Digital Built Environment and Data Science

SIG – Digital Built Environment and Data Science

Council of Heads of Built Environment “CHOBE Report”

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Executive Summary

From the preparation of the client brief, through conceptual and detailed design, to the construction and operation stages, various digital and data science technologies in integration with BIM processes have provided technical and management support to solve complex and multidisciplinary problems for all project stakeholders; e.g. clients, engineers, managers, contractors, and the supply chain.

The integration of Construction Data Modelling (e.g. BIM and the relevant construction data sharing and exchange technologies) with Data Analytic techniques enables the development of new graduates' skills which are in high demand for the new normal business practices in construction and built environment.

The findings of this report suggest that the integration of data science in built environment education is still in its infancy, and more needs to be done to ensure that the scope of data science is fully understood and embraced. The current trend of emphasising BIM in MSc programmes is not sufficient to fully integrate data science in built environment education. Other digital technologies need to be incorporated to provide future built environment professionals with a comprehensive understanding of how the integration of these technologies can lead to a productive, technologically advanced industry.

As a general understating on how Data Science is seen by built environment educators, Data Science knowledge can be categorised into two main domains as: Basic to Advanced knowledge and Soft to Hard knowledge which can cover all possible approaches to explicitly incorporates Data Science into various structures of built environment curricula

For the levels of learning outcomes to be achieved by built environment curricula, these can be defined on four levels: Awareness, Application, Competence, and Transformation. At the initial level of Awareness, the fundamental theories and use of Data Science are provided to the learners so that they know and understand Data Science. At the Application level, the learners are expected to solve close-ended built environment problems within given boundaries. These Awareness and Application levels of Data Science content can be introduced at the undergraduate level together with a broad range of built environment subject areas.

At the Competence level, learners are exposed to real-life scenarios expecting to make judgments within the actual environment. And finally, the Transformation level is intended to enable learners to make critical judgements based on sound Data Science knowledge and context and this specialisation can be achieved at the postgraduate level.

This proposed mapping of Data Science in Built Environment Education allows educators to map their programme with the intended level of cognitive complexity in Data Science content within their programme. This can be used to design learning objectives, assessments and activities that target required levels of cognitive complexity.

1. Introduction & Background

Digital platforms enable greater connectivity of production and construction processes by simulating, predicting, optimising and monitoring various sustainability targets within the Architecture/Engineering/Construction/Facility Management (AECFM) industries towards connecting the real and digital worlds. Such platforms are key in accomplishing sustainable engineering projects. In addition, modern economic visions always address the link between Data Analytics and Smart Cities as one of priority areas of concern.

The use of disruptive technologies is bolstering the construction industry with innovations such as: Building Information Modelling (BIM) technologies, Digital Twins, drones, radio frequency identification (RFID), pulsed radar object detection, smart wearables, immersive solutions (VR/AR/MR), 3D printing, big data, data analytics, AI, Internet of Things (IoT), modular construction, smart materials, and all related technologies to digital/circular economy and industry 4.0. With these recent developments, the construction industry has started its digital transformation journey. From the preparation of the client brief, through conceptual and detailed design, to the construction and operation stages, various digital and data science technologies in integration with BIM processes have provided technical and management support to solve complex and multidisciplinary problems for all project stakeholders; e.g. clients, engineers, managers, contractors, and the supply chain.

Various governmental, academic and industry agencies were established to disseminate and share the experiences in this field; including Centre of Digital Built Britain, BRE Digital Construction, BIM Task Groups, BIM hubs, UK BIM Alliance, etc. This also resonates with the aim of "Infrastructure Sensing" in the Research Council UK Collaboratorium for Research in Infrastructure & Cities[1] which has the ambition to underpin the renewal, sustainment and improvement of infrastructure and cities in the UK. With the continuous developments in the Internet of Things, many software vendors and highly innovative technology companies with specific interest in Digital Construction and BIM (e.g. IBM, Oracle, AutoDesk, Teckla, etc.) are heavily investing in these technologies. In addition, all education institutions (including Architecture and Built Environment) have started to develop curriculums that prepare new graduates with more advanced digital skills to face new challenges. In general terms, this approach has shown a growing interest in many fields and the JISC Building digital capability Framework[2] has defined six key elements to be fulfilled by digital leaders and staff with an overall responsibility for developing digital capability in their organisation.

Within the field of Built Environment, the majority of UK courses (and almost worldwide), cover this area within construction/project management programmes with a focus only on applying and managing various digital technologies, but with little capacity to deliver the breadth of knowledge and skills required for this field. In this sense, this Special Interest Group (SIG) ***"Digital Built Environment and Data Science"*** sponsored by the Council of Heads of Built Environment (UK) has taken a step forward and explored how Digital Built Environment should consider areas of Data Science to enable graduates obtain advanced knowledge and analysis skills in addition to applying and managing the technologies

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[1] https://www.ukcric.com/

[2] Building digital capabilities framework - Jisc data analytics (August 2022), https://repository.jisc.ac.uk/8846/1/2022_Jisc_BDC_Individual_Framework.pdf

themselves. The integration of Construction Data Modelling (e.g. BIM and the relevant construction data sharing and exchange technologies) with Data Analytic techniques enables the development of new graduates' skills which are in high demand for the new normal business practices in construction and built environment. Two recent industry reports on Digital Sustainability[3] on Smart Sustainability[4] have alluded to the importance of data analytics in enabling effective decision making, especially from a sustainability perspective. As outlined in the former, "*The deployment of data-driven solutions such as sensors, building information modelling (BIM), digital Twin, track-and-trace, material passport, 3D printing, and robotics is set to unleash an era of value-driven data analytics. This in turn takes a step beyond delivering insights toward achieving optimized decision-making based on artificial intelligence (AI) and machine learning (ML)*".

2 Data Science in BE curriculum: state of the nation

Despite popular narrative, the utilisation of BIM and data science are still not widely popular in the BE education. In this section we attempt to present the state of the Built Environment subject with respect to using digital construction including BIM and other data science content within the Masters' curriculum.

The recent Guardian University ranking list was utilised to identify 48 higher education institutions in the UK that offer MSc degree programmes in the building, construction, and planning fields of study. Initially, masters' programmes related to the built environment subject were identified within each higher education institution. This resulted in 75 programmes that provided masters level education in Built environment subject. Each programme was then reviewed individually for digital construction, BIM and data science content based on what was provided in the programme documents. With CMA regulations, the website content closely represents what is delivered in the programmes.

These programmes and associated higher education institutions were then classified into following categories as shown in Figure 1 and 2. The investigation of these 48 institutions revealed that 14 of them do not offer any modules related to Digital Construction within their MSc course content. Among the remaining 34 institutions, digital content was found to be embedded within the course contents of 29 institutions. However, it was observed that their focus was primarily on Building Information Modelling (BIM), with digitalisation being wholly or partially viewed in the context of BIM integration. This concentration on BIM is a trend that has been observed across the built environment education sector, with the majority of institutions emphasising BIM in their MSc programs. Importantly, two institutions were found to have attempted to expand beyond the confines of BIM in built environment education. These institutions have included specific modules related to data science, which represents a significant step in the integration of data science in built environment education. Moreover, a single institution was found to offer a wholly data science focused MSc degree course in the built environment education field.

