DOCTORAL THESIS

Facilitating BIM-enabled Learning in Construction Education

Theophilus Oluwarotimi Olatunde Olowa

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Theophilus Oluwarotimi Olatunde Olowa

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BIM'i kasutamine ehitusinseneride koolituses

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Contents

List of publications

The list of author's publications, on the basis of which this dissertation summary has been prepared:

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III Witt, E., Olowa, T., & Lill, I. (2021). Teaching Project Risk Management in a BIM-Enabled Learning Environment. In Auer, M. E. & T. Rüütmann (Eds.), ICL2020 – 23rd International Conference on Interactive Collaborative Learning (AISC 1328, pp. 162–173) **(conference paper: ETIS classification 3.1)**

IV Olowa, T., Witt, E., & Lill, I. (2021). Evaluating Construction Education Interventions (M. Auer & T. Ruutman (eds.); ICL 2020, pp. 497–508). https://doi.org/10.1007/978-3-030-68201-9_49 **(conference paper: ETIS classification 3.1)**

V Olowa, T., Witt, E., & Lill, I. (2021). Building information modelling (BIM) – enabled construction education: teaching project cash flow concepts. International Journal of Construction Management, 0(0), 1–12. https://doi.org/10.1080/15623599.2021.1979300 **(journal paper: ETIS Classification 1.1)**

VI Olowa, T., Witt, E., Morganti, C., Teittinen, T., & Lill, I. (2022). Defining a BIM-Enabled Learning Environment—An Adaptive Structuration Theory Perspective. Buildings, 12(3), 292. https://doi.org/10.3390/buildings12030292 **(journal paper: ETIS Classification 1.1)**

Other relevant publications:

VII Rüütmann, T., Witt, E., Olowa, T., Puolitaival, T., & Bragadin, M. (forthcoming). Evaluation of Immersive Project-Based Learning Experiences. Surviving and Thriving. Reykjavik: Reykjavik University **(conference paper: ETIS Classification 3.1)**

VIII Olowa, T., Witt, E., & Lill, I. (forthcoming). BIM for construction education in Nigeria. In S. Gottlieb (Ed.), The 11th Nordic Conference on Construction Economics and Organisation (p. forthcoming). Copenhagan: Springer Nature **(conference paper: ETIS Classification 3.1)**

Author's contribution to the publications

Contribution to the papers in this dissertation are:

I The conceptualisation of the research as a whole was done by Theophilus Olowa in consultation with Prof. Emlyn D.Q. Witt as the main supervisor. Research design, data collection and write-up of the first draft was done by the main author in collaboration with Prof. Emlyn D.Q. Witt. Refinement and re-structuring were done by Prof. Emlyn D.Q. Witt and Prof. Lill facilitated the research.

II Conceptualisation of the research was by Theophilus Olowa in consultation with Prof. Emlyn D.Q. Witt and Prof. Irene Lill as the main and co-supervisors respectively. Research design, data collection, analysis and initial write-ups were carried out by the main author in consultation with Prof. Emlyn D.Q. Witt. Refinement and re-structuring were done by Prof. Emlyn D.Q. Witt. Prof. Irene Lill facilitated the funding acquisition and publication of the research.

III Conceptualisation of the research was by Prof. Emlyn D.Q. Witt in collaboration with Theophilus Olowa. Research design, data collection, analysis and initial write-ups were carried out by the main author. Refinement and editing were done by Theophilus Olowa and Prof. Lill facilitated the research.

IV Conceptualisation of the research was by Theophilus Olowa in consultation with Prof. Emlyn D.Q. Witt. Research design, data collection, analysis and initial write-ups were carried out by the main author. Refinement, re-structuring and editing were done by Prof. Emlyn D.Q. Witt and Prof. Lill facilitated the research.

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Introduction

Background

The construction industry has been regarded by many as a technologically low-driven industry with many inefficiencies in its operations (Gallaher et al., 2004). To meet the demands of the 21st century, the construction industry is currently undergoing digitalization, which is causing a vortex of disruptions. The reason is that industry workflows change and these, in turn, require new approaches to information management, communication, and knowledge in order to deliver new and acceptable projects. This has led to a mismatch between graduates' competencies and their emerging roles in an industry striving towards the adoption of web 4.0 technologies. To address this, it is important for construction educators to devise novel and innovative ways to enhance teaching and increase the motivation to study among the new generation of construction students. Building Information Modelling (BIM) is the central phenomenon in this digitalization vortex. BIM refers to an integrated digital repository of parametric and non-parametric representation of all information relating to a construction asset's lifecycle that allows communication, collaboration, planning, simulations, and other activities to take place in a single, virtual environment. While BIM poses new challenges, it also offers opportunities for meeting some immediate and long-term industry needs of the 21st century through BIM for construction education.

BIM for construction education refers to all teaching and learning approaches engaged in promoting the acquisition of BIM skills and/or leveraging BIM for construction education (Olowa et al., 2020). BIM for construction education is carried out among academics and researchers in two basic forms. The first is through the instrumentalism perspective (Feenberg, 2006; Heidegger, 1977) where graduates are taught to understand and apply BIM skills for immediate industry needs. The second is through the substantivism perspective where BIM becomes the medium in which teaching and learning activities are performed - here BIM becomes an education pipeline or the vehicle that conveys teaching and learning.

Conversely, researchers and practitioners have agreed that introducing technologies like BIM into didactics improves learning and raises the motivation of students to learn (Barham et al., 2011; LóPez-Zaldívar et al., 2017; Wu & Kaushik, 2015). This has piqued the attention of educational authorities, academics, and researchers for BIM for construction education activities in the last decade. Generally, the evolution of BIM education has been categorised into 3 progressive stages:

1. BIM-aware, where graduates are made aware of the uses and exigencies of BIM relating to its implications for both digital and cultural transformation of the construction industry.
2. BIM-focused, involves graduates' abilities to use and manipulate BIM software in performing specific tasks such as modelling, clash detection, simulation etc.
3. BIM-enabled, where education takes place in a BIM-mediated virtual environment and BIM acts as a platform for learning (Underwood et al., 2013).

While the BIM-curriculum integration is generally in its embryonic stage (Underwood & Ayoade, 2015), evidence suggests that both BIM-aware and BIM-focused education have gained significant acceptance, with research to produce BIM-integrated curriculum gaining traction.

Problem statement

While BIM has become the gold standard in the present-day construction industry (Eastman et al., 2011), which requires graduates to demonstrate BIM skills and knowledge upon entry into the industry (and the backbone upon which many innovative technologies run in the industry), BIM for construction education on the other hand has experienced slow uptake and development in the academia leading to sub-optimal education in Architectural, Engineering, Architectural and Facilities Management (AEC/FM) disciplines. As a result of this lag, it has become difficult to appropriately align students' professional duties with the digitalization of the construction industry to improve not only their industry skill-fit and productivity but also their decision-making ability (Du et al., 2017; Hwang & Safa, 2017; Tranquillo et al., 2018).

The construction industry is moving away from fragmented and adversarial traditional construction methods towards digitally integrative and collaborative ways of working, whereas the pedagogical methods in construction education are still very much siloed based on disciplinarity and the knowledge created are fragmented. Students of different disciplines need to be taught on how to work collaboratively and they must also be provided a way to see how all the different construction concepts and knowledge garnered fit together in a complete sense to foster better understanding and proper knowledge application. BIM for construction education can address these challenges.

Hands-on learning has been the historical modus operandi for construction education (Glick et al., 2012). Many activities on construction sites, such as mounting and dismantling of cranes require on the job training, which sometimes leads to injuries and fatalities (Li et al., 2012). Moreover, the decreasing number of experiential construction laboratories in higher education institutions (Glick et al., 2012), inadequate construction sites to visit, time and logistics problems associated with site visits including safety issues have all created the challenge of developing instructional material that can equally generate practical understanding of spatial relations and its associated understanding of construction system components in a safer environment for both educators and students.

Despite the availability of rich-embedded real project data in BIM and the consensus about the pedagogical impact on students learning outcomes of introducing BIM pedagogy into construction education, there is still a lot of confusion about BIM for construction education. These issues concern what to teach, how to teach, where to teach and the evaluation mechanism to appraise the outcome and consequences of what is taught. This makes the opportunity offered by BIM to be under leveraged for construction education.

Aim and scope of the research

The ability of BIM to hold real industry data and to extract data therefrom provides an opportunity for problem/project-based teaching and active learning in an immersive BIM environment. Leveraging on this BIM characteristics is important for enhancing construction education. Hence, the aim of this research is to understand how BIM could be used to facilitate construction education. To achieve this aim, the following overall research question was formulated: **Overall research question:** How can BIM be leveraged for construction education? To adequately address the Substantial and complex issues raised in the overall research question, this was subsequently broken down into the following smaller research questions:

Research question 1: What are the existing cases of BIM for construction education?

Research question 2: How can BIM be used to teach engineering concepts?

Research question 3: What is the impact of BIM-enabled pedagogy on students' performance?

Research question 4: How can BIM-enabled learning be facilitated?

A pragmatic approach was used to explore the diverse themes imbued in these research questions by applying mixed methods to identify "what works" at every point of the research.

The scope of this study is limited to the observations and experiences of BIM for construction education in a participatory action research within a construction investment course and construction industry experts' opinions from three European countries: Estonia, Finland, and Italy.

Research significance and contribution

This doctoral research demonstrates the possibility and effectiveness of BIM-enabled learning in promoting safe, active and collaborative learning among construction students. The results of this research will update and add to the body of knowledge on construction education generally and BIM for construction education specifically by providing a typology and conceptual framework of BIM for construction education. Furthermore, the result will provide characteristics for an innovative platform that can promote competency-based BIM-enabled learning in an immersive environment. These characteristics will be useful for educational software developers in their future software deployments.

The BIM-enabled learning object and activities that will emanate because of this dissertation will be useful for educators in promoting safe-active learning in a BIM-enabled learning environment that will be helpful in achieving the six knowledge domains of Bloom's taxonomy. Describing and demonstrating BIM-enabled learning activities will help other academic researchers and practitioners in designing and implementing BIM for construction education. The result from this study will provide a systematic way for planning and implementing BIM for construction education interventions. This will contribute to the ongoing efforts in matching the graduates' competencies with their expected industry roles and further ensure motivation among industry professionals for continuous professional development.

Outline of the dissertation

This doctoral dissertation consists of four chapters based on six (6) paper publications. The introduction provides an overview of BIM for construction education. It outlines the purpose of the research, the research questions, scope, and justification for the study. Chapter 1 gives an overview of the research subject from the perspective of the extant literature; Chapter 2 discusses the methodological approaches. Chapter 3 presents the findings; Chapter 4 gives the conclusions and recommendations.

Abbreviations

BIM	Building Information Modelling
AEC/FM	Architectural, Engineering, Construction and Facility Management
AIT	Advanced Information Technology
AST	Adaptive Structuration Theory
STM	Strussian Theory Model
GT	Grounded Theory

Terms

Building Information Modelling	An integrated digital repository of parametric and non-parametric representation of all information relating to a construction asset's lifecycle that allows communication, collaboration, planning, simulations, and other activities to take place in a single, virtual environment
BIM-enabled learning	All teaching and learning that are carried out with the aid of BIM models
BIM-enabled learning environment	A spatial-temporal medium where BIM-enabled learning can take place
BIM for construction education	All teaching and learning approaches engaged in promoting the acquisition of BIM skills and/or leveraging BIM for construction education
Adaptive Structuration Theory	The framework that models the relationship between advanced information technologies, social structures, and human interaction
Advanced Information Technology	Technologies that use sophisticated information management to enable multiparty participation in organization activities
Grounded Theory	A method of developing a well-integrated set of concepts that provide a thorough theoretical explanation of social phenomena

1 Literature review

Digitalization is revolutionizing construction education, which is not only expressed through innovations in modes of teaching and learning but also through reproducing industry practice for improving construction education (Olowa et al., 2020). In the sections that follow, a review of BIM as the major driver of this digitalization is presented by considering its origin, impact on the industry, usefulness in education, and opportunity for improving construction education.

1.1 BIM and digitalization in AEC/FM industry

In many countries, the construction business is regarded as one of the most difficult (Haron et al., 2011). Even though it has been around longer than other industries, such as automotive and manufacturing, it still has a lot of difficulties to address in its traditional ways of doing things (ibid). After recognizing the drawbacks of sticking to the traditional approach (which include a 20% reduction in production compared to other industries and about 30% waste in processes and delivery methods (Gallaher et al., 2004; Haron et al., 2011)), the industry has begun to embrace smart and advanced digital technologies, such as 3-D scanning and printing, robotics, artificial intelligence (AI), internet of things (IoT), laser scanning and point cloud image capturing, photogrammetry, GIS, Sensors etc., (Forsythe et al., 2013). Yet, BIM has been used in different instances as the backbone or frame on which many of these smart and advanced technologies are effectively deployed in the construction industry (e.g., Osello et al., 2013).

BIM's initial impact was mostly felt on the design side, where it allowed architects to conceive and design a project in exciting new ways (Sweeney, 2018). Custom parametric objects make it feasible to model complicated geometries that were previously impossible or impractical to model (Eastman et al., 2008). Other significant members of the construction sector have also come to recognize the benefits of BIM. Contractors, for example, increasingly use BIM to estimate, schedule, and execute project construction more effectively (Sweeney, 2018).

The benefits of digitalization through BIM are enormous in construction industry practice and are well documented (Codinhoto et al., 2022; Gaur et al., 2021; Mahmoud et al., 2022; Omayer et al., 2022; Santos et al., 2022; Vigneshwar et al., 2022). These benefits are available throughout the lifecycle of a building. One of the primary benefits of BIM, according to several studies, is that it is a technology that facilitates cross-discipline collaboration (Boeykens, Stefan; De Somer, Pauline; Klein, Ralf; Saey, 2013; Bozoglu, 2016a; Mathews, 2013b; Matthews et al., 2018; Wu & Issa, 2014; S. Zhang et al., 2017). For example, collaboration and cooperation are fostered among project participants where BIM is used at the initiation and design phase (Bozoglu, 2016b), especially in projects requiring efficient communication in off-shoring or outsourcing with architectural and engineering designs (Ku & Mahabaleshwarkar, 2011), including execution and operation phases of construction programmes (Karji et al., 2017; Shi et al., 2016).

BIM can increase communication between businesses in the building industry and can help with information management and project lifecycle management. Architects, cost estimators, engineers, builders, and property owners can all use BIM to manage a project from start to finish in a timely manner. BIM will continue to demonstrate its worth in the management of buildings through building design, bidding, construction, and operation phases (Zhang et al., 2016). At operations phase, Love et al. (2014) argue that at least nine benefits are accruable to facility owners.

However, to sustain and expand these benefits, AEC/FM graduates need to be trained not just in BIM applications by including BIM curricula in their study programmes but also by devising alternative and improved pedagogical teaching methods of delivering them in ways that would motivate students' active participation and continuous learning. Some of the ways by which these are done are discussed in the next section.

1.2 BIM and construction education

Many researchers have canvassed for introducing BIM into education at different levels (e.g., Eastman et al. (2008) and Underwood et al. (2013)). According to Wong et al. (2011), incorporating BIM into higher education would not only meet the growing demand for BIM-capable workers, but it would also provide students with new opportunities in their professional careers, such as the ability to cope with new occupational issues with high level of efficiency. By focusing on curriculum content and teaching methodologies (Zhang et al., 2016), academics and education researchers have since realized that it is critical to respond to the construction industry trend and use technology such as BIM to accomplish numerous goals across AEC/FM curricula. These goals can be grouped into three areas:

1. Teaching students and professionals how to use BIM as a tool
2. Using BIM independently or in serious games to teach construction and engineering concepts that hitherto had been difficult to teach
3. Using BIM for active learning such as in problem and project-based learning including the development of learners' soft skills.

