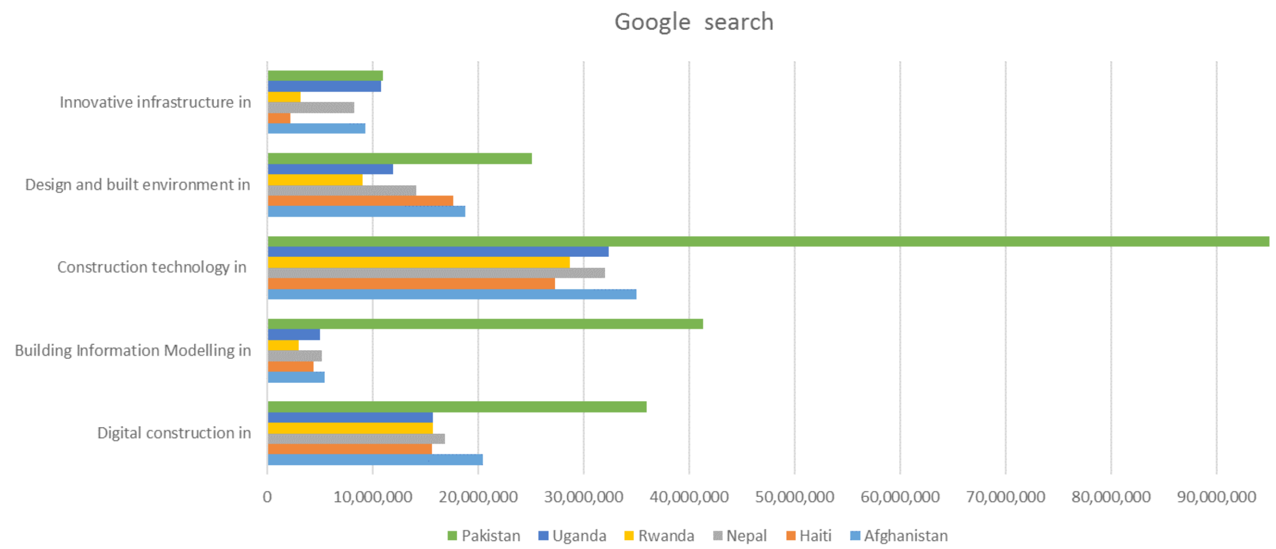
Overview of literature review – search terms and hits on Google Scholar (with LICs and Developing Countries search)



Overview of literature review – search terms and hits on Google Scholar (with LICs and Developing Countries search)



Overview of literature review – search terms and hits on Google Scholar (with LICs and Developing Countries search)



Overview of literature review – search terms and hits on Google Scholar (focused on six countries)

Annex 3: Consultation List

The following individuals (in no particular order) were consulted as part of the project:

NAME	POSITION	LOCATION	INSTITUTE / ORGANISATION
Caroline Ray	Regional Director for East Africa	UK	Arup
Dominic Cox	Project Architect and Skills Mentor in CAD, BIM and Document Control	Kenya	VVecotrProjects Kenya / Triad Architects
Mark Harvey	Head of Profession (Infrastructure)	UK	DFID
Shiraz Shahid	Infrastructure Adviser	Pakistan	DFID
Eleanor Bainbridge	Infrastructure / Urban Adviser	Nepal	DFID
Jonathan D. Paul	Research Associate	UK	Imperial College London
David Mathu Njuguna	Research Manager	Kenya	National Construction Authority
Prof Jim Hall	Director of the Environmental Change Institute, Professor of Climate and Environmental Risks	UK	University of Oxford
Kaitlin Shilling	Associate Principal (International Development)	Australia	Arup
Edmore Hove	CAD Manager	Zimbabwe	Arup
Fredrick Mukonoweshuro	Associate (Project Management)	UK	Arup
Brian Kimbui	Electrical Engineer (Buildings)	UK	Arup
Purnell Krams	Civil Engineer (Rail)	UK	Arup
Siraj Tahir	Environmental and Civil Engineer (Flooding)	UK	Arup
Hayley Gryc	Associate Director (International Development)	UK	Arup
Dr Chaminda Pathirage	Senior Lecturer/ Director of Postgraduate Research Studies	UK	University of Salford
Dr Kemi Adeyeye	Senior Lecturer	UK	University of Bath
Dr Patrick Manu	Senior Lecturer in Construction Project Management	UK	University of Manchester
Dr Eshrar Latif	Lecturer	UK	Cardiff University
Dr Eric Kofi Kontoh	Researcher	Canada	St. Catharines
Prof Bingunath Ingirige	Professor of Urban Resilience and Adaptation	UK	University of Salford

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