[3] https://damassets.autodesk.net/content/dam/autodesk/www/campaigns/emea/docs/FS_WP_Autodesk_DigitalSustainability.pdf

[4] https://www-smartinfrastructure.eng.cam.ac.uk/system/files/documents/smartsustainability.pdf

	DESCRIPTION	UNIVERSITY CODE
	The Master of Science courses "entirely" focused on data science in the field of building, construction surveying, and planning.	3
	The Master of Science courses "in part" focused on data science in the fields of building, construction surveying, and planning.	28
	The Master of Science Courses have specific "modules" on data science in the fields of building, construction surveying, and planning.	40, 41
	The Master of Science courses contain no data science content but are entirely or partially focused on digitalisation/BIM.	1, 2, 4, 5, 6, 8, 9, 10, 11, 12, 14, 15, 17, 18, 21, 22, 23, 24, 25, 26, 27, 30, 33, 35, 36, 37, 38, 39, 42, 45
	The Master of Science courses contain no data science or digitalisation content	7, 13, 16, 19, 20, 29, 31, 32, 34, 43, 44, 46, 47, 48

Figure 1: Data science in Built Environment Education in the UK – an analysis

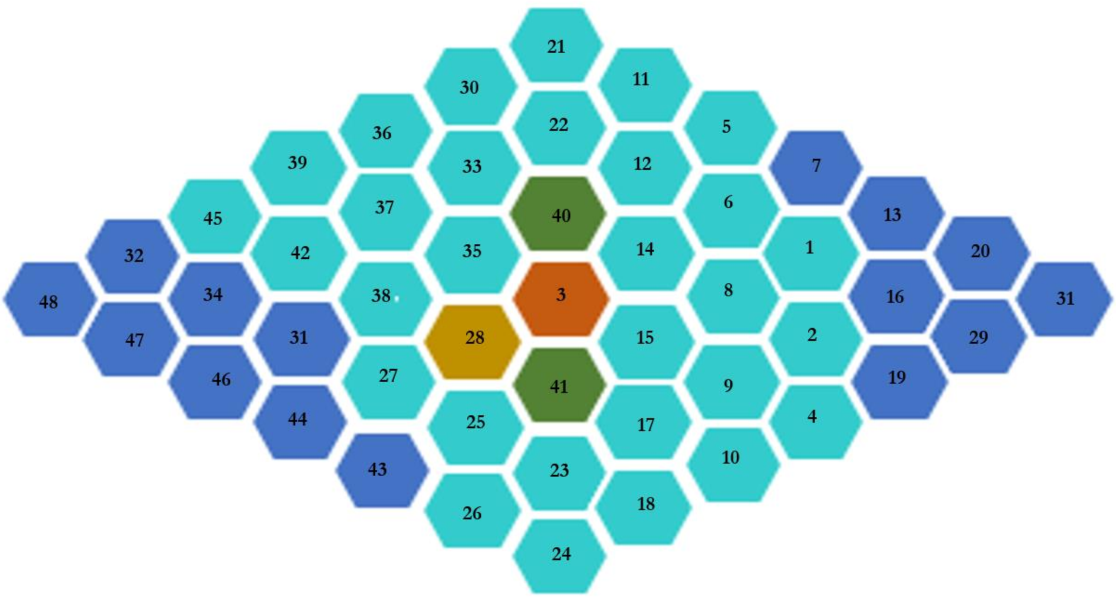

Figure 2: Data Science in BE curriculum: state of the nation

The preceding findings suggest that the integration of data science in built environment education is still in its infancy, and more needs to be done to ensure that the scope of data science is fully understood and embraced. The current trend of emphasising BIM in MSc programmes is not sufficient to fully integrate data science in built environment education. Other digital technologies need to be incorporated to provide future built environment professionals with a comprehensive understanding of how the integration of these technologies can lead to a productive, technologically advanced industry.

3 Where we are with Computing in Architecture

3.1 Contextualisation – Evolving Attempts at Integration

The discussion on data science or computing in architecture and other engineering disciplines is not new but has used different terminologies over the past 50 years. This commenced in the early 1960s with a clear recognition of the value of research in design and where an era of knowledge started to emerge, where no one would venture to act based on simple of intuition or common sense.

The Conference on Design Methods is widely acknowledged as one of the very important beginnings to think about design as it relates to research and information gathering and the need for knowledge. This conference represents the foundation of DRS or Design Research Society, which is still functioning and active through its annual conferences and the journal of Design Studies. The Conference sat the first stage in the development of design as a multi-disciplinary collection of complementary perspectives (from industrial design, industrial and systems engineering, architecture, and construction) discussing the vital importance of the design function in engineering activity. The conference was held between the 19th to 21st September 1962 in "*premises made available by the Department of Aeronautics, Imperial College, London.*" [5]

A couple of years later, one of the pioneering attempts to integrate data into a programme that enables the design of single storey layouts in hospital buildings was a PhD conducted the University of Liverpool with B. Whitehead (supervisor) and M.Z. Eldars (the PhD Student) and part of it was published in the journal of building science in 1964, volume 1,[6] which became journal of building and environment.

Specifically in architecture, the efforts have evolved into various areas, all of which introduced theories and advocated the need for data as generators of architectural design. These efforts have culminated into a series of studies and books; some examples that are not exclusive, but important and critical, are outlined here:

After about 10 years efforts at the UC Berkeley Centre of Environmental Structure, The Pattern Language coined by Christopher Alexander and colleagues in 1977 – to represent a formal/functional relationship that accommodates a recurrent human situation. A pattern language is an organised and coherent set of patterns, each of which describes a problem and the core of a solution that can be used in many ways within a specific field of expertise.

[5] See Design Research Society: https://www.drs2016.org/drs-history/2016/3/16/icl-1962
[6] B. WHITEHEAD and M. Z. ELDARS, Build. Sci. Vol. 1, pp. 127-139. Pergamon Press 1965 https://www.sciencedirect.com/science/article/abs/pii/0007362865900149 https://doi.org/10.1016/0007-3628(65)90014-9

Interestingly, the work of Alexander is well known to, and cited more by, computer scientists than architects or urbanists.[7]

The need for knowledge and data in design expanded in the theories and source books during the 1970s with the emergence of concepts and ideas related to pre-design activities where building briefs and programmes should be based on users and contextual data and where the building performance concept was coined, as evident in the work of Tom Markus and the BPRU or Building Performance Research Unit at the University of Strathclyde[8] and the work of Henry Sanoff and the Community Development Group at North Carolina State University Raleigh, North Carolina.[9] Most of the work of both was centred on schools and affordable housing.

The Social Logic of Space, conceived by Bill Hillier, Julienne Hanson, and colleagues at the Bartlett, University College London, introduced a new theory of space: how and why it is a vital component of how societies work.[10] The theory was developed based on a new way of describing and analysing the kinds of spatial patterns produced by buildings and towns, which led to the space syntax theory (and later a software package) that became widely used in understanding spaces in buildings and cities--their connectivity, fragmentation and integration among many other qualities.

Another endeavour, The Logic of Architecture by William Mitchell, was the first comprehensive, systematic, and modern treatment of the logical foundations of design thinking. It provides a detailed discussion of languages of architectural form, their specification by means of formal grammars, their interpretation, and their role in structuring design thinking. This led to his subsequent work in the 1990s including the City of Bits (Mitchell, 1995) where he examines architecture and urbanism in the context of the digital telecommunications revolution, the continuing miniaturisation of electronics, the commodification of bits, and the growing domination of the digital over the physical. Other books of William Mitchell include E-Topia (1999), ME ++ examine the way in which an electronically connected world will shape cities of the future and the associated urban relationships, with a focus on digital infrastructure and its implications for future daily lives.[11]

The preceding efforts were feeding into what is called "Computational Design" or Design Computing and the development of simulation tools and software packages underpinned by some of the preceding theories. Efforts have gone into many different directions where several scientific events on CD were critical for the adoption of computation-based approaches in architecture. Following the 1962 conference which I mentioned earlier, the 1st International Congress on *Performance* (1972) began the discussion on applying computation to simulate building performance. Other CD-related international conferences were consistently held in the following decades. Similarly, several scientific journals, such as

[7] Alexander, Christopher (1977). A Pattern Language: Towns, Buildings, Construction. Oxford University Press, Cambridge, MA, USA.
[8] Markus, Thomas (1972). Building Performance (Building Performance Research Unit, University of Strathclyde). Applied Science Publishers, London, UK
[9] Sanoff, Henry (1977). Methods of Architectural Programming. Dowden, Hutchinson and Ross, Pittsburgh, PA. USA (Re-published in 2018 by Routledge, London).
[10] Hillier, Bill and Hanson, Julianne (1984). The Social Logic of Space. Cambridge University Press, Cambridge, UK.
[11] See Mitchell WJ: City of bits: space, place, and the infobahn. Cambridge, MA: MIT Press. 1995; Mitchell WJ: E-Topia: Urban life, Jim—But not as we know it. Cambridge, MA: MIT Press.1999; and Mitchell WJ: Me++: The cyborg self and the networked city. Cambridge, MA MIT Press. 2003.