The important characteristics of BIM that make it particularly relevant in/for education have been identified by several authors, such as Eastman et al., (2008) and Underwood et al., (2013). Eastman et al., (2008) argue that a building's principal role is to provide climate-controlled space. An interior space's shape, volume, surfaces, and characteristics are all important aspects of a structure, which previous computer-aided design systems struggled to express explicitly. They further argue that the ability to automatically update digital parametric models makes BIM a powerful productivity tool with additional ability for "interaction, collaboration and communication among students through digital medium exchanged dialogue". For Wong et al., (2011), BIM is more than just a representation of a building's geometry when it comes to AEC/FM education. The sorts of materials, construction specifications, and scheduling of building parts for assembly can all be displayed and intelligently interpreted using BIM views especially in construction management courses. Because of this, Wong and his colleagues further state that BIM allows individuals from varied backgrounds to collaborate on a single BIM model of a building. While students learn to represent designs in BIM, they will also learn about BIM's other capabilities like new ways to illustrate construction details and methods, develop an understanding of the construction assembly of various building elements, opportunities for improved communication, and mentally creating a vision for the eventual paradigm shift from 2-D documents to full 3-D digitally based construction documents (ibid).

Forsythe et al., (2013) advocated for BIM inclusion in AEC/FM education by explicating the shortfalls in the traditional forms of teaching and learning among academia and how introducing BIM into AEC/FM curricula could come to the rescue. They argued that in the past, didactic 'chalk and talk' training has dominated AEC/FM training delivery and evaluation, which has not always resulted in acceptable knowledge transfer and learning results. They claim that many traditional techniques used to teach AEC/FM programs include isolated, static, and individual learning, which students sometimes find boring or irrelevant to their desired job prospects. As a result, these traditional methods tend to elicit low student motivation and thus limited learning potential because they do not expose students to the complex dynamics of real-world projects or the need to make decisions involving potentially conflicting variables, even though this is exactly what they will encounter once they begin working in industry (ibid). Again, Forsythe et al., (2013) argue that traditional mode of teaching AEC/FM students does not cater enough for students that are "visual-spatial" learners. They assert that this learning style is eight times faster for most learners compared to auditory-sequential learning style. They suggest that students who are visual-spatial learners think in terms of visualization, images, and spatial awareness; they can process concepts, apply inductive reasoning, and generate ideas by combining existing facts all at the same time. They concluded that an advantage of this learning style is that learning is permanent once the student is able to fit the information into the context of what they already know.

Finally, (Underwood & Ayoade, 2015) in expressing their perspective on BIM in higher education in UK to BIM Academic Forum (BAF) members succinctly state that:

> *"BIM models can be rigorously analyzed, and simulations can be performed… the visual nature of the information in BIM models provides a more universal medium for understanding that is more quickly absorbed than words alone…* and *offers engagement and exploration of teamwork, collaboration, and continuity across multiple construction stages"*

Having explicated the reasons and perceived attendant benefits of BIM in AEC/FM education has been clearly laid down by academia and BIM researchers, the next section presents how academics are incorporating BIM into AEC/FM curricula to overcome: the shortage of BIM experts' requirement of the construction industry; the perceived mismatch between industry requirement and construction graduates; and perceived shortcomings of traditional teaching and learning methods.

1.3 BIM education

In recent decades, there has been a boom of interests in BIM education from academics and researchers, with authors stressing various aspects of educational abilities, skills, attitudes, and knowledge domains (see Brioso, Murguia, and Urbina 2017; Fridrich and Kubečka 2014; Koutamanis, Heuer, and Könings 2017; Macdonald and Granroth 2013; Nawari 2013; Shanbari, Blinn, and Issa 2016a). Owing to contextual opportunities, challenges and priorities which differ from person to person and institution to institution, different BIM education strategies have been identified and documented (see Abdirad & Dossick, 2016; Denzer & Hedges, 2008; Olowa et al., 2020; Sacks & Barak, 2010).

BIM-aware education

Usually, BIM educational programs begin by raising BIM awareness both in the industry and in academia (Underwood et al., 2013). This awareness could simply be through words of mouth from person to person or group of persons with little distinction often made between CAD and BIM. This level of BIM for construction education is characterized by some sorts of confusion as people do not yet have a full understanding of what BIM really is. Some researchers have largely ascribed this confusion to the non-governmental pronouncement of BIM guidelines or deliverables in those countries' construction industry or education curricula (Maina, 2018).

BIM awareness could also be through workshop discussions and/or publications. In other cases, BIM forums are organized either formally by institutions or informally by BIM enthusiasts for the same purpose. While this stage of BIM education is still common in emerging economies like Nigeria, it is safe to say that it has been substantially addressed in developed economies. One other characteristic of emerging economies that is at this stage includes the publishing of papers or organizing workshops around issues like challenges, barriers, and benefits of BIM adoption. Examples of this include Amuda-Yusuf et al., 2017; Babatunde & Ekundayo, 2019; Maina, 2018; Sawhney & Singhal, 2013; Yan & Damian, 2008.

BIM-focused education

Following BIM awareness phase is the BIM focused phase where some level of awareness is already achieved in the system usually at a national level. At this stage, the attention is on how to develop BIM competencies among students and/or industrial trainees, especially in the use of specific industry BIM software products (such as Vico office, BEXEL, Revit, ArchiCAD, Navisworks, Rhino3D, Aconex, Green Building Studio and others) for modeling, viewing, simulating, estimating, scheduling, and data sharing etc., (Olowa et al., 2022). Several academics and researchers have also reported on BIM-focused education as a variant of BIM for construction education (see Bozoglu, 2016; Palomera-Arias & Liu, 2016b; Shanbari et al., 2016; Wang et al., 2014; Wu & Luo, 2016; Zhang et al., 2017). Evidence suggests that both BIM-aware and BIM-focused education have been generally recognized and initiatives to develop curricula to incorporate BIM have become widespread (Olowa et al., 2021). However, both BIM-aware and BIM-focused are both taught using the instrumentalist traditional teaching methods and no thought is given to how parametric BIM could be used as a vehicle for teaching and learning in construction education through a substantivism viewpoint.

Beyond the BIM focused stage is the BIM enabled education where efforts are made by both academic practitioners and researchers to explore the use of BIM as a medium for educational practices and purposes as advocated by Underwood and his colleagues (2013). Hence, the focus of this research is on this aspect of BIM for construction education, which was at its primal phase as at that time, this study was designed in over four years ago; and this is discussed further in the next section.

BIM-enabled education

In line with earlier arguments about how important it is to cater for learners of all kinds in AEC/FM education, Barfield et al. (1995) state that learners can be classified as auditory, visual, tactile, or kinesthetic based on their learning preferences. Auditory, visual, and kinesthetic learners learn through hearing, seeing, and doing respectively (Roark, 1998). Teaching AEC/FM classes while considering students' various learning styles is a difficult task (Barham et al., 2011). Barham et al. observed that traditional lecturing is prevalent in delivering AEC/FM courses with occasional visits to construction sites sometimes used to complement the lecturing approach. This teaching style provides an auditory and visual learning environment. However, it is not always possible to include site visits in the course schedule due to factors such as the lack of construction sites that match the class's demands, class scheduling conflicts, and safety concerns (Haque, 2007).

The typical lecture teaching method can often fall short of serving as an effective instrument for communicating knowledge to learners (Barham et al., 2011).

Since the launch of "Cyclone" in 1976, using computers to simulate building jobs has been the subject of numerous research articles AbouRizk & Shi (1994). Researchers now have more resources to run more accurate simulations because of the advances in technology. Modelling a full construction project, on the other hand, is far more difficult than simulating one or two components of it separately. Construction projects include an excessive number of activities and unpredictable variables, such as weather conditions that can radically alter any project outcome. Furthermore, one task can influence and be influenced by the others. The intricacy of construction projects is one of the key reasons why proper simulation is so challenging. As a result, numerous researchers have turned their attention to simpler simulation for instructional purposes (Nikolic et al., 2011).

BIM makes it easier to create knowledge libraries and learning settings that are favorable to learning. For data management, BIM is a wonderful tool. Through the 3D spatial model of the construction object, it enables easy and quick access to information contained in a single centralized database or in multiple databases kept at separate places. Auditory, visual, and kinesthetic learning environments occur because of BIM qualities such as simple access to information, visualization, and simulation capabilities. Access to the repository at any time and in real time via a 3D model creates a learning environment that is free of time and space constraints, allowing students to learn at their own speed (Barham et al., 2011).

BIM-enabled education can and does exist in different forms, a development that keeps unfolding in recent years. There are massive questions relating to what degree to depend on contextual factors, such as the need for approval from higher authorities, time coordination difficulty, previous BIM knowledge requirement, level of investment required in hardware and software, need for industry mentors and its availability, the number of faculty members needed and its availability, suitability of the model for teaching construction concepts, requirement for BIM mandate, requirement for change in curriculum, extent to which self-learning is involved, suitability for imparting a wide array of BIM concepts and ideas, promotion of interdisciplinary learning / communication / collaboration, time limitations and promotion of communication skills in students (Olowa et al., 2020). For example, Wei & Wang (2018) reported BIM-enhanced safety training within a BIM-enabled environment for occupational awareness improvement. Hu (2019) transformed a traditional Building Materials and Construction Methods course using a BIM-enabled pedagogical approach and teaching platform to help students understand fundamental concepts. Witt & Kähkönen (2019) assert that by enabling the use of real construction project data and simulating more realistic, multidisciplinary workflows in the educational environment, BIM-enabled education offers opportunities to enhance construction education didactics to better align graduate's competences with emerging and future needs, particularly those arising from the digitalization of the construction industry. However, in contrast to BIM-focused learning, the number of documented cases of BIM-enabled education is relatively scarce, suggesting that this stage of BIM education is still emerging.

From the foregoing, BIM-enabled learning very much supports the problem, case, and project based learning and its evolution is also a precursor to an inter-generational shift from the traditional mode of teaching delivery, which was prevalent before the advent of new generations of digital natives that are alleged to have very short attention spans.

Gallagher (1997) argues that these forms of learning emphasize students' learning through active inquiry in groups and integrating their conceptual knowledge with their procedural skills. By so doing it promotes intrinsic motivations and hence encourages questioning and association with and reflection on previously acquired knowledge – an approach referred to as learning how to learn through real-life problems by Boud & Feletti (1999).

BIM-enabled virtual learning environment

COVID-19 has significantly underscored the soaring demand for distributed collaborative, self-paced and adaptive learning among learners. Ku et al., (2011) have long identified these challenges and experimented on what they referred to as a BIM interactive Model (BiM). They described BiM as a platform that combines a virtual environment with BIM for learning purposes and proposed a theoretical web-based virtual world for engaging construction stakeholders in real-time social interaction using a game environment called the second life. The authors contended that integrating 2D and intelligent 3D BIM models would supplement construction education to overcome the limitation of location-based learning and make it accessible to anyone on the internet. Although the authors suggested that this environment could be adapted for learning, it had no ability to record or monitor students' performance, which is an important feature for any learning management system. Other limitations include: the absence of AEC/FM avatars and object libraries; requirement for high level of programming skill to create one; and the non-interoperability with BIM models. Therefore, the focus was mainly on experimenting with the possibility of integrating BIM with the game environment to promote learning with the aid of the internet.

Acknowledging the general consensus among previous developers and authors on the ability of virtual learning environments (VLE) to promote off-site training and education, Shen et al., (2012) used the 3D-UNITY game engine to create a web-based training environment for HVAC rehabilitation and improvement using the BIM model. In contrast to Ku et al., (2011) and the second life platform, the authors argued that game engines have been sufficiently developed for BIM interoperability, thereby making game creation cheaper and easier with little to no need of programming skill. With their research, Shen and his colleagues were able to demonstrate how BIM could be leveraged for teaching at topical level. In all, these studies show that BIM-based serious games can either be used by a single user or multiple users and made interactive by the addition of JavaScript. The level and complexity of the interaction for sustained interest to learn also depends on the level of complexity introduced through the JavaScript and other programming languages. In addition, the reports suggest that BIM-based games would need to be updated outside the game environment using BIM authoring tools before new lessons could be learned, thereby making the gaming less intuitive compared to when there is full and unrestricted access to the raw BIM model. This characteristic may not necessarily be a bad thing as some studies have suggested an inverse correlation between the length of training and training effectiveness in game simulations (Garris et al., 2002).

Accordingly, it is argued that the ultimate idea of most serious games is to encourage synchronous and/or asynchronous distributed learning (Ku et al., 2011; Shen et al., 2012). These arguments make the integration of game environment and learning management systems (LMS) necessary for effective progress monitoring and management of teaching and learning, especially when learning is designed to take place asynchronously. This system is particularly important where formative or summative assessment is required, and students or trainees need to be graded for certification. Identifying the characteristics of a robust BIM-enabled virtual learning environment could coalesce both VLE/LMS and BIM within a dynamic environment capable of fostering project-based learning with either guided or self-assessment and evaluation possibilities.

2 Research methodology

Research methodology is described as the procedure followed in achieving the aim and objective(s) of research (Ogolo, 1996). This research adopted a mixed method approach (i.e., both qualitative and quantitative methods of data collection and analysis were used) to answer the research questions. The main research question was: How can BIM be leveraged for construction education? A combination of primary and secondary sources of data were also employed in providing an answer to the question. The next sections of this chapter discuss the research philosophy, research design and processes adopted in the study.

2.1 Research philosophy

Digitalization is about application of technology for enterprise improvement. Building Information Modelling (BIM) is generally referred to as a technology or technological process among academics and industry practitioners (Azhar, 2011; Bosch-Sijtsema & Gluch, 2021; Gao et al., 2015; Kensek, 2012; Wang & Chien, 2014; Zhang et al., 2021; Zhou & Gao, 2017). The philosophy of technology plays a significant role in the formulation of the research design and in its execution. The philosophy considers technology from two vantage positions, namely power of control (i.e., instrumentalism or substantivism) and value boundedness (i.e., whether technology is value laden or value neutral). The philosophy of instrumentalism considers technology simply as a technique with a definite purpose and outcome. This notion of technology as a simple technique has been criticized by many technology philosophers. For example, Heidegger argues that technology is not value neutral but has intrinsic potential waiting to be revealed by those that interact with it (Heidegger, 1977). This was referred to as *under-determination* and *contingent character* of technology by Feenberg (2012), meaning that the usefulness of any technology cannot be said to be absolute due to many possible contextual factors. So, the way a technology is used is dependent on the agent using it and the agent is morally responsible for its outcome. As such, the view of philosophy of substantivism is that technology is not a neutral instrument but has a deterministic influence on how humans are related to things or one another and that it has a way of influencing our society and culture. This study is premised on the notion that BIM is designed for specific industry domain uses but it also accepts that it could be exploited for other “beneficial” uses in academia to promote active and life-long learning in construction education. Given the foregoing, the specific philosophical and sociological paradigms of ontology, epistemology, and axiology underpinning this research are explicated below.

According to Saunders et al. (2007), research philosophy articulates the assumptions about the way in which a researcher views the world. The philosophical paradigm determines the origin, nature, and development of knowledge that facilitates the selection of acceptable procedures for conducting a research inquiry (Bazeley, 2013). Since this research aims to find and proffer practical and useful ways to leverage BIM for construction education in AEC/FM disciplines, it is considered suitable to approach the study from a pragmatic perspective of “what works” in order to find effective answers to the research questions (Deering et al., 2020; Kelly and Cordeiro, 2020; Bilau, 2018). Pragmatists often use both qualitative and quantitative methodologies to study distinct aspects of a research subject, combining positivist and constructivist concepts in the same research effort. The main principles of pragmatism imbued in this study relate to change and determinism (Corbin & Strauss, 1990). With change, phenomena and reality are not thought of as static but as constantly evolving, interpreted, and renegotiated in reaction to new and unpredictable situations. An important component of this research is to incorporate change into the construction education approach through a process and this suits well within pragmatism. Pragmatism rejects both absolute-determinism and non-determinism because actors are believed to have the ability to control their fate by their choices including responses to conditions surrounding them (Corbin & Strauss, 1990). Consequently, it is accepted that, for some of the research objectives, the researcher's background plays a significant role in the study. Similarly, the study results are largely determined by the lived experiences, backgrounds, and values of the research participants, such as the literature authors and expert interviewees from whom data were collected (Bazeley, 2013; Bilau, 2018).