Automation in Construction (1992), *International Journal of Architectural Computing* (2003), and *Journal of Building Performance Simulation* (2008), exclusively focused on CD research. Others gradually incorporated CD topics, such as *Architectural Design* and *Design Studies* (1979). Figure 3 shows a diagram developed to demonstrate a timeline of CD-related conferences and journals.[12]

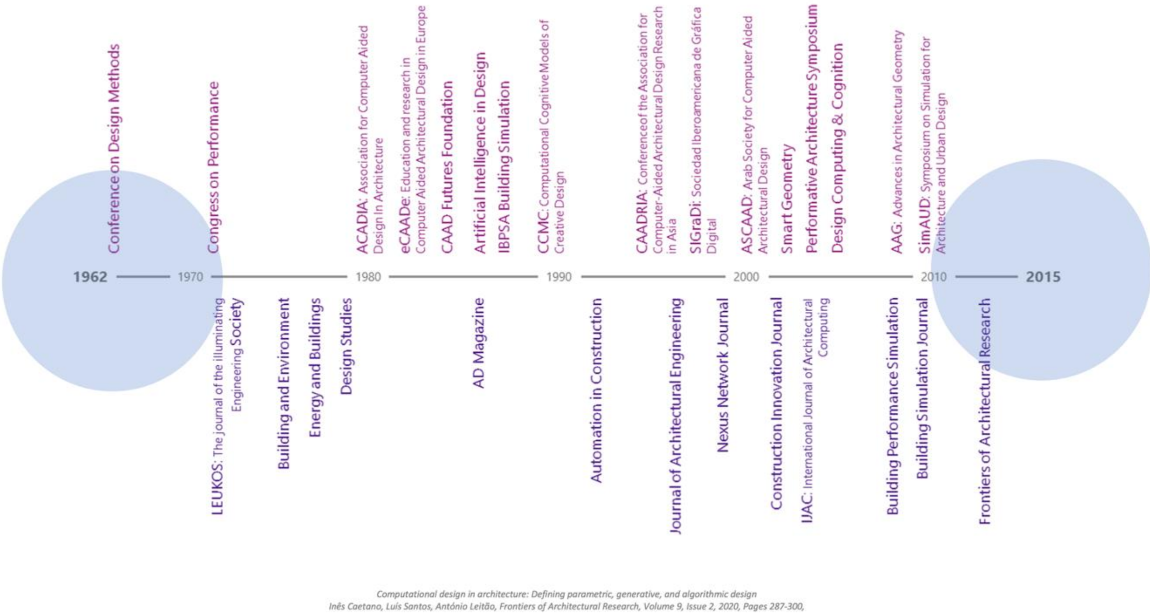

Figure 3: Timeline of CD-related conferences and journals

3.2 Contemporary Developments

Data science was applied directly to architecture and urban design through a number of efforts underscoring certain angles of what is digital. This can be best explained by three design approaches or typologies[12].

PD: Parametric Design

An approach that describes a design symbolically based on the use of parameters. It is regarded as a design process based on algorithmic thinking that uses parameters and rules to constrain them. For example, instead of designing walls using exact positions, lengths, heights, and thicknesses, these properties are replaced by symbolic parameters that have specific domains.

GD: Generative Design

An effort to aim at the development of systems which can develop, evolve, or design architectural structures, objects, or spaces autonomously. The use of the "virtual space of the computer in a manner analogous to evolutionary processes in nature – The development of "systems which can develop, evolve, or design architectural structures, objects, or spaces more or less autonomously (…)." For many scholars ---

[12] Inês **Caetano**, Luís **Santos**, António **Leitão**, Frontiers of Architectural Research, Volume 9, Issue 2, 2020, Pages 287-300

these systems are evolutionary-based and search a design space for solutions that meet formal and performance requirements.

Algorithmic Design

A design process based on algorithms. The scope of AD overlaps with those of PD and GD, generating some inconsistencies in the understanding of AD. For example, some authors state that AD includes GD, others mention that AD and GD are the same thing.

Some architectural examples of AD applications include the recent work on Sagrada Familia done by Burry and Burry (2006 - ongoing) and the Morpheus Hotel by Zaha Hadid Architects (2013-2018). In both cases, the implemented algorithms preserved the traceability properties between the program or algorithms and the product of their execution to generate forms and shapes and produced consistent results (Figure 4).

Figure 4: Cases of Algorithmic Design

3.3 The Way forward

Despite all these efforts which span over 60 years, digital architecture and design have not managed to penetrate the thick skin of traditional architectural education which still relies on legacy models inherited from the enlightenment and industrial revolution. Research into pedagogy in architecture and design reveals that in many cases, this language and this thinking is introduced in very specialised master programmes or as option studios or classes in the final senior years. But notably utilised as an outcome of using a software package but the underpinning concepts and theories always taking a back seat.

Recent research work highlights some of the individual efforts in pedagogical research which reflected the need for the digital to have room within architectural and design pedagogy including ideas about paperless studios, collaboration in virtual environments, ideas related to digital communities and so on.[13] This leads us to pose a number of points that enable capturing the way forward with CD and data analytics in architecture.

- ***A.*** Data analysis in architecture helps to visualise, present, and communicate the essence of an architectural design. Data analysis in architecture can help designers make better decisions about where to build, what type of materials to use, and how much of each material to use. But if one doesn't know how to analyse data, it's unlikely that they will be able to make the right choices.
- ***B.*** The key point to understand about data analysis in architecture is that it's about understanding the context in which decisions are made. This is one of the biggest reasons why data analysis is useful: it gives us the ability to make better decisions in the future.
- ***C.*** Data analysis can help determine if the proposed project is feasible, whether it is structurally sound, and whether it fits into its surroundings.
- ***D.*** The role data analysis plays is that it enables decision about many design qualities relevant to human building performance and human behaviour including wayfinding, privacy, comfort, health and wellbeing, inclusivity and analysing users profiles, energy performance and low or zero carbon design. Both at the building and city scales.
- ***E.*** When data analysis should not be used is an important point. The most significant mistake architects make is that they use data analysis to decide what features to implement.

4 The SIG "Digital Built Environment and Data Science"

This report is part of the activities of the Special Interest Group (SIG) ***"Digital Built Environment and Data Science"*** sponsored by the Council of Heads of Built Environment (UK) to investigate the challenges facing Built Environment educators when developing curriculums that enable BE learners to obtain advanced knowledge and data analytics skills in addition to applying and managing the digital technologies themselves. The group is set up jointly by Ulster University and Northumbria University. Both institutions are highly recognised in Built Environment education within the UK and internationally. Based on the above efforts and other available guidance (e.g. QAA Subject Benchmark Statement, Professional Standards and core competencies), this SIG is exploring in more details the possible integrated approaches for digital built environment and data science disciplines. The SIG aims to develop a Guidance on Fundamentals and advanced knowledge of Data Science to be embedded in Built Environment curriculums including philosophy and aims; graduate attributes and skills; learning outcomes; assessment approach; delivery methods; and resources to support learning activities. The overall objectives of the SIG were to:

- Develop a common understanding of the integration of Digital Built Environment and Data Science disciplines.