Ontology is concerned with how individuals experience reality, its nature, and its assumptions including the study of being (Crotty, 2020; Easterby-Smith, 2008). Ontology is linked to realism and idealism as the two ends of a continuum in ontological notions that try to explain how things 'actually are' and how things 'truly work'. Therefore, based on the nature of inquiry in this dissertation, the ontological assumption implies that the nature of reality concerning the usefulness of BIM for construction education is external to the researcher by exploring how BIM for construction education is done and how it can work within a selected context.

Epistemology is concerned with the development of knowledge and the nature of that knowledge; as a study of knowledge, it helps in the quest of determining and knowing what reality is. Hence, epistemology deals with what constitutes acceptable knowledge in a certain field (Saunders et al., 2009). According to Eriksson & Kovalainen (2011) this knowledge could either be objective (positivism/post-positivism), subjective (constructivism) or both – like in the case of pragmatism, which offers a different interpretive framework from both objective and subjective knowledge and focuses on the research problem and its consequences (Corbin & Strauss, 1990). The development of knowledge and its nature in this research revolves around the objective and measurable reality of positivism using structured questionnaires, the contextualized causal understanding of realism via semi-structured interviews, and the subjective plurality of interpretivism through grounded theory.

Axiology is concerned with what kinds of things are of value and why they are (Houkes, 2009). Questions relating to what morally matters in exploiting BIM phenomenon through BIM for construction education are viewed under axiology. A researcher's personal values, beliefs and experiences play important roles in shaping the narrative of research and this may either be acknowledged to influence the research giving rise to (value-laden) interpretivist research or the researcher may attempt to be unbiased regarding values – positivist, value-neutral research (Houkes, 2009). Mixed method research presupposes a combination of qualitative and quantitative research in its implementation. Qualitative research is inherently value-laden because of its subjectivity. This study adopts a mixed method approach by recognizing the value-boundedness in the qualitative aspects of the study and making efforts to preserve the integrity of the findings by being consciously reflecting on possible interference of personal values in the research results.

Based on the aim of this research, knowledge could be acquired from both within and outside the current social phenomena – thus suggesting critical realist ontology and symbolic interactionism epistemology. The critical realist stance holds that while technology exists independent of its users, users socially construct technology through their use of it. This implies that technological practices should always be addressed with a critical agenda that asks if there are better ways to use the technology (Çıdık et al., 2017). Similarly, symbolic interactionism holds that "human beings act toward things on the basis of the meanings that the things have for them… the meaning of such things is derived from, or arises out of, the social interaction that one has with one's fellows… these meanings are handled in, and modified through, an interpretative process used by the person in dealing with the things he encounters" (Bumer, 1986). The pragmatic viewpoint allows knowledge to emerge without being bound by a particular interpretation of reality. It recognizes that research takes place in a variety of historical, social, and political contexts, and it allows for the use of various data gathering and analytic methodologies for knowledge production (Creswell., 2013).

2.2 Research design

This study employed a cross-sectional exploratory research design (Hair et al., 2020). Some of the key characteristics considered in selecting this type of research design include:

1) It allows the study to be phased and each phase concluded within a reasonable period with data for each phase collected at a single point in time.
2) It does not involve manipulating variables since the study is predominantly a qualitative study.
3) The ability to consider many attributes at the same time in a study.
4) The ability to explore and derive understanding about the prevailing characteristics in a particular population at a particular time (Levin, 2006).

The detailed research process is discussed in the next section.

Research process

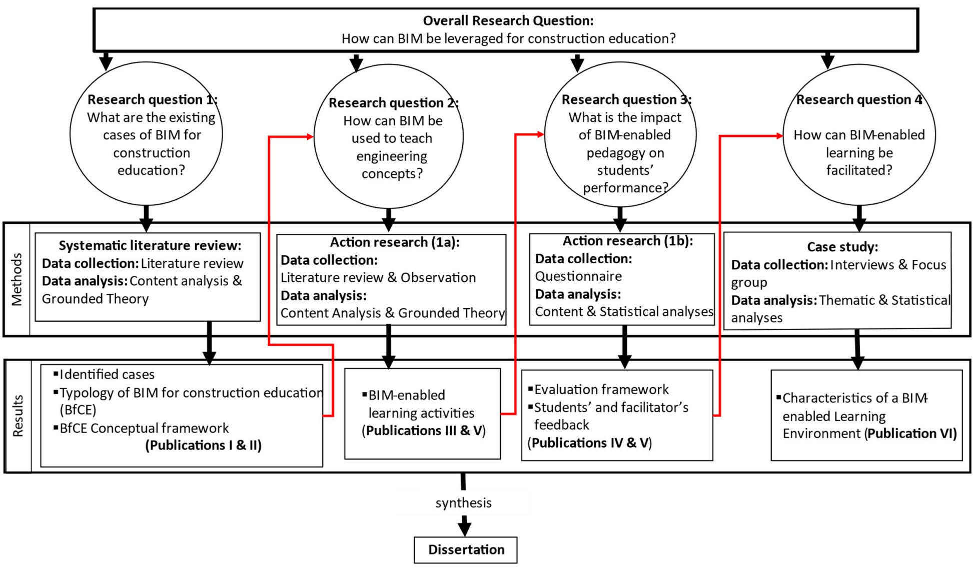

Figure 1: Research process and outcome

Figure 1 diagrammatically represents the research process. The complexity of the research aim requires decomposing the overall research question into four specific research questions such that the synthesis of their answers will result in providing effective response to the overall research question. As such, the research started by identifying the state of the art of general BIM education in AEC/FM disciplines and making sense of the different publicly available documented BIM educational practices. This was done by using a systematic literature review upon which the conceptual framework for understanding BIM education implementation strategies was derived, as later shown and discussed in Figure 3 under section 3.3. The systematic literature review and the developed conceptual framework for BIM for construction education inspired the action research that was followed. A survey of expert opinions was then carried out to identify and validate the characteristics of a BIM-enabled learning environment to facilitate more convenient delivery of BIM for construction education initiatives in the future. A summary description of these processes is given in the next section with detailed description in respective publications.

Systematic literature review

The systematic literature review was carried out in two stages to address research questions one and two. The aim of the preliminary review was to get a better understanding of existing BIM education examples, their characteristics, the obstacles they experience in implementation, and any clear trends to ensure that the doctoral research effort may be focused (Olowa et al., 2019). The second aim was to understand and make sense of the diverse BIM for construction education practices.

The literature search was carried out in September 2018 and updated in February 2019. Keyword searches were conducted in six databases that were chosen for their extensive coverage of peer-reviewed journal articles and conference proceedings namely EBSCOhost Web, Science Direct, ASCE Library, Emerald Insight, Scopus, and Web of Science. The algorithms of the database search engines listed the articles returned from database searches in order of relevance, with the articles most aligned with the search string and filters appearing at the top of the list and those increasingly less aligned with the search terms appearing further down the list. The articles were evaluated based on their titles and, if necessary, their abstracts, to determine their relevance to this investigation. The articles (as pdf files) were downloaded using the Mendeley online plugin in conjunction with the Google Chrome browser for further analysis. Using Mendeley reference management software, the files were combined to detect and delete duplicates. This yielded a total of 305 relevant BIM for construction education articles (Olowa et al., 2020). Findings were drawn from the paper leading to conceptual framework for understanding BIM for construction education approaches and gap analysis on which the action research described in the next section could be carried out to further address research question two and provide insight into research question three.

Action research

The action research was used to further illuminate research question two and provide answer to question three. The action research followed the five-phase process recommended by Susman & Evered (2016), as represented in Figure 2. These cyclic process phases include diagnosing, planning, action taking, evaluating, and specifying learning. Action research has been argued to offer a systematic procedure to address teaching improvements in their educational setting (Creswell 2012). Action research methodologies have been used successfully in BIM education studies where it was necessary to simultaneously carry on intervention implementation while interacting with staff and students to evaluate what works, what does not, and to trial changes. (e.g., Comiskey et al., 2017; Pärn & Edwards, 2017; Puolitaival & Forsythe, 2016; Williams et al., 2004).

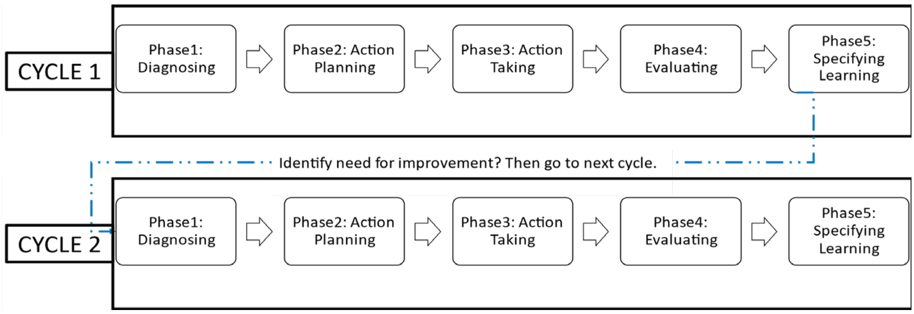

Figure 2: The action research process applied

The action research was carried out in two successive cycles among student participants of a construction investment course in 2019 and 2020. The action research resulted in a BIM for construction education learning object and activity design at a topical level and a framework of engineering evaluation which was used to evaluate the BIM for construction education intervention (Figure 4). The experiences of the action research prepared the ground and assisted in the design of a case study to respond to the fourth research question, as described in the next section.

Case study

Case study approach was adopted to answer research question four by exploring how BIM-enabled learning could be facilitated. According to Baxter & Jack (2008) "case study methodology provides tools for researchers to study complex phenomena within their contexts… using a variety of data sources". This guarantees that the topic is not examined through a single lens but rather through a multitude of lenses, allowing for the discovery and understanding of numerous aspects of the events (ibid). One of the benefits of this approach is the close collaboration between the researcher and the participant, as well as the ability for participants to share their own stories (Crabtree & Miller, 1999). Participants can convey their perceptions of reality through these stories, which allows the researcher to better comprehend the participants' activities (Robottom & Hart, 1993). According to Yin (2003), a case study research approach is suitable when: (a) the study is concerned with "how" and "why" questions; (b) it is impossible to control the behaviour of the participants in the study; (c) the contextual conditions are relevant to the study; or (d) it is difficult to clearly delineate the boundaries between the phenomenon and context.

Adaptive structuration theory (AST) is used to understand and evaluate the interaction between advanced information technologies (AITs), social structures, and human interaction (DeSanctis & Poole, 1994; Gopal et al., 1992). According to (DeSanctis & Poole, 1994), AIT is described as information technology that supports and establishes organizational procedures relating to task performance, coordination among people, and interpersonal exchanges. The intention to define a BIM-enabled learning was borne from the challenges experienced during the participatory action research, where cordination of the learning activity was considered chaotic. In this research, AST offered the opportunity to identify the characteristics for a platform that can promote similar experiences in a less challenging way (Theophilus Olowa et al., 2022).

Applying AST concepts, an exploratory case study of the characteristics for a platform capable of enhancing BIM for construction education was conducted. The inquiry considered the case of educators and trainers in three EU countries of Italy, Finland and Estonia in AEC/FM disciplines that were either in private or public institutions. Data were collected via both semi-structured interview and online questionnaire. Before the interview began, some BIM for construction education cases were analysed through desk study and faculty reflections to identify a priori some themes relating to the phenomenon and these guided in the development of the interview and questionnaire designs. 31 participants took part in the interview that lasted between 45 and 60 minutes after their consents were sought and received. The interviewees were purposively selected because of the technicality of the subject under study. The interviews were audio recorded, transcribed and analysed using thematic analysis with the aid of NVivo (QSR International Pty Ltd, 2020). Afterwards, the questionnaires were distributed during an online workshop among some 30 BIM experts (both from industry and academia) with 10 questionnaires completed and used for the validation of the results from the analysed interviews.

The result identified 33 characteristics of a platform that would support BIM for construction education in an immersive environment with real industry data (Olowa et al., 2022).

3 Findings

This chapter presents major findings of the research. The study sets out to explore how BIM could be leveraged for construction education. Findings included in this chapter relate to the challenges confronting BIM for construction education, typology of BIM for construction education, BIM for construction education conceptual framework, BIM for construction education evaluation framework, Bloom's taxonomy and BIM for construction education, and the characteristics of a BIM-enabled learning environment.

3.1 Challenges of BIM for construction education

This section identifies several issues associated with BIM for construction education practices that constitute some form of challenges and barriers in one way or another. Improper attention and management of these issues could render ineffective or totally defeat the intentions and/or learning outcomes for which the interventions were initiated.

Challenges and barriers were identified from a systematic review of the literature, experience and reflections from the action research, and expert interviews carried out in three countries in Europe.

Differing skill levels among learners, time and workload

Findings show that it is difficult (if not impossible) for all learners to be at the same skill level, especially with BIM technology and its workflow management. Learners in a particular group or class do have different exposures to construction industry activities and workflows in terms of hand on experiences, construction backgrounds or even professional practice. Having different skill levels among learners should not be viewed as anything bad as it could create a more interesting and engaging learning experience for those involved if properly managed. This is also a typical phenomenon in the broader construction industry, whence professionals of different discipline and varying degree of skills must communicate, collaborate, and negotiate in delivering construction projects.

When preparing BIM for construction education group activities, the educator must identify learners of different skills, exposure, discipline, and experience and make sure to balance the group composition with all of these in mind. Conversely, the level of learning activities must be based on the time available for such activities in the curriculum. Adequate consideration must also be given to the learners' workload in other courses to avoid excessive workload for them.

Technical support Interoperability problems

The research also found that achieving a seamless handshake between BIM software developed by different vendors was problematic. As such, extra time is expended on software selection in teaching practice to avoid chaos and time wastage during the actual class activity. The software architecture of BIM software from different vendors does not align in most cases making it difficult to open BIM files in non-native application. This is understandable from the business perspective of the vendors because they would rather want their suite of software to be patronized and increase their bottom line therefrom. Unfortunately, this does not promote interoperability and makes integration difficult.

A great effort is already going into interoperability of BIM software through initiatives like those championed by buildingSMART international to create OpenBIM that aims to guarantee seamless handshake among industry BIM software. This will likely benefit all stakeholders and the management of assets' lifecycles. Industry Foundation Class (IFC) is the foundation on which OpenBIM runs and it has recently been updated with two specific features (i.e., design transfer and reference views) in IFC4. With IFC4 it is becoming more possible to carry out data transfer and exchanges in a completely vendor-neutral manner with reduced glitches in data integrity. Construction Building Information Exchange (COBie), common BIM requirement (coBIM) etc., are similar initiatives geared toward the same goal of ensuring interoperability. These initiatives give hope that BIM exercises in the classroom and training centers will get easier in the future.

What to teach and learning content

A major constraint to BIM for construction education among academics and trainers is the confusion of knowing how to go about competency-based BIM for construction education. This was found to be a challenge in situations where already designed curriculums to which academics could tailor their trainings were nonexistent or unclear. Curriculum design requires additional skills from academics and not all academics have such a skill, which sometimes results in their unwillingness to change. These skills include setting objectives and designing contents to achieve such objectives, including means of objectively conducting formative and summative assessment and evaluation in line with acceptable standard knowledge domains by supervising authorities etc.