[13] See Salama, Ashraf M. (2015). Spatial Design Education: New Directions for Pedagogy in Architecture and Beyond. London, UK: Routledge; and Salama, Ashraf M. and Wilkinson, Nicholas (2007). Design Studio Pedagogy: Horizons for the Future. Gateshead, UK: Urban International Press.

- Define the most appropriate approaches for implementing this integration (e.g. designing standalone modules and who is best to deliver them, embedding LOs in existing modules, joint courses from already existing courses)

This report presents the outcomes of the SIG activities that have been conducted over a six-month period (Sep. 2022 – Feb. 2023) which included:

- Conducting a wide survey among the Built Environment educators to explore views on the integration between Built Environment curriculum and Data Science subjects.
- Focus group attended by a number of Built Environment educators to develop a draft for the proposed Guidance on Fundamentals and advanced knowledge of Data Science to be embedded in Built Environment curriculum.
- CHOBE webinar to disseminate the SIG findings and validate the Framework.

5 Key Findings

This section presents and discusses the key findings of the SIG activities (Focus Group and Survey). Appendix A shows the questions of the survey. Figure 5 below shows the different disciplines of the respondents to the survey.

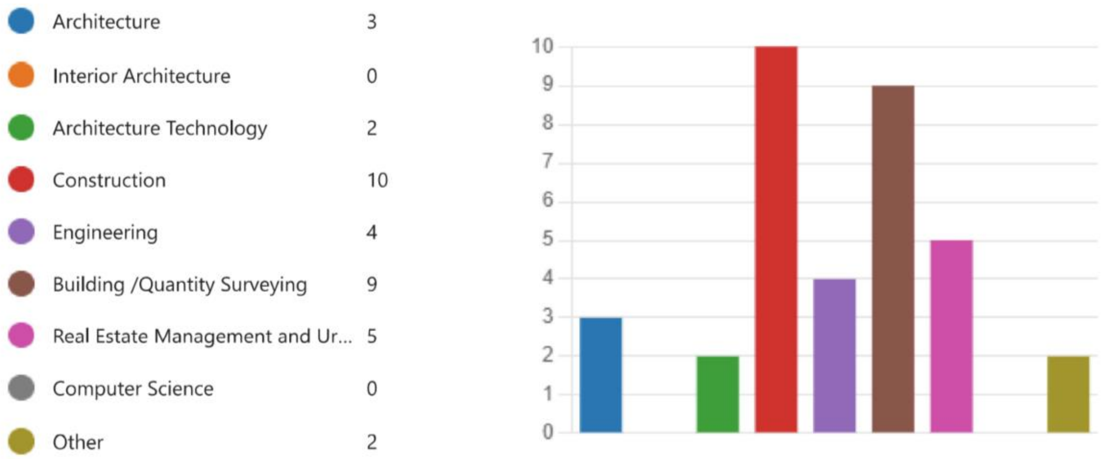

Figure 5: The disciplines of the respondents to the survey.

Built Environment (BE) discipline and its various sub-disciplines (e.g. Architecture Technology, Quantity Surveying, Construction Management, etc.) can be considered a well-established multi-disciplinary field. However, the particular knowledge of each sub-discipline is not always defined well because of the level of vocational content and the overlap between many of these sub-disciplines. This will affect the approach adopted by each sub-discipline to embed Data Science in its curricula and, in other view, may also help develop a common approach to be applicable for more than one sub-discipline. While Chynoweth (2009) has reported that no clearly established boundaries are easily defined for the built environment subject, Griffiths (2004) has described BE discipline as "*a range of practice-oriented subjects concerned with the design, development and management of buildings, spaces and places*".

Table 1 below summarises different classifications of the BE sub-disciplines as reported in Thurairajah et al (2011)[14].

Exploring the approaches to embed Data Science in BE sub-disciplines required first an explanation of how BE educators understand about Data Science. In general terms and from public domain, **Data science**[15] is an interdisciplinary field that uses scientific methods, processes, algorithms and systems to extract or extrapolate knowledge and insights from noisy, structured and unstructured data, and apply knowledge from data across a broad range of application domains. Data science is related to data mining, machine learning, big data, computational statistics and analytics.

Different levels of knowledge are defined by the Data Science discipline which build up from fundamental to more advanced levels. When surveying various Data Science syllabus, these levels can be summarized as shown in Table 2.

The SIG focus group and survey on Digital BE and Data Science have resulted in a general understating on how Data Science is seen by BE educators. Data Science knowledge can be categorised into two main domains as:

1. Basic to Advanced knowledge
2. Soft to Hard knowledge

Based on these categorisations, various approaches can be developed to embed the Data Science discipline into BE curricula. From the results of the conducted focus group and survey, it can be concluded that a two-dimensions continuum from “soft” to “hard” and from “basic” to “advanced” can cover all possible approaches to explicitly incorporates DS into various structures of BE curricula, as shown in Figure 6. The adopted definitions of these dimensions are:

“soft”	: Theory of relevant data science and math
“hard”	: Practical and application of knowledge on relevant data science and math
“basic”	: Fundamental knowledge on data science
“advanced”	: Medium to High knowledge on data science and basic math

Considering the various definition and categories of BE as a multi-disciplinary field, Data science can serve all its sub-disciplines in two dimensions. One dimension is the “General Knowledge” that all sub-disciplines need to embed in their curricula and the “special discipline requirements” where each sub-discipline need to identify the most relevant contents to embed suitable for it. Therefore, each sub-discipline should refer to its own main themes when defining the Data Science elements in its curricula.

From the reviewed classifications of the BE sub-disciplines (as shown in Table 1), there are common subjects often exist in many BE specialists’ programmes: classically “economics, law, management” and recently “IT”. These subjects may be covered in shared modules.

[14] Thurairajah, Palliyaguru, and Williams (2011). Open Resources in Built Environment Education, Internal Report, Wolverhampton University, UK
[15] https://en.wikipedia.org/wiki/Data_science