As a result of the versatility of BIM and the difficulty of teaching everything that is BIM-based, there is no consensus among academics on what is considered best to teach and how to teach it.

Complexity of example projects

BIM-enabled learning requires BIM models that are suitable for class activities with reasonable level of detail that is commensurate with the learning objective. While it is good to train students with real project data, in most cases, the structure of the data is not organized for classroom exercise. To make the industry data useful for class activities, the instructor needs to spend some time in cleaning up and re-arranging the data. Thus, it requires serious effort on the part of the instructor during the design of the learning activities. This effort could be reduced if the model is designed for the purpose of education from the beginning by commissioning a designer or group of designers. A cost benefit analysis can determine the appropriateness of commissioning designers for educational BIM models. The cost may not be justifiable if the BIM-enabled learning is at a topical level. But might be advisable for a programme wide course.

Associated with this problem is the issue of not infringing on the intellectual property rights of the originators of the example projects. This issue is limited where designers are commissioned to design BIM examples – this is also prone to oversimplification of reality. As such, in planning for the learning activity, a balance must be sought on the best source for the example projects.

While BIM-enabled learning was generally accepted by the students and regarded as engaging and instructive, it was also observed that some students were not favorably disposed to it. This could be due to a couple of reasons. Firstly, not all students learn at the same pace. And since the activities in the class exercises are time bound, it is understandable that learners not able to meet up with the deliverables are likely to be disenchanted because of the fear of having low scores in their formative/summative assessment – since most students are motivated to learn because of assessment. Secondly, despite the widespread and general social acceptance of technology, it cannot be completely ruled out that some students might also be technophobic for whatever reason.

Again, the fact that the course in which the exercise was trialed is one of the few courses whose language of instruction is in English at the university, a few local and international exchange students (who might not understand the language of instruction in other courses) sometimes prefer to register for the course. Some of these students were also non-construction specialty students. Taking a construction investment course at such a level without prior construction background knowledge requires extra effort, which could be frustrating if the time is not available.

Skill levels among educators

This research has found that the level of BIM skill among educators should be commensurate to what is being taught as it is difficult for 'something to come out of nothing'. In the case of the BIM exercise conducted in this research, part of the aim was to demonstrate how BIM model at different BIM workflow stages is progressively elaborated to reflect industry practice. With the cashflow exercise, the important skill required was the ability to extract data from BIM model and manipulate it using excel spreadsheet before updating the BIM model data. Therefore, for different objectives, more diverse skills may be required.

The level of teamwork and collaboration required among educators from different courses or disciplines to execute the BIM-enabled learning could also be a challenge if not properly managed, especially in integrated capstone courses.

Accreditation and curriculum constraints issues

It takes a lot of conviction on the part of an educator to pursue a curriculum that has not been expressly sanctioned by accreditation and academic governing bodies. This is apart from the difficulty of finding a suitable space for BIM-enabled learning in curriculums that are usually already deemed tight and sometimes overloaded. Moreover, extra effort is required on the part of the educators because when topics/courses are not allowed for in a curriculum, the paraphernalia or resources required to conveniently implement them are usually non-existent or in short supply. The study found the need for accreditors to embrace the paradigm shift in the design, implementation, and general ways of working in the construction sector that must be reflected also in the classroom. Educators cannot keep training analog graduates for a digital industry.

BIM-enabled learning is technology intensive especially at an inter-institutional level where different disciplines in AEC/FM are to collaborate. This type of collaboration will also require investment in technologies for delivering blended learning in an effective manner for institutions that lack them. Further details regarding the identification of challenges and how some of these could be resolved can be found in **publications I-VI**.

3.2 Typology of BIM for construction education

In this research, ten distinct approaches to BIM for construction education were identified (Table 1). The different strategies engaged by academic practitioners and education researchers to engender BIM for construction education within AEC/FM curricula were typified in a framework. This was important to understand the different approaches to BIM for construction education that were currently in practice in order to overcome the challenges of "what, where and how to teach". The naming convention was based on four attributes, namely level(s) of curriculum activity, discipline(s) involved, scope or reach of the learning activity, and the number of institutions involved. The ten approaches are listed below:

1) Undergraduate single discipline (Topic) – in a single institution
2) Undergraduate single discipline (Course) – in a single institution
3) Undergraduate Multidisciplinary (Course) – in a single institution

4) Undergraduate Multidisciplinary (Course) – in multiple institutions
5) Postgraduate single discipline (Course) – in a single institution
6) Postgraduate multidisciplinary (Course) – in a single institution
7) Mixed Level Single Discipline (Course) – in a single institution
8) Mixed Level Multidisciplinary (Course) – in single institutions
9) Mixed Level Multidisciplinary (Course) – in multiple institutions
10) Mixed-MULTIPLE Levels Multidisciplinary (Course) – in a single institution

Table 1: Typology of BIM for construction education approaches with examples

Level			Discipline		Scope			Institutions		Examples found in the literature
Undergraduate	Postgraduate	Mixed	Single	Multiple	Topic(s) within course	Full course	Multiple courses / programme	Single	Multiple	
X			X		X			X		Sharag-Eldin & Nawari (2010)
X			X				X	X		Kim (2014); Palomera-Arias (2015); Zhang, Xie, & Li (2017)
X			X			X		X		Pikas et al. (2013); Brioso et al. (2017); Wang & Leite (2014); Dougherty & Parfitt (2013); Mathews (2013); Sands et al., (2018); Shenton et al. (2014); Livingston (2008); Barham et al. (2011); Palomera-Arias & Liu (2016); Shanbari et al., (2016); Yi & Yun (2018)
X				X			X	X		Comiskey et al., (2017); Solnosky & Parfitt (2015); Wong et al., (2011)
X				X		X		X		Bozoglu (2016); Zhang, Wu, & Li (2018); Pikas et al. (2013); Monson & Dossick (2014); Jin et al. (2018); Nawari et al., (2014)
X				X			X		X	Comiskey et al. (2017)
	X		X				X	X		Hijazi, Donaubauer, & Kolbe (2018)
	X		X			X		X		Wang & Leite, (2014); Suwal & Singh (2018); Sampaio, (2015); Pikas et al. (2013); Nassar (2012)
	X			X		X		X		Bozoglu (2016); Charlesraj et al., (2015); Pikas et al., 2013; Shanbari et al., 2016
		X	X			X		X		Wu & Hyatt (2016); Lewis et al. (2015); Hu (2019)
		X		X		X		X		Chiuini et al., (2013); Rassati et al., (2010); Leite (2016)
		X		X		X			X	Becerik-Gerber et al., (2012); Zhao et al., (2015)

The typology in Table 1, presents a clearer path to the available methods and strategies for implementing BIM for construction education initiatives at any individual level. It was, however, important to also understand how all this is connected in the global digitalization drive of the construction industry and the educational context. This understanding was explored through the development of the conceptual framework in the next section.

3.3 BIM for construction education conceptual framework

The conceptual framework in Figure 3 gives a broad explanation of the strategies available to academics for BIM-enabled education and the resulting consequences from a global perspective on the digitalization of the construction industry.

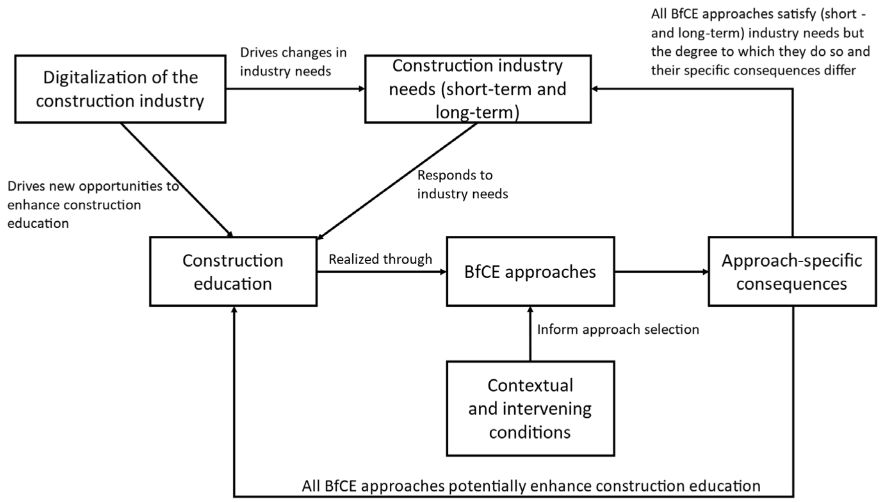

Figure 3: Conceptual framework of BIM for construction education

The research uncovers substantial rethinking and re-organization in the operational and delivery mode of the construction industry's workflows and management processes due to the ongoing digitalization and globalization. This re-organization also demands new industry roles that hitherto were not part of the construction industry's culture. The new roles require new skills, knowledge, and attitudes, which are all dictated by the form and nature of digitalization and the requirement for global culture in sustainable education. The urgency of providing competent graduates to fulfil these roles also demands a restructuring of the construction education with the infusion of BIM as the backbone on which some other prominently important smart and digital technologies of the digitalization processes can ride. As the demand for BIM competent graduates required to fill new roles are met (the short-term needs), new and innovative opportunities are simultaneously presented to academics in AEC/FM disciplines to leverage BIM for their teaching practices by experimenting with alternative didactic methodologies in meeting both the short-term and the long-term needs). Because there is no single "truth" in the way academics perceive the usefulness of BIM technology in the classroom, exploring its benefit led to the emergence of several approaches and implementation strategies among academics. Examples of these approaches include integrating curricula within and across courses/disciplines and using real project data for closer connection of the education and industry environments – for enhanced teaching and learning in the form of BIM-enabled education. While these approaches are intended to meet the industry needs, the choice of approach is guided by the prevailing context. Whatever approach is adopted, it results in a specific consequence, which in turn impacts the construction industry. The different specific approaches with their description are available in **publication II**.

3.4 Evaluation framework

Evaluation was found to be an important aspect of intervention endeavors, which was observed as not explicitly practiced and reported among the extant literature in this research. The purpose of evaluation is to know what works and what needs improvement, without which academics would be conducting their practices in an inefficient manner. During the development of the learning activity that preceded the action research intervention in this research, it was observed that no standard evaluation technique had been documented that was useful to evaluate the proposed study.

Consequently, a desk study and a literature review study were carried out to establish an acceptable and rigorous framework to be applied as shown in Figure 4.

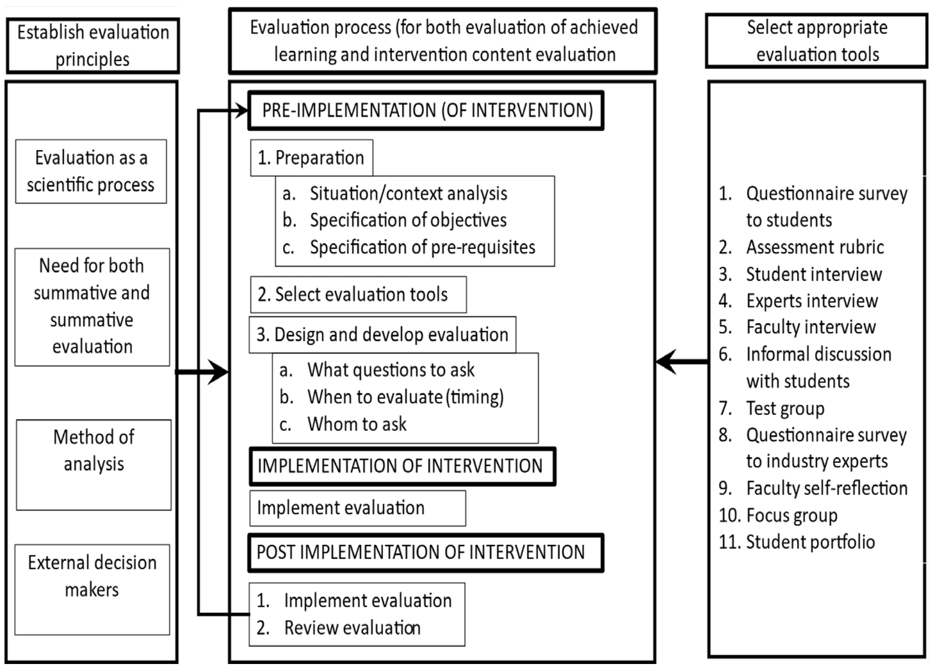

Figure 4: Framework for construction engineering evaluation

The development of this framework guided in deciding on the appropriate evaluation principle by giving prior thoughts and consciously deciding on whether evaluation was considered as a subjective or objective activity; whether it was possible to carry out both formative and summative evaluations; type of suitable evaluation analysis; and the involvement of external stakeholders or evaluators in the evaluation exercise. The framework also guided the three stages of pre-implementation, implementation and post-implementation plans and the selection of suitable evaluation tools for each of the three stages of the intervention.

In the first iteration of the intervention and before the development of the framework, evaluation was only conducted at the post-implementation stage. However, in the second iteration, evaluation was possible during both the pre- and post-implementation stages only as there was no opportunity for "implementation" stage evaluation in the type of intervention conducted in this research. Using both the questionnaire survey to students and the faculty reflection, the impact of the learning activity (cashflow exercise) is reported in section 3.5.

3.5 Cashflow exercise impact findings

This section presents the result of the questionnaire survey distributed to student participants during the cashflow learning activities. Table 2 shows the descriptive statistical analysis of the five questions asked after the exercise was completed. The questions were designed in a Likert scale format where 5 = Absolute Yes, 4 = Qualified Yes, 3 = Neutral, 2 = Qualified No and 1 = Absolute No.

Table 2: Implementation survey results of students' satisfaction in cycle 1

Question	Mean	Std. Deviation
Was the purpose of the exercise clear?	4.50	0.548
Did you find the exercise interesting?	4.33	.2.11
Was it helpful to link the exercise to 'real' project data?	4.33	0.816
Was it helpful to link the exercise to the BIM workflow?	3.50	1.378
Did the exercise complement previous course materials or lessons?	4.33	0.816

The results showed that majority of the student participants responded positively to the questions asked. They indicated that the purpose of the exercise was clear and engaging; the link to real project data and BIM workflow was helpful; and that it complemented their previous learning experiences. However, the response to whether "it was helpful to link the exercise to the BIM workflow" received a relatively lower positive response compared to the rest of the questions asked.

The results of the implementation survey for the second cycle are shown in Table 3. Students' opinions on the learning activity were sought twice in the cycle 2. The result of the first round of the questionnaire distributed is reflected under "pre-implementation" column while that of the second round is under the "post-implementation" column.

The results indicate that very few students acknowledged ever being taught any BIM related topics and that they have a limited understanding of what it entails. Despite this deficiency there was an observable jump in three important indicators that the exercise was well received by the students. The first was the question "Do you understand how cash flow and cash flow calculations relate to construction projects?" The second was the question "Do you understand how cash flow relates to a BIM workflow?" Lastly, the question "Do you understand how different companies involved in a construction project can collaborate in order to optimize the project cash flow?" The mean responses jumped from 2.94, 1.69, 2.28 at the pre-implementation stage to 3.92, 3.33, 4.14 at the post-implementation stage. Section 3.6 explains how this relates to the Bloom's taxonomy of cognitive knowledge domains.

Table 3: Implementation survey results in cycle 2

Questions	Pre-implementation		Post-implementation	
	Mean	Std. deviation	Mean	Std. deviation
Have you been taught about Building Information Modelling (BIM) in any previous courses?	2.83	2.007	NA	NA
If yes, how would you rate your current understanding of BIM?	1.64	1.391	NA	NA
Do you enjoy working in groups/teams?	4.56	0.856	4.59	1.004
Do you find it useful for your own understanding to discuss problems/calculations/solutions with your peers?	4.56	1.149	4.82	0.728
Do you understand how cash flow and cash flow calculations relate to construction projects?	2.94	1.097	3.92	0.493
Do you understand how cash flow relates to a BIM workflow?	1.69	0.910	3.33	0.924
Do you understand how different companies involved in a construction project can collaborate in order to optimize the project cash flow?	2.28	1.239	4.14	0.660
How important are cash flows to companies involved in construction projects?	NA	NA	4.56	0.482
Would you be interested if a similar BIM workflow is used to explain other subjects (concepts) apart from cash flow?	NA	NA	4.06	0.906
Was the purpose of the exercise clear?	NA	NA	4.28	1.074
Did you find the exercise interesting?	NA	NA	4.83	0.707
Did the exercise complement previous course materials or lessons?	NA	NA	4.94	0.243
Did the exercise improve your overall knowledge of cash flow?	NA	NA	4.56	0.856
Was it helpful to link the exercise to 'real' project data?	NA	NA	5.00	0.000

* NA=Not applicable.

3.6 Bloom's taxonomy and BIM for construction education

Bloom's revised taxonomy of educational objectives was applied in the research because it is a popular tool for setting teaching goals and designing relevant learning outcomes. It is also very useful in assessing the cognitive domain (knowledge) level attainable from a learning activity. The lower order skills in the taxonomy include remember, understand, and apply while the higher order skills include analyze, evaluate, and create. A robust learning activity is the one that can take learners through the behavioral outcome rungs from knowledge all the way to create.

Figure 5 shows how the BIM-based learning activities offered learners to move through all the stages of the lower order skills to the higher order skills. In other cases, a combination of several learning activities may be required to achieve behavioral change that would accommodate all the six levels of Bloom's taxonomy – that is also acceptable in teaching practice. However, with the BIM-enabled learning activity, these behavioral outcomes were attained within a period of 3 – 4 contact hours which could be considered as an effective and productive time for knowledge transfer.

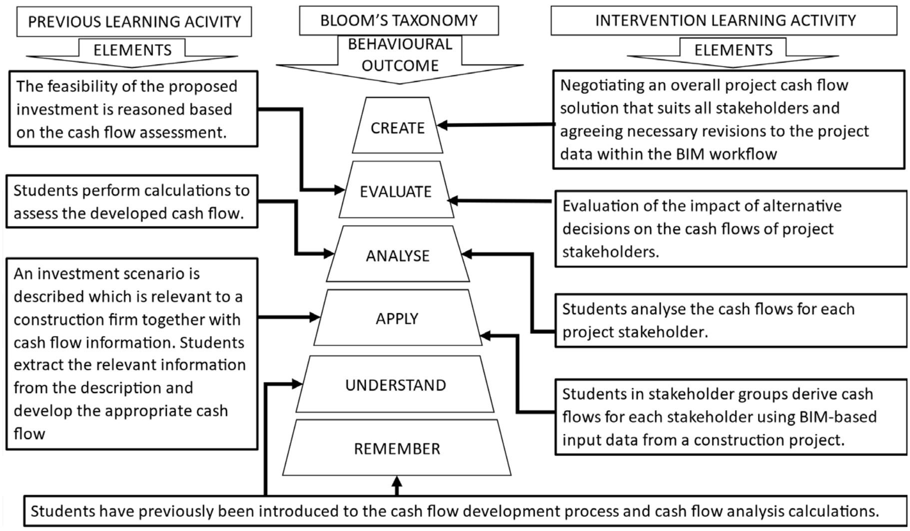

Figure 5: Learning activities and outcomes for the BIM-enabled intervention

3.7 Characteristics of a BIM-enabled learning environment

A purpose-built BIM-enabled Learning Environment would facilitate improved and more efficient BIM-enabled learning activities and experiences. Presently, based on the experiences from the action research and case studies (**publication V**), learning in a BIM-enabled environment can only be conducted using non-integrated and independent proprietary software applications like Revit, Navisworks, Excel, MS teams, Google sheets, Moodle, Tekla structures etc. Because of this, seamlessly exchanging data and managing data versions were difficult to achieve. Hence, a platform that would provide a single environment for hosting learning objects, learning management, collaboration, communication, learning reflections (e-portfolios), and assessment would be instrumental in enhancing BIM-enabled education.

In exploring the ideal characteristics of such a platform (also referred to as "BIM-enabled learning environment"), 33 functional requirements were identified as shown in Figure 6. These were grouped into three functional domains: virtual learning function, collaboration function and BIM function.

Function type	Function
	Student feedback.
	Questionnaire creation, completing, submission
	Assessment / grading functions - grade entering for individuals / groups, grade book.
	Data security/password protection
	Video playback
	Gamification
Virtual learning function	Registration of users (learners/instructors)
	Integration of platform with external systems/business
	Hosting of different courses
	File upload, storage, download, sharing, editing.
	Individual learners' storage for learning materials
	Instructor access and monitoring of groups and group work.
	Recording of lessons/ group sessions
	Linking with other courses
Collaboration function	Document collaborative viewing and editing.
	Spreadsheet collaborative viewing and editing.
	Group formation.
	Collaboration in groups.
	Collaboration between groups.
	Live interactions between users
	Simulation of project development process (BIM workflow, in stakeholder groups)
	Common Data Environment for project data.
	Version management
	XR: AR/ VR/ MR functions
	BIM model data extraction.
BIM function	BIM model collaborative viewing and editing.
	BIM model checking.
	BIM model editing.
	BIM model creating.
	BIM model repository.
	BIM model viewing.
	BIM object creation and editing
	BIM model sharing.

Figure 6: Characteristics of BIM-enabled learning

4 Conclusions and recommendations

4.1 Conclusion

Digitalization is influencing the pedagogical methodologies in construction education. Building Information Modelling (BIM) is at the center of this change, and it offers opportunities for teaching and learning improvements.

This doctoral research aimed to explore how BIM could be leveraged to enhance construction education through qualitative research. The research adopted a pragmatic approach to this exploration by approaching the study from different viewpoints and adopting methods that are most suited for each area of study. As such, a mixed method research involving systematic literature reviews, action research and case study were employed in this exploratory study.

As theoretical and practical contributions, the research identified, demonstrated, and evaluated how Building Information Modelling could be used to facilitate construction education. The research also identified several challenges militating against BIM for construction education among academics in higher institutions and was able to address some of the identified BIM for construction education challenges by developing a typology of BIM for construction education approaches to provide academics and researchers an informed list of available approaches for executing BIM for construction education. This will assist academics to determine what to teach and how to teach it. The study also observed that the lack of documented clear guidance on evaluating BIM for construction education could also reduce the effectiveness of BIM for construction education intervention. Therefore, a BIM for construction education evaluation framework was developed. This framework is useful in providing guidance for evaluating academic interventions in the AEC/FM disciplines. This could also be extended to other similar educational initiatives in other disciplines.

Furthermore, the study also demonstrates how a BIM for construction education intervention at a topical level could be achieved and used to promote both lower and higher order skills of Bloom's cognitive knowledge domain. The learning object and activities were used to actively engage the students in near real industry collaborative experience in a BIM-enabled learning and immersive environment. At the end, most students were positively disposed toward the initiative. The value of this type of BIM for construction education approach is confirmed by the responses from student participants' surveys and facilitators' comments at the end of each cycle. The topical level of the intervention has the advantage of not requiring a significant change in the existing curriculum, but it does require a significant amount of time to provide the learning activity contextual knowledge.

Additionally, a list of characteristics for an ideal BIM-enabled learning environment was identified and validated in this research. The concept of advanced information technology in Adaptive Structuration Theory (AST) assisted in interpreting and understanding these characteristics. The 33 characteristics identified and validated were grouped into three domains of virtual learning functions, BIM functions and collaborative functions. These functions are necessary in a BIM-enabled learning environment. In interpreting and understanding the characteristics for a BIM-enabled learning environment, AST also provides an opportunity to evaluate the social impact of their use in different organizations.

4.2 Limitations

The barriers identified in this research for BIM for construction education include those from the literature database used in this study, the key words used and from the BIM for construction education initiative presented in the action research cycles. Using a different database or keyword might produce an additional list of challenges facing BIM for construction education just as conducting BIM for construction education initiative under a different context.

The learning activities reported in this study took place in only two iterations within the same context while the facilitators were also directly involved in the evaluation design and implementation. Thus, the reported positive disposition of the student participants in this study could be biased due to the involvement of the facilitators in data collection albeit anonymously. This could have resulted in giving a false positive report.

The list of characteristics for an immersive BIM-enabled learning environment was generated based on a limited number of experts from three European countries. This might not be robust enough, considering the different possible contexts and approaches available for BIM for construction education.

4.3 Recommendation for further research

Based on the above conclusions and observed limitations, further research should be carried out using a different set of keywords to identify any other challenges that might not have been identified in this study. Likewise, the BIM for construction education typology developed in this research should also be expanded upon by the same means.

Research should probe into how the BIM-enabled learning activities could be carried out in other social and organizational contexts by varying the subjects, student level, type of institution etc. Where possible, evaluations of BIM for construction education in these contexts should also engage independent evaluators to avoid possible bias in evaluation and thus provide a true objective reflection of the intervention outcome. A longitudinal study that considers how BIM for construction education impacts student learning and motivation for lifelong learning is also recommended.

Additionally, future research should attempt to explore or investigate additional characteristics for a versatile and robust immersive BIM-enabled learning environment.

List of figures

List of tables

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# Abstract

Facilitating BIM-enabled learning in construction education

To meet the demands of the 21st century, the construction industry is currently undergoing digitalisation which is causing a vortex of disruptions as industry workflows change and these, in turn, require new approaches to information management, communication, and knowledge in order to deliver new and acceptable projects. This has led to a mismatch between graduates' competencies and their emerging roles in an industry striving towards the adoption of web 4.0 technologies. To address this, it is important for construction educators to devise novel and innovative ways to enhance teaching and increase the motivation to study among the new generation of construction students.

Building Information Modelling (BIM) – the digital representation of all information relating to a constructed asset throughout its life – is a central phenomenon in this revolution and, while BIM is pivotal to the disruption of the construction industry, it also offers opportunities for enhancing education both in the classroom and for continuous professional development in practice. Since BIM incorporates real industry data that are conveniently structured around 3D parametric models of buildings and other constructed assets, it can be leveraged to enable problem- and project-based teaching and active learning within immersive, digital, model-based learning environments. Despite the educational possibilities inherent in BIM, neither robust frameworks for educators and trainers to understand the strategies available for exploiting BIM for construction education nor sufficient teaching and learning resources are yet in place.

The purpose of this research was to understand how BIM can be used to facilitate construction education. The overall research question was formulated as: How can BIM be leveraged for construction education? This was decomposed into four, specific research questions, each of which highlighted particular themes of the inquiry while also shaping succeeding research questions:

- Research question 1: What are the existing cases of BIM for construction education?
- Research question 2: How can BIM be used to teach engineering concepts?
- Research question 3: What is the impact of BIM-enabled pedagogy on students' performance?
- Research question 4: How can BIM-enabled learning be facilitated?

With the focus of this research on action to reform construction education in response to contextual changes, pragmatism was adopted as the research paradigm. The philosophical and methodological approaches were thus selected on the basis that they were most appropriate to the particular research problem being investigated, leading to mixed methods research. For research question 1 (What are the existing cases of BIM for construction education?), a systematic literature review of existing cases of BIM for construction education in universities was carried out. The cases were identified and described, then qualitatively analysed using the Straussian Theory Model of Grounded Theory in order to understand and classify the different approaches to BIM for construction education and to derive a conceptual framework relating the different approaches to the construction industry and educational contexts.

Research question 2 (How can BIM be used to teach engineering concepts?) was explored on the basis of document analysis and reflection culminating in a comparative

description of the current and the proposed approaches to teaching project risk management. In addition, academic articles and educational (non-research) guidance literature were reviewed to identify existing evaluation models and to determine specific evaluation methods for application to BIM-enabled education initiatives. These were subsequently applied in the evaluation of a BIM-enabled cash flow exercise carried out to simulate integrated practice and implemented using a participatory action research methodology in relation to research question 3 (What is the impact of BIM-enabled pedagogy on students' performance?).

A mixed methods design was adopted for research question 4 (How can BIM-enabled learning be facilitated?) using a desk study, interviews, and a questionnaire survey to identify, validate and understand the characteristics of a proposed BIM-enabled learning environment. An Adaptive Structuration Theory (AST) perspective was applied to interpret the results and as a framework for future investigations of the use and performance of BIM-enabled learning environments within organisations.

Altogether, and in terms of the overall research question (How can BIM be leveraged for construction education?), this research revealed inadequacies in the current mode of delivering construction education and demonstrated how BIM can be leveraged to overcome them and improve learning. In addition, the characteristics of an innovative platform that promotes BIM-enabled learning in an immersive environment have been derived and explained. In doing so, it has made theoretical and practical contributions regarding the implementation and evaluation of BIM for construction education initiatives.

In terms of its theoretical contribution, the study has compiled, updated, and added to the body of knowledge on construction education by providing a typology and conceptual framework of BIM for construction education. For construction education researchers, the proposed learning activities and learning environment offer models upon which further interventions may be designed, developed, implemented and evaluated. For construction education practice, the BIM-enabled learning objects and activities developed in this study provide useful guidance for educators seeking to promote active learning in BIM-enabled learning environments. In addition, the evaluation framework developed in this research will be useful in planning and implementing performance evaluation of BIM-enabled learning interventions. The characteristics of the proposed BIM-enabled learning environment offer guidance and insights to educational software developers for building immersive learning environments. Ultimately, the research contributes to the ongoing efforts to align graduates' competencies with their future industry roles.

However, the study was only able to trial the BIM-enabled learning initiatives at topical level and with a particular level of students in a single university – this is a limitation. Similarly, the opinions expressed in this research with respect to the effectiveness of the BIM-enabled learning exercises carried out are informed solely by two iterations of an action research cycle. The characteristics of the proposed immersive BIM-enabled learning environment identified and validated in this study are based on data gathered from a relatively small number of people (31 interviewees) from only 3 European countries.

Future research should be geared toward wider experimentation with BIM-enabled initiatives covering more diverse topics. This experimentation should also be expanded beyond topic level to whole courses and multiple levels of studies. The research on the characteristics of a BIM-enabled learning platform should be expanded to include more

participants from more countries, both in Europe and in other continents in order to generate a more comprehensive, robust and reliable set of needs for a globally relevant BIM-enabled education platform.

Keywords: Building information modelling (BIM); BIM-enabled learning; BIM education; AEC/FM; construction management; Grounded Theory; construction education; Adaptive Structuration Theory (AST).

Lühikokkuvõte

BIM’i kasutamine ehitusinseneride koolituses

Vastamaks 21. sajandi nõuetele toimub ehituse valdkonnas digitaliseerimisprotsess, millega kaasnevad töövoogude muutused, mis omakorda eeldavad uutmoodi lähenemist nii projektlahendustele, teabehaldusele kui osapooltevahelisele kommunikatsioonile. See on tekitanud web 4.0 tehnoloogial põhinevate rakenduste poole pürgival ehitusalal ebakõla ülikooli lõpetajate teadmiste ja nende tulevaste rollide vahel. Probleemi lahendamiseks on oluline, et haridusasutused kaasaksid ja motiveeriksid uue põlvkonna üliõpilasi innovatiivsel viisil.

Ehitusinfomudel (BIM) – ehitiste koguinfot hõlmav elukaarekeskse teabe digitaalne väljund, on digirevolutsiooni keskne fenomen ja kuigi BIM põhjustab ehituses teatud häireid, pakub see ühtlasi võimalusi muuta haridus kaasahaaravaks nii üliõpilastele kui ka elukeskses õppes osalevatele spetsialistidele. Kuna BIM kaasab 3D mudelitena hoonete ja rajatiste struktureeritud tegelikke andmeid, sobib see nii probleem- ja projektipõhiseks õpetamiseks kui ka aktiivseks õppimiseks süüvides digitaalsesse, modelleerimisel põhinevasse õppekeskkonda. Kuigi BIM küll juba siseneb õppeprotsessi, pole siiani välja töötatud arvestatavaid juhiseid õpetajatele ja koolitajatele selle kasutamiseks ehitusinseneride hariduses ega loodud piisavalt vajalikke õpperessursse.