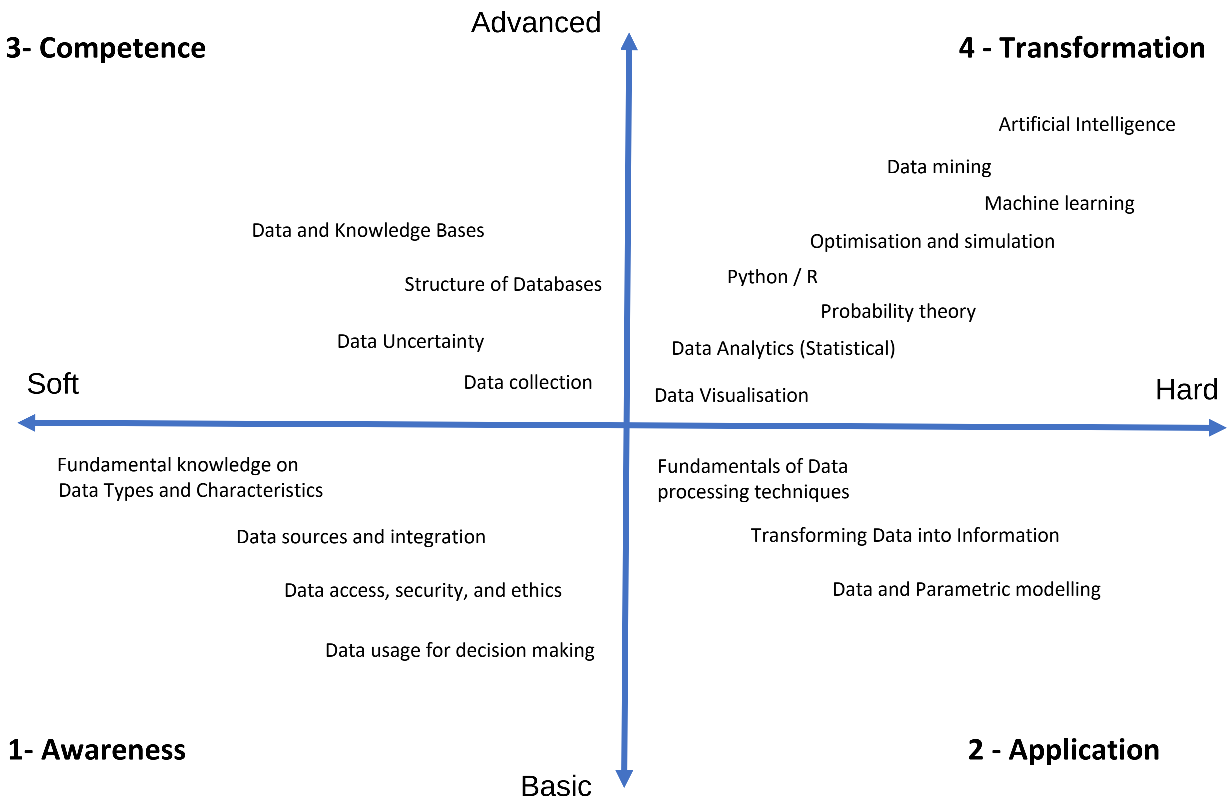

Figure 6: Data Science subjects in relation to Built Environment

In addition, each sub-discipline has specialised areas and specific competencies and skills as specified by their professional bodies. Usually, the competencies are categorised under Mandatory, Core, and Optional competencies relevant to their identified pathways.

While it is beyond the scope of this report to recommend under which competency the Data Science knowledge and skills should be listed, the relevant areas of knowledge are generally categorised as: Personal skills, Technical knowledge, and Professional knowledge. The results of this SIG focus group and survey show that Data Science contents can be mostly classified under Personal skills and Technical knowledge.

Table 1 Built Environment sub-disciplines

HEFCE (2005)	Quality Assurance Agency for Higher Education (QAA)	Temple (2004)	Chynoweth (2009)
• Architecture • Building science and engineering • Construction • Landscape and urbanism	• Architectural technology • Architecture • Landscape architecture • Construction, property and surveying • Town and country planning	• Architecture • Building and construction management • Planning, real estate management • Survey	• Management • Economics • Law • Technology • Design

Table 2 Examples from Data Science syllabus

Basic level of Data Science knowledge:	Medium level of Data Science knowledge:	Advanced level of Data Science knowledge:
• Data collection and curation process • Concept of ethics, security and reliability • Data processing workflow • Cloud computing (principles, architectures, existing technologies such as Microsoft Azure) • Data analytics (statistical modelling, basic concepts, experiment design, pitfalls, Python / R programming, machine learning) • Data interpretation and use (visualisation techniques, pitfalls, libraries) • High-performance computing (parallel databases, MapReduce, Hadoop, NoSQL, stream processing)	• Business Intelligence and Data Mining • Data Warehousing • Types of data, data cleaning, data integration and transformation • Classification and predictive modelling • Generating patterns of data and structuring business intelligence • Online market analysis • Data and web mining • Business process improvement • Business Intelligence systems (e.g. Pentaho) • Data Visualisation and Presentation • Ethics, regulation, data privacy, ownership and protection • Expert Systems, Artificial Intelligence, On-line analytical processing (OLAP)	• Machine learning concepts • Data modelling relates to machine learning • Insights into data (classification, regression, kernels, visualisation) • Learning from data including missing values and unbalanced data • Dimensionality reduction (feature extraction and feature selection) • Supervised/unsupervised learning including deep learning • Probabilistic graphical modelling • Sequential data, hidden markov models • Recommendation systems and collaborative filtering

There are various delivery approaches to include Data Science related content in BE programmes. The results obtained from the surveyed institutions identified these approaches:

1. Majority of opinions suggested a combined approach of introducing new module and embedding in existing modules. For example, a common module (in early years of study) contains general digital and data related syllabus. This should act as preparatory/bridge module to improve data science skills before embarking on full-fledged modules. This is followed by a one/more modules in higher years to include more use of data analytics in the relevant studied subjects.

2. The surveyed staff also suggested just embedding Data Science concepts in several existing modules in existing programmes which need such knowledge (e.g. in modules for: Construction Economics, Surveying, Measurement, Integrated Project, Research Methods, CAD, IT in design, Development and investment software tools, Geographical Information Systems (GIS), Spatial data visualisation, manipulation and analysis, Modelling of buildings and design Analysis). It is worth mentioning that most Data Science content in these suggested modules is only related to Quantification analysis which shows little attention is given to the Qualitative data tools and techniques.

3. The opinion of having a new or standalone module in a programme was also indicated to but with careful consideration as there might be a risk of low rate of student progression in few of Built Environment programmes for such subjects.

4. Short training modules, sessions, workshops, or webinars delivered by a specialised teaching unit or group (e.g. Digital Construction, BIM, etc.) on specific topics related to Data Science. The content of these sessions usually covers simple and common related Data Science technologies (e.g. use of Excel in statistics, basic database tools).

The key barriers to teach Data Science related subjects in Built Environment programmes as indicated by the surveyed staff are summarised in Figure 7.

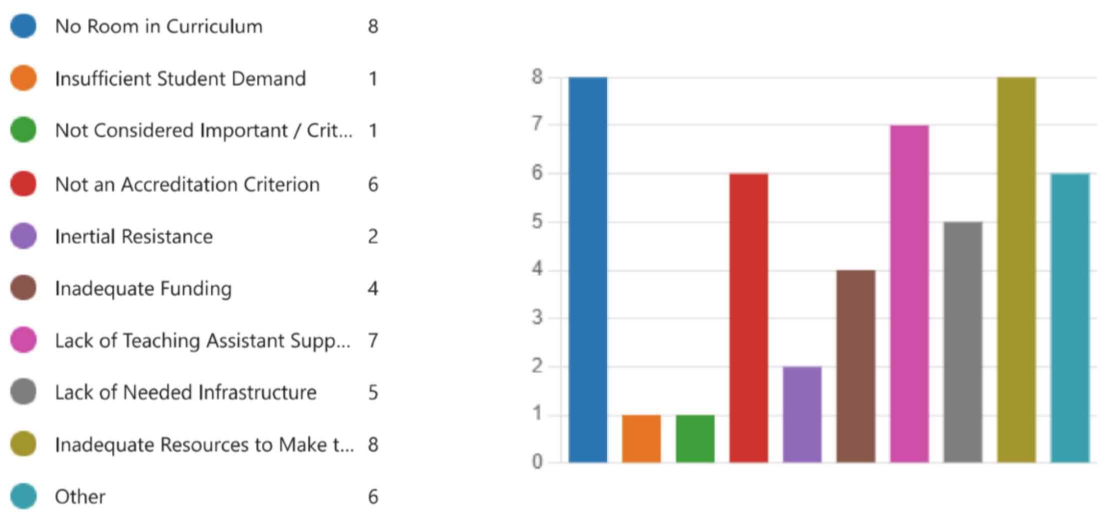

Figure 7: The key barriers to teach Data Science related subjects in Built Environment programmes

6 Discussion

This section introduces the Guidance on Fundamentals and advanced knowledge of Data Science (as learnt from the SIG activities) to be embedded in Built Environment curriculums including:

- Philosophy and aims
- Graduate attributes and skills
- Learning outcomes
- Delivery methods and Assessment approach

6.1 Philosophy and aims:

The philosophy behind a course of this nature is in its response to the need to digitise/digitalise and to transform the way Built Environment is designed, delivered, and operated through digital and connected technology systems in order to achieve sustainability, improve performance, benefit enterprise and communities, meet clients' expectations and appeal to building users. Within the field of Built Environment, the majority of UK courses (and almost worldwide), cover this area with a focus only on applying and managing various digital technologies with little capacity to deliver the breadth of knowledge and skills required for this field. Digital Built Environment includes range of digital technologies for data capture, data analytics, modelling and for communication that can be applied to any stage of a project life cycle to make it more effective. In this sense, this integration of Digital Built Environment and Data Science can enable graduates obtain advanced knowledge and analysis skills in addition to applying and managing the technologies themselves. This integration will develop new graduates' skills that become in high demand for the new normal business practices in Built Environment. Students should be challenged to develop strategic and critical thinking abilities, enabling them to identify and implement the best technological solutions that can transform industry by addressing the economic, environmental and social challenges facing the relevant stakeholders.