Käesoleva uurimuse eesmärk oli leida lahendus, kuidas saaks BIM-i kasutada ehituinsenride hariduses. Põhiküsimus oli: ***Milliseid eeliseid annab ehitusinseneride haridusele BIM****?* Probleemi püstitus jaguneb neljaks alamteemaks, millest igaüks keskendub kindlale uurimisküsimusele:

1. Milline on BIM-i kasutamise senine praktika ehitusinseneride hariduses?
2. Kuidas saaks BIM-i kasutada inseneriteaduste õpetamisel?
3. Milline on BIM-i kaasamise mõju üliõpilaste õpingutulemustele?
4. Kuidas hõlbustada BIM-keskset õpet?

Kuna uuring keskendub ehitusinseneride hariduse reformimisele vastavalt toimuvatele muutustele ehitussektoris, on pragmatism uuringu paradigma. Filosoofilised ja metodoloogilised lähenemised valiti selliselt, et need oleksid sobivaimad konkreetse probleemi lahendamiseks, seega kasutati kombineeritud uurimismeetodid.

Vastamaks esimesele uuringuküsimusele (milline on BIM-i kasutamise senine praktika ehitusinseneride hariduses?) viidi läbi süstemaatiline kirjanduse ülevaade BIM-i juhtumiuuringutest ülikoolides. Juhtumid identifitseeriti ja kirjeldati ning selleks, et mõista ja liigitada erinevaid lähenemisi, tehti kvalitatiivne analüüs *Straussian Theory Model of Grounded Theory* meetodil. Erinevate lähenemiste alusel tuletati selle põhjal kontseptuaalne raamistik BIM- kesksele ehitusele ja -ehitusharidusele.

Teine uuringuküsimus (kuidas saaks BIM-i kasutada inseneriteaduste õpetamisel?) hõlmas dokumentide analüüsi, mille järeldused kulmineerusid riskijuhtimise õpetamise praeguste ja soovitatud lähenemiste võrdleva kirjeldusena. Olemasolevate hindamismudelite ja BIM-põhiste haridusalgatuste spetsiifiliste hindamismeetodite selgitamiseks anti ülevaade nii teadusartiklitest kui ka haridusala (mitteakadeemilistest) juhendmaterjalidest. Tulemusi rakendati BIM-i toel lahendatavate rahavoogude ülesannete hindamiseks, mille käigus toimus integreeritud tegevuse simuleerimine ja seose loomine kolmanda uuringuküsimusega (milline on BIM-I kaasamise mõju üliõpilaste tulemustele?) osalusuuringute meetodil.

Neljanda uuringuküsimuse (kuidas hõlbustada BIM-keskset õpet?) lahendamisel kasutati kombineeritud meetodit. Selgitamaks, kinnistamaks ja mõistmaks BIM-keskse õppekeskkonna omadusi viidi läbi auditoorselt, rakendades intervjuusid ja küsitlusi. Tulemuste interpreteerimiseks ja tulevaste uurimissuundade leidmiseks organisatsioonis, kasutati AST *(Adaptive Structuration Theory)* meetodit.

Kokkuvõttes ja põhiuurimusküsimuse seisukohast (milliseid eeliseid annab ehitusinseneride haridusele BIM?) kaardistati puudujäägid praeguses ehitusinseneride hariduses ja demonstreeriti, kuidas BIM-põhine õpe võimaldab nendest üle saada ning tõsta õpetamise kvaliteeti. Lisaks on kirjeldatud innovatiivse BIM-keskse õpetamise platvormi omadusi. Sellega anti teoreetiline ja praktiline panus süvendatud BIM-põhise õppe rakendamiseks ehitusinseneride hariduses.

Teoreetilises vaates koostati ja ajakohastati ehitusinseneride BIM-põhise õppe raamistik koos vajalike juhistega. Ehitusinseneride hariduse valdkonna teadlastele on välja on pakutud õppeprotsesside ja -keskkonna mudelid, mille põhjal saab otsustada, kuidas tulevasi muudatusi kavandada, arendada, rakendada ja hinnata. Praktilises rakenduses annavad BIM-kesksed õppeobjektid ja -tegevused kasulikke juhiseid aktiivõppe korraldamiseks BIM õpikeskkonnas. Lisaks on käesolevas uurimustöös loodud hindamisjuhised uute ülesannete kavandamiseks, rakendamiseks ja hindamiseks. Välja töötatud BIM õpikeskkonna indikaatorid annavad suunised ka ehituse valdkonna tarkvaraarendajatele. Lõppkokkuvõttes panustab uurimus jätkuvatesse jõupingutustesse viia lõpetajate teadmised vastavusse nende tulevaste töökohtade vajadustega.

Siiski oli uuringul ka teatud piirangud – BIM õpikeskkonda katsetati piiratud teemade osas ja ühe ülikooli tudengite peal. Sarnaselt kujundati uuringus põhinevad arvamused BIM-keskkonna õppeülesannete efektiivsuse kohta kahe õppetsükli alusel. Süvendatud BIM-keskse õpikeskkonna omadused valideeriti suhteliselt väikese andmekogumi baasil (31 intervjueeritavat kolmest Euroopa riigist).

Tulevane uurimistöö peaks keskenduma ulatuslikumale eksperimenteerimisele ja katma rohkem erinevaid teemasid. Katsetusi tuleks laiendada käesoleva uurimustöö teemast väljapoole ja need peaksid hõlmama terveid kursusi ja erinevaid õppetasemeid. Kõikehõlmava, kindla, usaldusväärse ja rahvusvahelise BIM-keskse õpiplatvormi loomiseks tuleks kaasata rohkem osalejaid erinevatest riikidest nii Euroopast kui ka mujalt.

Võtmesõnad: Ehitisinformatsiooni modelleerimine (BIM); BIM-keskne õpe; BIM-põhine haridus; kinnisvarakorraldus; ehituskorraldus; põhjendatud teooria (*Grounded Theory*); ehitusharidus; Adaptiivne Struktuuriteooria (AST - *Adaptive Structuration Theory*)

Appendices

Publication I

Olowa, T. O. O., Witt, E., & Lill, I. (2019). BIM for Construction Education: Initial Findings from a Literature Review. 2, 305–313.
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BIM for Construction Education: Initial Findings from a Literature Review

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Abstract

Purpose – BIM education for construction professionals has tended to lag industry developments. This investigation initiates doctoral research into the use of BIM for construction education. The purpose of this study is to gain an understanding of existing examples of BIM education, their characteristics, the challenges faced in their implementation and any clear trends to focus the doctoral research effort.

Design/Methodology/Approach – A systematic search of peer-reviewed BIM education literature was carried out. From the articles captured, 51 specific cases of BIM education were identified and analysed.

Findings – Most cases are from the USA with a more global spread from 2013. A tendency towards interdisciplinary collaboration was apparent though single discipline courses remain important. BIM software in education is dominated by Autodesk products. Most cases were found to be BIM-focused with few examples of BIM-enabled education. This was consistent with the most significant BIM education challenges that were found to relate to the skill levels of students, time and the availability of technical support.

Research Limitations/Implications – This is an initial study. It is based on only 51 cases of BIM education, which were partially described in peer reviewed conference and journal papers available in international databases.

Practical Implications – The investigation has shed some light on existing examples of BIM education and these are useful in designing BIM education initiatives as well as directing further research efforts.

Originality/Value – The study offers an original perspective on global BIM education. It also represents the commencement of doctoral research.

Keywords Building Information Modelling, BIM, BIM education, Construction education, Education, Literature review

All papers within this proceedings volume have been peer reviewed by the scientific committee of the 10th Nordic Conference on Construction Economics and Organization (CEO 2019).

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1. Introduction

There has been widespread adoption of BIM in the construction industry, but this adoption has been constrained by a lack of adequately educated and trained construction professionals (Ahn *et al.*, 2013; Beceric-Gerber *et al.*, 2011) and their education has tended to lag industry BIM developments (Forgues & Beceric-Gerber, 2013; Lee *et al.* 2013). There is a consequent and widely recognised need for the incorporation of BIM education into university-level architecture, engineering and construction (AEC) programmes to address this (e.g. Bozoglu, 2016). Indeed, the incorporation of BIM into the university curriculum is seen as offering opportunities to improve AEC education more generally and overcome some of the current problems it faces (Arnett and Quadrato, 2012; Forsythe *et al.* 2013)

In this context, this research is a first step to initiate doctoral research into BIM education and the use of BIM for construction education in higher education institutions (HEIs). Its purpose is to identify existing examples of BIM education from the literature and gain an understanding of their characteristics, the challenges faced in their implementation and any clear trends in the state of the art in order to focus the doctoral research effort.

A systematic search of the academic literature was carried out to identify peer-reviewed journal and conference papers on BIM education. Cases of BIM education for AEC students in HEIs reported in these papers were then identified and analysed. The literature search criteria and analysis process are described in Section 2. Section 3 presents the main findings from the analysis of the cases identified and these are discussed in Section 4 before conclusions and implications for further research are drawn.

2. Research Methodology

2.1. Systematic search to identify the source literature

The systematic literature search procedure followed that recommended by Bearman *et al.* (2012). The search inclusion criteria were defined to include all available peer-reviewed BIM education articles that describe current practice. Pre-2007 articles were excluded on the grounds that the year 2007 saw an international upsurge in BIM interest with the publication of key BIM standards such as CoBIM, and GSA 2007, so it was considered a sensible start year for the literature search. Only articles in English were considered for inclusion.

The following major literature databases were selected after initial trial searches to ensure good coverage of the available literature and particularly that peer-reviewed conference papers would be included:

- ASCE Library
- EBSCOhost Web
- Scopus
- Web of Science Core Collection

The Boolean phrase (“Education” OR “Training” OR “Learning”) AND (“Building Information Modeling” OR “Building Information Modelling” OR “Virtual Design and Construction”) was used in advanced searches to match “Anywhere in document” (i.e. all text and all fields).

The intention was to cast a wide net in order to capture everything relating to BIM education in the search but not including articles about BIM which had nothing to do with education.

Database search returns were listed in order of relevance. Each article title and, if necessary, abstract were checked to establish relevance / eliminate irrelevant articles. Relevant articles were then saved to a reference management program (Mendeley Desktop version 1.17.13). This enabled the convenient elimination of duplicates (see Table 1).

2.2. Identification of cases and analysis of their contents

All of the articles were then screened to determine which of them reported actual cases of education and / or training, and a total of 92 reported cases of education / training were found. Of these, 51 cases referred to the education of students in construction-related disciplines in HEIs and therefore fell within the scope of this investigation with the remaining cases being excluded from further analysis.

Content analysis of the selected articles with their reported cases followed a Grounded Theory approach in that data extracted from the multiple research articles were coded into themes and categories by the analyst as they emerged from the articles' content. This qualitative approach was adopted as the intention was to understand the complexities of BIM education implementation in HEIs (Cresswell, 2014).

In addition, quantitative metrics were also considered to be of interest in this study, for example, with regard to identifying trends and levels of significance of the various issues identified. Overall, the data collection and analysis procedures followed may be described as a mixed methods approach. To expedite the analyses, NVivo Plus (v.12) software was used, which enabled both the convenient coding of the articles' content to different themes and also the organisation of the descriptive metrics (date, subject, student level, location, etc.) for each reported case of BIM education.

3. Findings

3.1. Cases by country and year

Table 2 shows the distribution of the 51 sample cases by country and the year in which they were reported.

Most of the cases in the sample (32 out of 51) took place in the USA. This may be explained to some extent by the main sources of conference and journal papers which the search found to be the American Society of Engineering Education (ASEE) Conference proceedings (2008–2017) and the ASCE Journal of Professional Issues in Engineering Education and Practice, both from the USA. However, the domination by the USA in this area does seem to be a robust finding that reflects the relatively early uptake of BIM in US industry, development and support for BIM by professional organisations (e.g. the AIA) and federal government agencies (e.g. NIBS and GSA) as well as the active promotion of BIM by industry players and software vendors (e.g. in encouraging and sponsoring BIM competitions – Herrmann *et al.* [2015]).

Although the USA-based cases are distributed quite evenly over the 2007-2017 period, outside the USA, there does seem to be an overall increase in the total number of cases

Articles	ASCE Library	EBSCOhost Web	Scopus	Web of Science	Overall (no duplicates)
Number of articles returned from search	613	3730	1673	174	Not application
Relevant articles after screening	67	63	210	108	308

Table 1. Returns from Literature Database Searches

Table 2.
Cases by Country and Year of Reporting

Country	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	TOTAL
Australia	1					1	1					**3**
Belgium							1					**1**
Chile										1		**1**
China							1					**1**
Denmark											1	**1**
Germany									1			**1**
India									1			**1**
Ireland							1					**1**
Israel							1					**1**
New Zealand										1		**1**
Portugal											1	**1**
Spain											1	**1**
Thailand									1			**1**
UAE											1	**1**
UK								1	1		1	**3**
USA	1	4	1	3	1	6	4	1	6	3	2	**32**
TOTAL	**2**	**4**	**1**	**3**	**1**	**7**	**9**	**2**	**10**	**5**	**7**	**51**

reported from 2013 onwards. Finally, it is notable that Africa is the only continent which does not contribute any cases to the sample.

3.2. Cases by discipline

The cases were classified according to the disciplines they involved - Architecture, Civil and structural engineering, Construction, MEP Engineering and Other (Figures 1 and 2). The category 'Other' included disparate disciplines which did not fit within the other 4 categories but could not be combined into a single, broader discipline and were not represented in sufficient numbers to warrant separate categories. Examples include: Facilities Management, Environmental Engineering and Industrial Technologies Engineering.

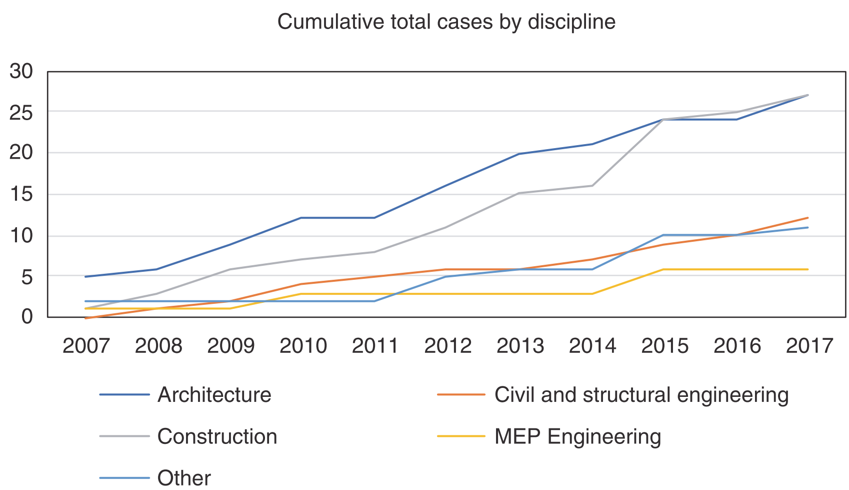

Figure 1.
Cumulative Distribution of Cases by Discipline Over Time

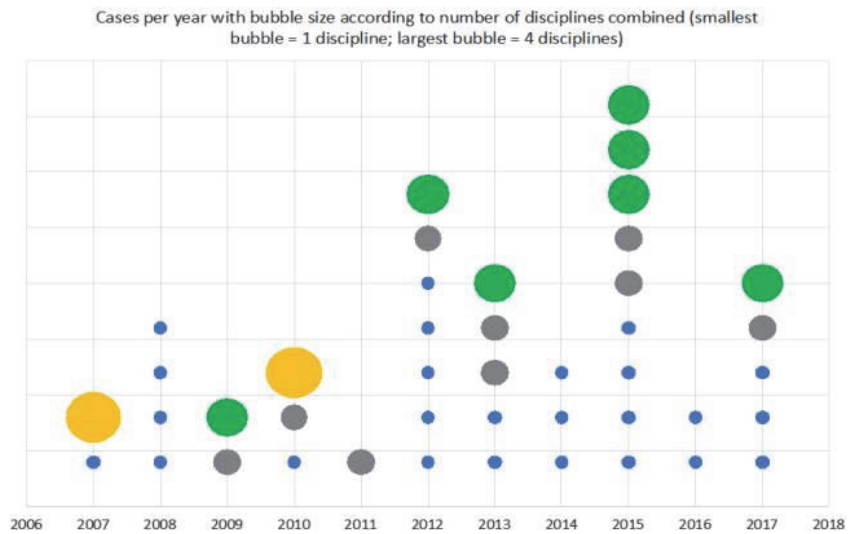

Figure 2.
Number of Disciplines Combined Per Case Per Year

Slightly less than half of the cases involve more than one discipline. There is no apparent trend towards more combining. Indeed, the most diverse combinations (combining four disciplines) were from 2007 and 2010.

BIM education in AEC courses has proceeded in various modes: by seminars or workshops (Gledson & Dawson, 2017; Gnaur *et al.* 2012), embedding BIM in existing courses (Huang, 2016) and creation of a new single course to accommodate what could not be embedded in existing courses, as in integrated capstone courses (e.g. Ghosh *et al.* 2015).

Civil and structural and MEP engineering courses have witnessed a steady rise in the number of cases reported from 2007 to 2017 although not at the same rate as architecture and construction courses.

BIM education offers opportunities to take advantage of the greater interdisciplinary collaboration inherent in BIM. Numerous studies have suggested a more integrated approach to teaching which aims to bridge the traditional boundaries between AEC industry professions that have been replicated in industry and educational structures (e.g. Forgues & Farah, 2013). Our data reflects this with many of the identified cases exhibiting interdisciplinary collaborative and integrated learning. However, Solnosky *et al.* (2015) suggest that most cases that involve interdisciplinary learning have started from single disciplines then expanded to embrace others.

3.3. Software used in the cases

Subheadings should also be numbered in accordance with their section and the sequence of subheadings.

Software has been grouped into three categories (see Figure 3):

(1) modelling software;

(2) software for model-based viewing, checking, simulations, etc.; and

(3) data sharing and collaboration software.

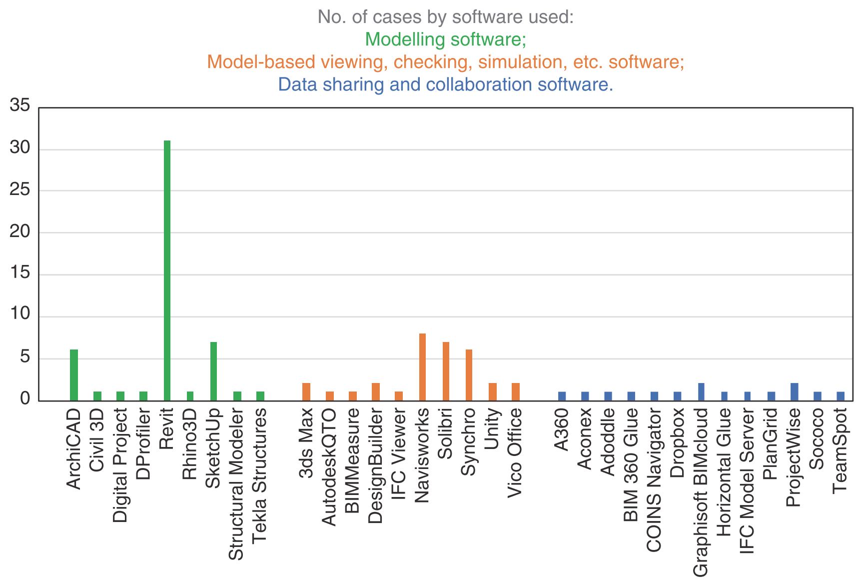

Figure 3.
Software Used in the Identified Cases

Revit, SketchUp and ArchiCAD are shown to be prevalent for modelling. Navisworks, Solibri and Synchro dominate for model-based applications and Graphisoft BIMcloud and (Bentley) ProjectWise take the lead in file sharing platforms among the cases considered. It is tentatively suggested that, with the great majority of cases being in the USA, this may tend to emphasise the dominance of Autodesk products (Revit and Navisworks) and other USA-based products in BIM applications.

3.4. BIM-enabled versus BIM-focused

Underwood *et al.* (2013) conceptualise the development of BIM education in three progressive stages:

(1) BIM-aware - ensuring that graduates are aware of BIM and the changes it is bringing about;

(2) BIM-focused - students are instructed how to use BIM in the peformance of specific tasks; and

(3) BIM-enabled - where learning is embedded in the virtual BIM environment and BIM acts as a "vehicle" for learning.

The identified cases were classified according to these stages (Table 3) with the intention of testing for any obvious trends.

Most of the cases were found to be BIM-focused while only five cases were considered to be BIM-enabled (one reported in 2011, three in 2012 and one in 2015 with all of them from the USA). There were no BIM-aware cases identified. Advances between 2011 and 2015 demonstrate the efforts of faculty to create a more immersive and engaging environment by leveraging BIM applications, tools and products to enhance students' learning. The examples of this BIM-enabled learning were found in Arnett and Quadrato (2012), Ambrose (2012), Clevenger *et al.* (2012, 2015) and Nawari *et al.* (2014).

Table 3. Categorisation of Cases as BIM-Focused/BIM-Enabled

Year	Number of cases BIM-focused	BIM-enabled
2007	2	
2008	4	
2009	2	
2010	3	
2011		1
2012	4	3
2013	9	
2014	2	
2015	9	1
2016	5	
2017	6	
TOTAL	**46**	**5**

3.5. Emergent themes from the content analysis - challenges

Qualitative content analysis was carried out using a Grounded Theory approach. The most obvious emergent theme was that relating to the implementation challenges faced in BIM education (Table 4).

BIM learning undoubtedly requires extra effort on the parts of both the faculty (who have to prepare learning modules, source for industry participants where required or even take up role playing) and the students who, in most cases, have different exposures to technology and practical experiences.

Most of the challenges noted have existing initiatives aimed at their resolution: e.g. interoperability problems – IFC, Open BIM, etc. – but they remain challenges at least for the short to medium term. Also, skills levels among students and staff as well as in industry are clearly improving, considering the progressive increase of BIM learning over the years and this can only help BIM education going forward.

Table 4. Identified Challenges

Challenge description	#sources referencing challenge
Skill levels among students	13
Time / Workload	13
Technical support	11
Interoperability problems	6
What to teach / learning content	6
Classroom and technical equipment	5
Educators' resistance to change	4
Limitations of BIM-based learning (some students prefer traditional teaching)	3
Difficulties with assessment	2
Complexity of example projects	2
Skill levels among educators	2
Teamwork and collaboration	2
Accreditation issues	1
Curriculum constraints / inflexibility	1
Intellectual property issues (for model owners)	1
Disagreements over learning content	1
Universality-cultural, economic and academic differenceson BIM learning	1

5. Conclusions

This preliminary study to initiate doctoral research has systematically searched literature to identify cases of BIM education for AEC disciplines in HEIs. Fifty one specific cases were identified and reviewed in order to understand their characteristics, the challenges faced in their implementation and any clear trends in the state-of-the-art so as to focus the doctoral research effort.

We have noted a domination of the US cases and a more global spread of BIM education cases from 2013 onwards. Domination by architecture and construction over engineering disciplines with a tendency towards interdisciplinary collaboration between them though single discipline BIM education courses remain in a slight majority.

A diversity of software programs supports BIM education, but there is domination by Autodesk products, particularly for modelling and, to a lesser extent, for model-based viewing, checking and simulations.

Classification of the identified cases according to progressive stages of BIM education revealed only 5 examples of BIM-enabled education with the remaining 46 cases being considered primarily BIM-focused. This finding suggests the emphasis in HEIs remains on teaching students to "do" BIM rather than leveraging BIM in the teaching of other, fundamental or non-BIM concepts and topics. It is also backed up by our findings on the challenges faced when implementing BIM education which emerged from the qualitative content analysis of the case study articles. The most significant challenges were found to relate to the skill levels of students, the time / workload requirements and availability of technical support – all of which allude to a continued need for BIM-focused education before the full potential of BIM-enabled education can be realised.

In terms of directing further research, the following possibilities for investigations became apparent in the course of this study:

- Pedagogical approaches to BIM education – many of the cases adopted problem-based and project-based methods a detailed classification and comparison would offer further insights.
- Enablers/motivators/challenges of BIM-enabled learning – with increasing empirical evidence becoming available, a more in-depth exploration of the suggested progression to BIM-enabled AEC education is called for.
- Similarly, the increasingly available evidence should be used towards understanding the costs and benefits of BIM education.

Most specifically, the study has inspired a desire for engagement in action research regarding the implementation of a specific BIM-enabled education pilot case.

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Publication II

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CONCEPTUALISING BUILDING INFORMATION MODELLING FOR CONSTRUCTION EDUCATION

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Abstract. Digitalisation of the construction industry is both driving changes in construction education to meet emerging industry needs and providing opportunities for new delivery approaches. Universities are responding to these challenges in diverse ways including in their use of Building Information Modelling for construction education (BfCE). This research is aimed at understanding the existing approaches to BfCE. A systematic literature review of BfCE in universities was carried out which identified 305 relevant articles including 44 specific cases of BfCE. These were qualitatively analysed and a Straussian Theory Model (STM) was adopted to understand the different BfCE approaches reported in the literature, the contextual and intervening conditions which give rise to them and their consequences in order to develop a conceptual framework which sets out the relationships between these and the digitalisation of the construction industry. This study provides construction educators with a descriptive typology that depicts all possible BfCE approaches and which could assist them in determining suitable approaches and to conceptualise new approaches for teaching students to use Building Information Modelling (BIM) and also for leveraging BIM to enhance their teaching of other topics.

Keywords: Building Information Modelling, BIM education, AEC-FM, Grounded Theory, Straussian Theory Model, systematic literature review, construction education.

Introduction

Building Information Modelling (BIM) is revolutionising didactic methodologies in construction education at a time when Architectural, Engineering, Construction and Facilities Management (AEC-FM) educators are faced with the challenge of educating students so that their professional roles would properly align with the digitalisation of the construction industry to enhance not only their productivity but also their decision-making ability (Du et al., 2017; Hwang & Safa, 2017; Tranquillo et al., 2018). Education that is mediated by technological innovations, such as BIM, has been shown to support students' motivation, satisfaction and performance both academically and professionally (Ferrandiz et al., 2018).

There are intrinsically two aspects of BIM that need AEC-FM educators' and researchers' attention. The first, from an instrumentalist world view (Feenberg, 2001, 2017; Heidegger, 1977), which is generally acknowledged and predominantly studied is that AEC-FM graduates would understand the use and application of BIM in the industry (Puolitaival & Forsythe, 2016; Ramalingam, 2018; Solnosky, 2018; Wu & Luo, 2016) – this is taken to be a short-term industry need where "teaching BIM is prioritized" (Witt & Kähkönen, 2019). The second aspect, based on substantivism, is the use of BIM as a platform or medium for AEC-FM education. Moreover, and for both aspects, curriculum design and evaluation criteria have been reported to be major challenges especially in the face of multiple ways of embedding BIM into the AEC-FM curriculum in any educational institution with their unique context, policies and strategies (Sacks & Pikas, 2013).

BIM for construction education (BfCE) is a term used in this study to refer to all efforts by academia in educating AEC-FM students both on how to use BIM and / or leveraging BIM to enhance learning. Earlier research by the authors has confirmed a number of existing cases of BfCE reported in the academic literature and suggests that these are dominated by architectural disciplines and that reports on construction management related courses are increasing with time. Only two literature reviews on general BIM education were found (Abdirad & Dossick, 2016; Pikas et al., 2013) that focused on curriculum design frameworks. However, understanding the development

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process of BfCE model offerings is important for designing appropriate BfCE approaches in universities. Whereas previous studies have effectively reported developments in BIM education, none of them has attempted to conceptualise the patterns underlying the dispersed facts.

The scarcity of extant literature relating to the classification of approaches to BfCE is also notable. To our knowledge, there are only two studies that have reported on the categorisation of different models of BfCE offerings in higher education institutions (Solnosky & Parfitt, 2015; Suwal & Singh, 2018) and none on universities specifically. According to Solnosky and Parfitt (2015) "The number and types of methods for teaching and integrating BIM… into building related architectural engineering related curriculums… is varied due to its broad definition and based on the wide body of different building expertise." With this explanation, they came up with a categorisation that is based on number of disciplines involved, course design and number of institutions involved. Suwal and Singh (2018) base their categorisation solely on course design and number of disciplines involved. However, neither of these studies systematically define the human actions and interactions involved in their categorisations thereby giving explanations for their use. Both Solnosky and Parfitt (2015) and Suwal and Singh (2018) are already somewhat dated and, since more examples of BfCE now exist, a more rigorous attempt at categorisation is now feasible.

This study is an attempt to fill this gap by synthesising the evidence from the extant literature on BfCE cases to gain an understanding of existing BfCE implementation strategies in universities and develop a typology of BfCE approaches in AEC-FM disciplines as well as a conceptual framework to explain the drivers and processes associated with BfCE. This is a first step in addressing the wider research problem: how can BIM be leveraged to improve engineering education in AEC-FM disciplines?

A systematic search of the academic literature was carried out to identify peer-reviewed journal and conference papers on BIM education in higher education institutions (HEIs). Cases of BIM for construction education for AEC-FM students in universities reported in these papers were then identified and analysed. The literature search criteria and analysis process are described in Section 1. Section 2 presents the main findings from the analysis of the cases identified and these are discussed and interpreted in Section 3 where a typology of BfCE approaches and a conceptual framework for BfCE are derived before conclusions and implications for further research are drawn.

1. Research methodology

Systematic literature reviews are "rigorously designed and conducted literature reviews that aim to exhaustively search for, identify, and appraise the quality of and synthesize all the high-quality research evidence in order to answer a specific research question" (Phillips et al., 2018). This approach enables the comprehensive review of the extant literature within the scope of the research in a reproducible and rigorous manner and, moreover, the results of systematic literature reviews have been argued to be as valuable as those of any other evidence-based methodologies in educational interventions (Evans & Benefield, 2001; Phillips et al., 2018). The methodology adopted for this research followed the recommendations of Gough (2007) for conducting systematic literature reviews as summarised under the following 9 process steps by Bearman et al. (2012): "(1) establishing the review question; (2) defining inclusion and exclusion criteria; (3) articulating the search strategy, including information sources; (4) screening the articles to see if they meet the inclusion and exclusion criteria; (5) reporting the results of the search strategy, usually through a flowchart; (6) extracting relevant data from included studies; (7) assessing the methodological quality or rigour of the included studies; (8) synthesising, either quantitatively or qualitatively, the collective evidence of the included studies; (9) drawing conclusions and communicating these findings in a manner which is relevant to readership".

Establishing the review question: The review question guiding the direction of this study was: What are the existing cases of BfCE in universities?

Defining inclusion and exclusion criteria: All academic publications relating to BfCE from any year and any country were included but only English language publications were considered. Academic publications refer to peer reviewed journal articles and conference proceedings that report on actual research on any aspect of BIM education in universities. Trade publications, and other non-academic sources and books were excluded on the grounds that the quality of their content could not be similarly assured (e.g. these could include promotional content).