A course strategy should provide a balance between theory and practice with hands-on approach on solving real industry problems. This strategy will provide graduates with key critical thinking and analysis skills that are transferrable and applicable across a wide range of industry sectors. The course should aim to enable students to obtain theoretical background on the concepts and themes of Digital Built Environment supported by the relevant Data Science foundations, and to appraise current and future operational strategies in this field.

6.2 Graduate attributes and skills:

A course of this nature should offer an opportunity for all Built Environment related graduates to enrol in order to develop a range of transferable/generic graduate attributes and digital/analytical skills to maintain their employability. The generic graduate attributes include:

- Strategic and Critical thinking
- Creative and problem solvers
- Team Players and Communicators
- Life-long learners able to reflect and improve their own performance

The key skills required:

- Ability to identify and value data/information for BE organisation;

- Ability to analyse, manage, share and communicate data/information including the methodologies and techniques most appropriate to collect, collate and store data
- Ability to integrate the knowledge acquired in order to handle data-driven decision making
- Ability to evaluate appropriate methodologies for dealing with complex problems and identifying opportunities for improvement
- Ability to understand the legal and security implications of data/information exchange
- Ability to establish and manage modelling systems on projects including the collaborative process and technological principles involved
- Demonstrating competence in the use of Digital data processing and analysis software and applications through the use of digital data/information systems

This SIG has also identified the following list of computing literacies which are relevant to the success of students in the future workforce in the order from most to least importance. It is also as collected from the surveyed staff shown in Fig. 8.

- Data Structure / Data Analytics / Database Design
- AI / Machine Learning / Optimisation
- Network / Cloud Computing Services
- Human Computer Interaction
- Programming Languages
- Generative Design
- Big data/Spatial data manipulation and analysis

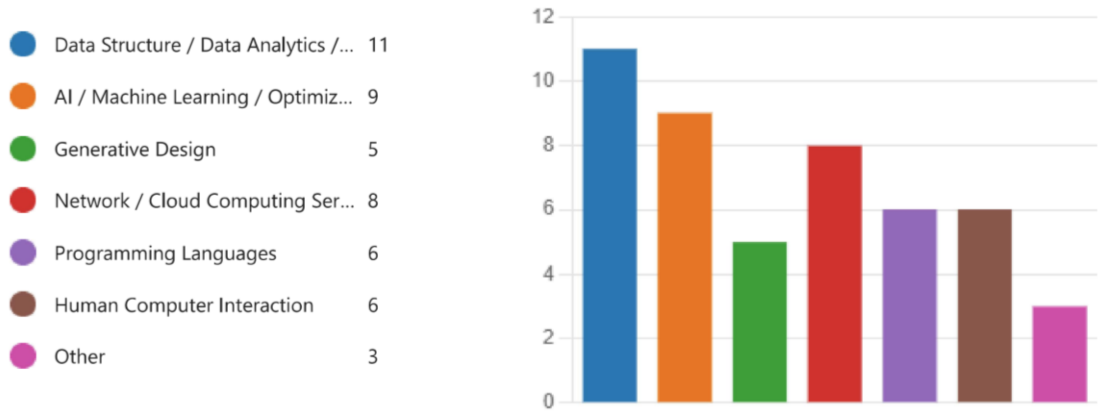

Figure 8: Computing literacies relevant to the success of students in future workforce

6.3 Learning outcomes related to Data Science for BE:

Built environment is a multidisciplinary subject area drawing on knowledge from various fields of knowledge. The integration of Data Science is lacking in the built environment education and needs further attention. Data Science is mainly based on technical calculative elements that focus on improving declarative and procedural knowledge; however, to make these meaningful, calculative elements require interpretation and sense-making within the given context. On the other hand, the cognitive processes associated with learning get complex at every level (Anderson et al., 2003). Within this mind, the following approach is proposed in introducing Data Science content within built environment education.

Based on Bloom's taxonomy (1956), following the categories detailed in Figure 6, Figure 9 introduces an increasing level of cognitive complexity of Data Science content and how it could lead to business and societal dividends in real-life situations. At the initial level of Awareness and Familiarity, the fundamental theories and use of Data Science are provided to the learners so that they know and understand Data Science. This awareness will future-proof built environment education. In the Application level, the learners are expected to solve close-ended built environment problems within given boundaries. This could be carried out in a classroom setting through a summative or formative assessment. These Awareness and Application levels of Data Science content can be introduced at the undergraduate level together with a broad range of built environment subject areas.

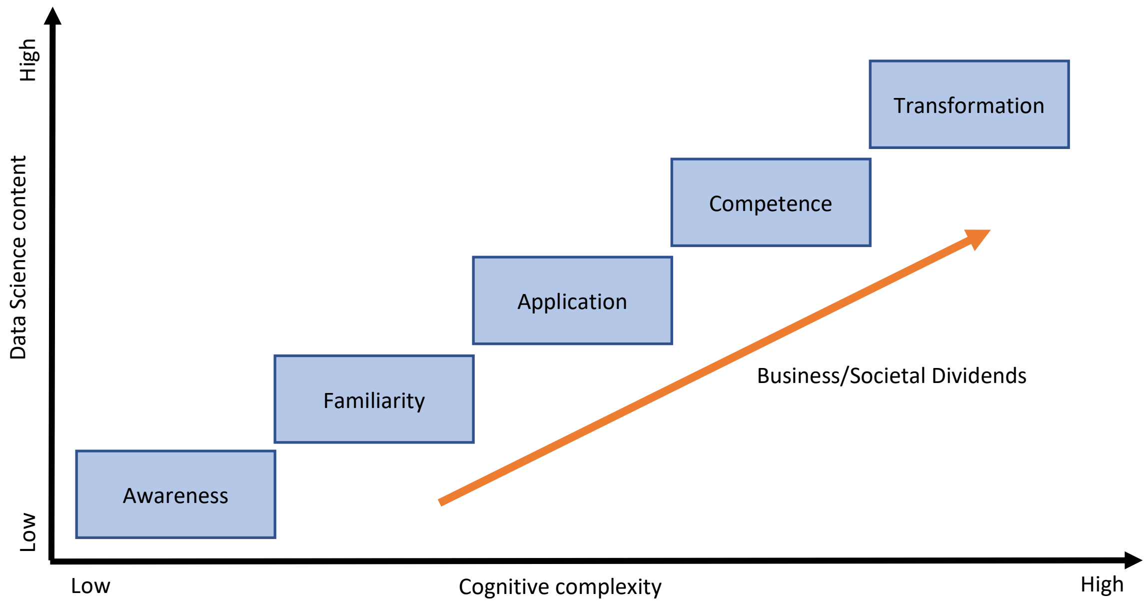

Figure 9: Data Science in Built Environment Education Taxonomy

At the Competence level as illustrated in Figure 10, learners are exposed to real-life scenarios expecting to make judgments within the actual environment. Hence Data science is needed here to tackle open-ended problems and produce unique solutions. And, finally, the Transformation level is intended to enable learners to make critical judgements based on sound Data Science knowledge and context. This will require several modules intended to help the learner to find solutions with critical reflection that can lead to long-term business/societal dividends. Hence at the Transformation level, an entire programme is expected to specialise in Data Science and apply theories and knowledge to the built environment context. Built Environment education and practice presents several open case studies suitable to explore within educational settings and this specialisation can be achieved at the postgraduate level.

The Data Science in Built Environment Education mapping is not intended to help programmes to move through the increasing level of cognitive complexity of Data Science content. Rather, it allows educators to map their programme with the intended level of cognitive complexity in Data Science content within their programme. This can be used to design learning objectives, assessments and activities that target required levels of cognitive complexity.

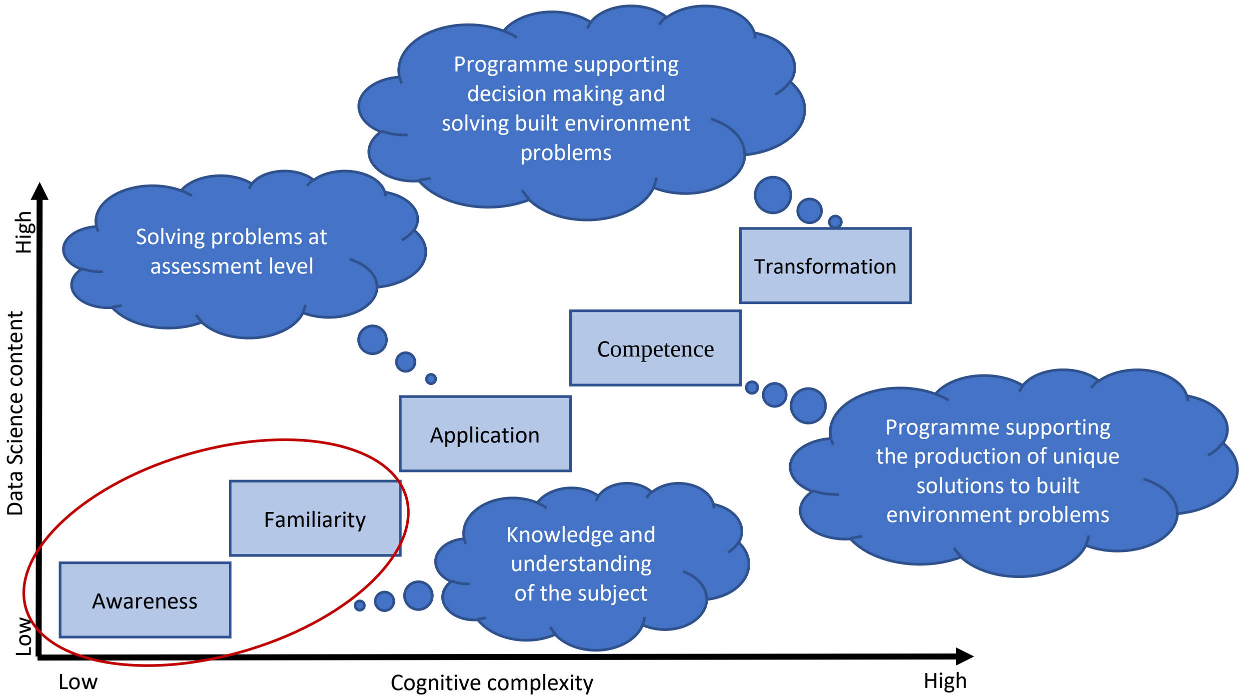

Figure 10: Data Science in Built Environment Education mapping

6.4 Delivery method and Assessment approach

As a new area, a research-led approach should be adopted to deliver such course with an emphasis on challenge and collaboration, exploring new concepts and real-world Built Environment problems. Project-driven and enquiry-based approaches to learning should be also central to the course design, which includes practical challenges, real-world case studies, team-driven assessments/presentations and industry projects. The approach to conduct these activities is to use a number of Learning and Teaching methods: Case studies, Group work, Blogs, discussion boards, wiki's etc, Simulations, Presentations, site visits, Guest Lecturers/Industry experts, Peer Review, and Portfolios.

The assessment strategy seeks to assess the attainment of the key graduate skills and attributes identified and ensure the learning outcomes are achieved through a range of authentic assessments. A range of assessment techniques can be used to enable students to demonstrate their knowledge and understanding of the course concepts and content but also to enable interaction with their peers and the course team. These can include:

• Blogs, chats and on-line discussions are aimed at engendering ongoing participation and collaboration with both peers and academic staff and to facilitate an ongoing process of formative feedback;

• Essays and reports will assess knowledge and academic rigour;

• Student presentations and simulations will assess communication, collaboration, problem solving and team work skills;

• Peer review will encourage reflection and the ability to give and receive feedback. All assessments will have clearly identified marking criteria and students will be provided with clear briefs.
• A research component can aim to engender an interest for in-depth research and facilitate evaluation of the student's critical research and thinking skills to promote research-based learning.

7 Conclusions & Emerging Opportunities / Recommendations

In conclusion, this SIG activities have identified key areas and recommendations for HE institutions to work on. Given the trajectory of technology, there are emerging opportunities and tasks which are envisioned for students in the near future (5 to 10 years) that are generally not required to do today. Among these:

- Making greater use of variety of open source and paid for data
- Data analysis to understand the link between professional inputs and the national economy
- Coding (programming languages) even at lighter level
- Greater demand for applying data analytics to whole life analysis/costing
- More Human Computer Interaction in the form of humans supporting computer decisions
- Much more automation, dynamo scripting, dash boarding and data management
- Semantic Analysis for qualitative data such as for Dispute Resolution
- Visual Analytics for Progress Review
- Network Analysis for Complexity Assessment
- Predictive Analytics for uncertain events and Risk Assessment
- Apply modern tools, techniques and procedures for optimal construction solutions

To prepare students for these upcoming challenges, there are changes to the undergraduate and graduate curriculums that institutions should make now. Some of these changes are also at the employers' and authorities' side.

- Balance the theory and practice of computational applications/technologies
- The embedding of digitalisation and data analytics tools and techniques (such as ML and AI) in virtually all relevant modules at undergraduate level.
- Create space in the curriculum by removing outdated content
- Design and delivery of short modules to support students of less analytical mindsets
- More hands on approaches, greater complexity of BIM in education using real world projects, greater diversity of tools/software used.
- Incorporate curriculum change and review the same periodically aligning with disruptive changes in the market.
- Recruit appropriately qualified staff and develop domain expertise in digitalisation areas to design innovative solutions to challenging problems
- more staff to expand curriculum and space in timetables to deliver additional sessions
- Finance and political will
- Continuous Professional Development and Training and development of the faculty and staff

- Employers need to lead the way in practice to ensure HE is coping with their requirements
- Better link between research & teaching
- Better IT support and infrastructure as well as better links with industry through knowledge exchange on digitalisation within the construction industry.
- Closer collaboration with Data Science colleagues
- We need workshops to be introduced to aspects of the digital world, with opportunities to explore how / case studies as to how these can help us.
- Cross discipline modules
- Better Professional Body and Government support
- Funding and staff who can teach the subject area.
- Real example projects data
- Incentive package for staff Digital infrastructure
- Modern applications and technologies setup and implementation strategies at the Institute level.

However, there is also a list of identified barriers to teaching Data science related content in BE programmes as indicated by the surveyed staff and this SIG activities. As shown, there are staff-related, institution-related, professional body-related, and employer-related barriers.

- Inertial Resistance
- No Room in Curriculum
- Not an Accreditation Criterion
- Inadequate Resources to Make the Curriculum Change
- Inadequate Funding
- Issues with assessment and detecting plagiarism where information can be shared widely and rapidly
- Difficulty level is frequently too high for students and is a barrier to retention
- Time for staff development
- Not Considered Important / Critical
- Undergraduate curriculum is lacking in of digital transformation. This renders post-graduate students under-prepared for data science skills to be taught at PG level
- Lack of Teaching Assistant Support
- Lack of Needed Infrastructure
- Inadequate Resources to make the Curriculum Change
- Insufficient Student Demand
- Employers not clearly demanding skills or supporting development of such subjects

Appendix A

1. About your Teaching

1.1. Please name the institution you are working at and in which country? (this is optional)
…………………………………………..

1.2. Please leave your name and contact details if you want to hear about the results of the survey (this is optional)
……………………………………………

1.3. What is the title of your undergraduate degree?
BSc in ………………………………………….
BA in …………………………………………...

1.4. What is your current role?

- Professor (Head of Department, Associate Head)
- Professor
- Associate Professor, Reader, Senior Lecturer
- Assistant Professor, Lecturer
- Teaching fellow/assistant
- Other *(please enter below)*

1.5. What level of students do you teach at your institution? *(choose all that apply)*

- Undergraduates
- Postgraduates
- Others *(please enter below)*

1.6. In which program or academic area do you teach? *(choose all that apply)*

- Architecture
- Interior Architecture
- Engineering
- Construction
- Building /Quantity Surveying
- Architecture Technology
- Real Estate Management and Urban Planning
- Computer Science
- Others *(please enter below)*

2. About your Program

2.1. What core skills and knowledge are a major concern, a concern, less of a concern, or not a problem for the future of Built Environment?

	A major concern	A concern	Less of a concern	Not a problem
Digitalisation/Computing/Data science skills				
Problem-solving skills				
Communication skills				
Team working skills				
Leadership skills				
Life-long learning skills				

2.2. How important is teaching Digitalisation/Computing/Data science skills in BE undergraduate programmes?

High priority	Medium priority	Low priority	Not important

2.3. How well do the undergraduate Built Environment programmes you are familiar with/aware of meet requirements (as mentioned in the introduction) of the Digitalisation vision?

Very well	Well	In a limited way	Minimum	Not at all

2.4. How well do the current Built Environment graduates meet requirements (as mentioned in the introduction) to deliver the Digitalisation vision?

Very well	Well	In a limited way	Minimum	Not at all

2.5. Please provide details of the courses/modules which are relevant to Digitalisation in BE at your institution (title and brief syllabus).

2.6. How would you define Digitalisation/Computing/Data science skills as learning outcomes or attributes?

Please provide example/s of learning outcomes and attributes that can define Digitalisation/Computing/Data science relevant skills/knowledge.

2.7. What are the main barriers to teaching Digitalisation/Computing/Data science skills in your programmes?

- ☐ No Room in Curriculum
- ☐ Insufficient Student Demand
- ☐ Not Considered Important / Critical
- ☐ Not an Accreditation Criterion
- ☐ Inertial Resistance
- ☐ Inadequate Funding
- ☐ Lack of Teaching Assistant Support

☑ Lack of Needed Infrastructure

☐ Inadequate Resources to Make the Curriculum Change

☐ Any Other Barriers (please list examples below)

2.8. Based on your experience, what is the best or most effective method to teach Digitalisation/Computing/Data science technologies to undergraduate students in your opinion?

☐ A new or standalone module in a programme

☐ Embedding Digitalisation concepts in several existing modules in an existing programme

☐ A combined approach of introducing new module and embedding in existing modules

☐ Need to develop a new programme to cover these concepts

☐ Other

3. Computing and Data Science Literacies & Technologies

3.1. Please indicate whether these computing literacies are relevant to the success of your students in the future workforce: *(choose all that apply)*

☐ Data Structure / Data Analytics / Database Design

☐ AI / Machine Learning / Optimization

☐ Generative Design

☐ Network / Cloud Computing Services

☐ Programming Languages

☐ Human Computer Interaction

☑ Others *(please enter below)*

3.2. Which of the following computational applications/technologies are used by students in their class or project work? And which are covered within the program curriculum (for example, taught in a course)? *(choose all that apply)*

	Used By Students	Covered Within Program Curriculum (Taught in a Course)
BIM	☐	☐
Parametric Design	☐	☐
Computer-Aided Drawing / Design	☐	☐

	Used By Students	Covered Within Program Curriculum (Taught in a Course)
Visualization / Augmented Reality / Virtual Reality / Mixed Reality / Extended Reality	☐	☐
Analysis / Simulation / Engineering Calculations	☐	☐
Algorithms / Automations	☐	☐
Data Management / Decision Support	☐	☐
Sensing / 3D Scanning / Unmanned Aerial Vehicles (Drones)	☐	☐
Programming Languages (MATLAB, MATHCAD, R, Grasshopper / Dynamo, Python, Visual Basic, Java, JavaScript, C++, C#, or C)	☐	☐
Others *(please enter below)*		

3.3. Given the trajectory of technology, what tasks do you envision your students doing in the near future (5 to 10 years) that are generally not required to do today? (Please list at least three key tasks)

3.4. What changes to undergraduate and graduate curriculums should faculty make now to better prepare students for the tasks you listed above? (Please list at least relevant changes)

3.5. What types of support are needed to enable/empower the faculty or the department to successfully make these changes? (Please list at least three types of support)

3.6. Bloom's model on knowledge domains has been recognized as one of the important models for students learning and acting. To answer this question please check the following revised Bloom's taxonomy definitions:
0. Not important or no need 1. Remembering 2. Understanding
3. Applying 4. Analysing 5. Evaluating 6. Creating

Indicate to what extent Built Environment graduates need to master the following data and digitalisation skills on a scale of 0 to 6 based on the revised Bloom's taxonomy definitions described above.

	0	1	2	3	4	5	6
Statistics							
Data Science (including data management & machine learning)							
Programming and coding							
Process control and optimisation							
Modelling and simulation							
Cloud computing							
Virtual Reality (including AR)							
IoT (including smart sensors and digital infrastructure)							
Cyber security							
Others *(please enter below)*							

3.7. To answer this question please check the following revised Bloom's taxonomy definitions:
0. Not covered 1. Remembering 2. Understanding
3. Applying 4. Analysing 5. Evaluating 6. Creating

Which of the following subjects are currently covered in your undergraduate Built Environment curriculum?

	0	1	2	3	4	5	6
Statistics							
Data Science (including data management & machine learning)							
Programming and coding							
Process control and optimisation							
Modelling and simulation							
Cloud computing							
Virtual Reality (including AR)							
IoT (including smart sensors and digital infrastructure)							
Cyber security							
Others *(please enter below)*							

3.8. Please evaluate your level of data and digitalisation skills on a scale of 0 to 6 based on the revised Bloom's taxonomy definitions
0. No knowledge 1. Remembering 2. Understanding 3. Applying
4. Analysing 5. Evaluating 6. Creating (also covers areas your research/expertise fit into)

	0	1	2	3	4	5	6
Statistics							

Data Science (including data management & machine learning)							
Programming and coding							
Process control and optimisation							
Modelling and simulation							
Cloud computing							
Virtual Reality (including AR)							
IoT (including smart sensors and digital infrastructure)							
Cyber security							
Others *(please enter below)*							

Thank you for participating in this survey!

If you want to make changes to any previous response, please do so now. By clicking Submit Now, your responses will be submitted.