Articulating the search strategy: An initial search was conducted on two online databases (ASCE journal and ASEE conference papers that were published in 2018) to identify the appropriate search terms. The Boolean phrase with the following search operators was used: ("Building Information Mode?l*" OR "BIM") AND ("Educat*" OR "Teach*" OR "Learn*") AND ("Construction management" OR "Project Management" OR "Engineering Management") to locate relevant references. This was done reiteratively with the introduction of wildcard (? – e.g. Mode?ing) and truncation (* – e.g. Model*) search operators to exhaustively glean all relevant references. The following online databases were searched for relevant articles (i.e. articles containing the search terms which are generated automatically by the search engine): EBSCOhost Web; EBSCO eBooks Collection; ASCE Library; ASME Journals and Conference Proceedings; Cambridge Core; Emerald; ScienceDirect; Scopus (Elsevier); Web of Science (Clarivate Analytics). However, not all databases proved equally relevant and the articles returned are shown in Table 1.

Screening the articles: The articles returned from the search of databases were listed in order of relevance by the algorithms of the database search engines such that

Table 1. Databases with breakdown of articles returned

Databases	Articles returned from search expression	Relevant articles after screening
EBSCOhost Web	3,968(*)	192
Science Direct	269	12
ASCE Library	1921	211
Emerald Insight	237	15
Scopus	2558(*)	118
Web of Science	504	68
Overall (*with duplicates removed*)	*N/A*	305

the articles most aligned with the search string and filters were returned at the top of the list and those increasingly less aligned with the search terms appeared further down the list. The articles were screened using their titles and, where necessary, their abstracts were also read to establish their relevance to this enquiry. The Mendeley web plugin was used in conjunction with the Google Chrome browser to download the articles (as pdf files) into individual folders for each database for further analysis. All of the files from all the folders were then collated into a single folder to identify and eliminate duplicates using Mendeley reference management software which resulted in a total of 305 relevant BfCE articles. From the total of 305 articles found, forty-four (44) articles were found to report actual cases (using action or case study research) of BfCE in AEC-FM in universities. These 44 cases were found to have adequately similar data so that a constant comparative analysis could be carried out.

Reporting the results of the search: Table 1 shows the results of the search strategy.

Note that the high number of returns from the EBSCOhost Web and Scopus databases were mostly irrelevant – the screening process (going through each paper's title and, where necessary, abstract) was discontinued at return record #600 (EBSCOhost Web) and record #1100 (Scopus) after a full 50 records (listed according to relevance) in sequence had been found to be irrelevant. The results of the constant comparative analysis are reported in Section 2 and further discussed and interpreted in Section 3.

Data Extraction from included studies: Data extraction followed a qualitative approach which was achieved with the aid of NVivo Plus (v.12) software. The research question guided the mining of data, and contents were probed accordingly throughout the extraction process for comparative content analysis of the cases. Themes and patterns were coded as they emerged. The analysis also considered some quantitative metrics to clearly present trends of all the considered factors that impact on BfCE in this study. Therefore, this study adopted a mixed method approach in the collection, organisation, analysis of data and presentation of results (the results are presented in Section 2).

Assessing the methodological quality or rigour of the included studies: The quality and rigour of the studies included was premised on their appearance in peer-reviewed journal and conference proceedings publications and all included studies were considered to be equally valid.

Synthesizing the evidence: A Grounded Theory (GT) approach was adopted for synthesis. Specifically, a meta-analysis and content comparison of cases were carried out using the Straussian Theory Model (STM). The data from relevant extant textual cases were coded following a constant comparative analysis. The identified themes were linked into concepts, from concepts to sub-categories and subsequently into categories to explore the conditions, context, consequences, and strategies (actions and interactions) as well as the relationships between them as suggested by Corbin and Strauss (1990), Creswell (2012). On this basis, a typology and conceptual framework for BfCE in universities were derived (as presented in Section 3).

Grounded Theory (GT) is a rigorous systematic inductive approach to understanding social process(es) by analyzing any form of data and allowing the analyst to freely come up with substantive theory that is both compatible and consistent with empirical observation without the restriction of precepts of any existing theory about a phenomenon (Urquhart, 1997). Since this study is aimed at understanding the BfCE phenomenon on the basis of extant cases and in the absence of existing theory, GT provides a convenient approach for doing this. Specifically, the Straussian Theory Model (STM) of GT was adopted as a prescriptive methodology for the meta-analysis, content comparison and theory generation from the cases.

Figure 1 illustrates the STM as presented by Creswell (2012). In generating substantive theory using GT, Creswell (2012) suggests that emphasis should be on process rather than consequences. A process in GT research, according to Strauss and Corbin (1998), "is a sequence of actions and interactions among people and events pertaining to a topic". In adopting STM, BfCE was thus considered as a social process and the analysis proceeded according to three prescribed steps (Strauss & Corbin, 1998; Creswell, 2012):

1. Open coding – formation of initial categories of information regarding the phenomenon;
2. Axial coding – identifying a core category and determining the relationships between that and the other identified categories (see Figure 1);
3. Selective coding – theory development in attempting to explain the relationships determined above.

Drawing conclusions: The 9th step in the systematic literature review process described by Bearman et al. (2012) relates to drawing conclusions from the outcomes of the research. Our conclusions are presented in the final section.

2. Results

2.1. Summary of BfCE cases

Table 2 shows the summary of all the BfCE cases in this study categorized according to the type of disciplines engaged, what was taught and how they were taught.

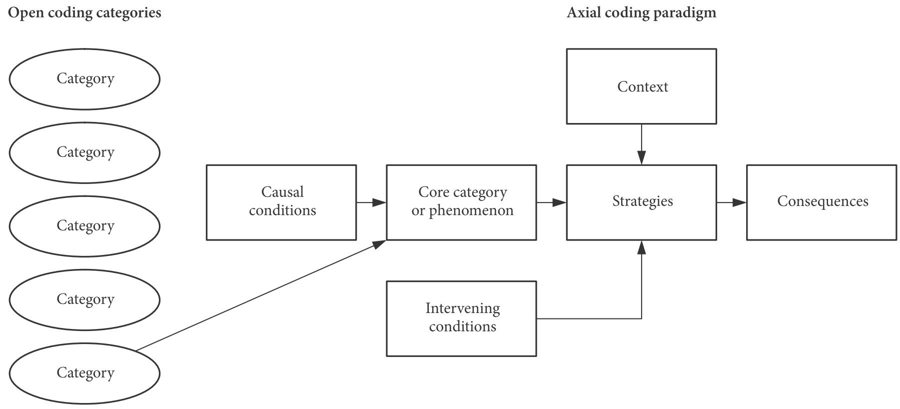

Figure 1. Grounded Theory coding from open coding to the axial coding paradigm (Creswell, 2012)

Table 2. Summary table of BfCE cases

Discipline	# cases	Teaching basis*	Learning foci	Delivery
Architecture	12	project (5) case (3) problem (5)	capstone (course integration); design integration; building materials, technology and systems; construction; sustainability	Undergraduate, postgraduate or both combined. Single topic within course to full course. Less than 1–10 semesters. Single or multiple institutions
Construction	12	project (3) case (6) problem (5)	capstone (course integration); IT for construction; construction principles and practice; building technology and systems; energy simulation; BIM process and applications; collaboration	Undergraduate, postgraduate or both combined. Full course. 1–8 semesters. Single institutions
Civil and structural	4	project (0) case (0) problem (3)	BIM awareness; BIM terminology and process, applications and tools; visualisation	Undergraduate or postgraduate. Full course. 1 semester. Single institutions.
Other (individual) disciplines (Building and Real Estate; Geoinformatics; undefined)	3	project (1) case (1) problem (0)	Development of CAD in construction. BIM awareness; BIM applications and tools; BIM for FM; BIM futures	Undergraduate. Full course. 1 semester. Single institution
Combinations of (2–8) disciplines	13	project (3) case (4) problem (4)	Capstone (course integration – for solar decathlon competition); BIM applications; interoperability	Undergraduate, postgraduate or both combined. Full course. 1–6 semesters. Single or multiple institutions.

Note: *Some cases contain more than 1 type or none at all.

Of the 44 cases identified, the majority (34) were from the USA, 4 were from China, 2 from the UAE and the remainder from other countries across the globe contributing only 1 case each to the sample.

2.2. Disciplines

Table 2 shows the spectrum of disciplines engaged in the BfCE studies which were explicitly or implicitly extracted from the cases and how they are combined in some cases. 28 of the cases involved just a single discipline. Architecture and Construction were the dominant disciplines with 12 cases each. The rest are combinations of different disciplines with two being the least and the greatest number of combined disciplines in a single case was found to be 8 (see Bozoglu, 2016; Chiuini et al., 2013). It was, however, not possible to get the same detail from one of the cases due to its non-specificity and lack of any indication to implicitly deduce the discipline to which it referred. Nevertheless, the diversity of possibilities in which BfCE is executed among AEC-FM disciplines in universities was apparent – and this even extends beyond solely AEC-FM disciplines in one of the cases to Business and Communication disciplines.

2.3. Teaching basis

Expanding the ideas of Mills and Treagust (2003) regarding project- and problem-based learning, we have included a third category for the purpose of this study, which is case-based learning as defined by Barison and Santos (2018). The dissenting ideas about project-based and problem-based learning have prompted the publication of many articles, for example, Mills and Treagust (2003) and Helle et al. (2006). Helle et al. (2006) in their exploration of project-based learning (PrBL) in education highlight the general characteristics of PrBL as: "(1) [projects] involve the solution of a problem; often, though not necessarily, set by the student himself [or herself]; (2) they involve initiative by the student or group of students, and necessitate a variety of educational activities; (3) they commonly result in an end product (e.g., thesis, report, design plans, computer programme and model); (4) work often goes on for a considerable length of time; (5) teaching staff are involved in an advisory, rather than authoritarian, role at any or all of the stages – initiation, conduct and conclusion".

Although these general characteristics do not specifically refer to projects as being real-life, in the context of BIM and AEC-FM disciplines, projects generally refer to construction and their ancillary works which are always real-life (Mills & Treagust, 2003). While problem-based learning (PBL) was not within the exploratory scope of Helle et al. (2006) they, however, argued that some common features between PrBL and PBL include the presence of problem orientation, i.e. learning is propagated through the formation of a problem; and collaboration and cooperation among group members. Furthermore, they suggest that the difference is in the way knowledge is applied to the problem formed. In PBL this typically involves the application of already acquired knowledge, while PrBL requires the acquisition of new knowledge. We found, in the literature reviewed, that the terms PrBL, PBL and also case-based learning were used loosely and interchangeably in many of the articles that we analysed. Therefore, to avoid misrepresentation, we have defined the concepts of PrBL, PBL and CBL as used for the classification of articles in this study. Project-based learning is centred around real-life projects where students/learners take active roles in the execution of the projects or collaborate closely with the professionals on the project. Case-based learning is centred around completed real life projects where students/learners have no active roles to perform in the execution of the project but have access to some or all the professionals on such projects to obtain partial or full information on the project (Barison & Santos, 2018). In problem-based learning, the learners are totally dissociated from both the project and the professionals on the project. Problems, having semblance of real-life based on the experience of the educator, are usually built on hypothetical cases for learners to solve.

Table 2 illustrates that all 3 of these approaches have been popular in BfCE with almost all identified cases employing 1 or more of them as a basis for teaching. The first case reported on BfCE had no indication of the teaching basis adopted in the study, references to the basis of teaching started emerging a year after the first case was reported. The reporting of project-based cases stopped in 2015 with the highest number reported in 2013. There is no apparent preference for either problem-based or case-based approaches to BfCE.

2.4. Learning foci

Learning foci in the cases ranged from BIM awareness, applications, tools and processes to BIM-based course integration in capstone projects and the subject areas spanned the whole life of constructed assets. The application of theoretical topics leading to practical design and/or construction documentation, especially in capstone projects, were prominent. In addition, dissertation and thesis writing on BIM by Masters and PhD students were also observed to be of interest to some authors.

2.5. Delivery

The cases showed a variety of delivery possibilities in relation to:

- whether the BfCE intervention was a topic within a course or a full course;
- the level of students – undergraduate and postgraduate as well as combinations of both;
- the length of courses – from less than 1 to a full 10 semesters;
- the number of institutions involved in the delivery.

2.6. Approaches

10 specific types of approaches were identified from the literature and these are:

Approach Type 1: Undergraduate Mono-discipline (*Topic*) *– in a single institution*: In this category, BfCE only involves undergraduates who are in the same institution and share the same discipline. This approach is particularly favoured by faculties that practice BIM-enabled education. In this approach, AEC-FM concepts such as cashflow, estimating, structures, etc., which go beyond emphasising the digitalisation of the construction industry, are taught at topical levels. In most cases, there is no space in the curriculum for faculties to have a full-blown course for BfCE. Furthermore, this method of BfCE does not require any prerequisite course(s), mentoring, involvement of alumni nor guest speakers for its implementation. An example of a case with this approach is Sharag-Eldin and Nawari (2010), where the teaching and learning also happened in both traditional classroom and a studio setting.

Approach Type 2: Undergraduate Mono-discipline (*Course*) *– in a single institution*: This approach, though similar to the first type, is different in that the combined condition under which this is practiced allows extended time for such teaching and learning which culminates in a dedicated course for BfCE. This approach allows for either training students on basic engineering concepts or how to use BIM software. This approach can include the participation of guest lecturers and the requirement that students have already completed prerequisite courses. Teaching and learning may be carried out in a combined environment i.e. both traditional classroom and laboratory/studio setting (e.g. Kim, 2014).

Approach Type 3: Undergraduate Multidisciplinary (*Course*) *– in a single institution*: This approach is widely used and encompasses multiple disciplines, but all located in the same institution. Properties of this approach with varied nuances include prerequisite courses, combined environments, guest lecturers. Example cases include Comiskey et al. (2017), Solnosky and Parfitt (2015), Wong et al. (2011), Bozoglu (2016), Zhang et al. (2017, 2018), Pikas et al. (2013), Monson and Dossick (2014), Jin et al. (2018), Nawari et al. (2014).

Approach Type 4: Undergraduate Multidisciplinary (*Course*) *– in multiple institutions*: This refers to the extension of BfCE beyond a single institution by collaborating with other institutions. The maximum combination of institutions recorded in this study is two. This approach is undertaken where there is adequate time (usually at least a semester) to carry out the teaching and learning with the support/mandate of participating institutions. Of paramount importance for such arrangements is the availability of complementary technology such as an online collaboration platform and ability for time coordination in cases where the institutions have different time zones. This approach may be adopted in cases where institutions wish to leverage individual strengths in areas like core discipline focus and availability of technical resources. Properties of this approach include courses being carried out in a combined environment with some prerequisite knowledge required by the students and facilitated by guest lecturers (e.g. Comiskey et al., 2017).

Approach Type 5: Postgraduate Mono-discipline (*Course*) *– in a single institution*: This involves teaching and learning of BfCE activities among master's students and sometimes doctoral students. However, the involvement of the doctoral students is usually for facilitating i.e. they are involved because their supervisors or departmental heads are teaching the subject and are consequently needed in BfCE role playing. The conditions which impact the choice of this approach include the organisational structure of the institution in that the faculty possesses the authority, the skill in BIM software application with the time and resources required for the implementation of this approach. The examples of this approach involved learning taking place in a combined environment, with or without requiring the completion of prerequisite courses and with or without the participation of guest lecturers and/or industry experts. Cases included Hijazi et al. (2018), Wang and Leite (2014), Suwal and Singh (2018), Sampaio (2015), Pikas et al. (2013), Nassar (2012).

Approach Type 6: Postgraduate multidisciplinary (*Course*) *– in a single institution*: The notable feature of this approach type is the diversity of the students involved. This is made possible by the presence of other, complementary disciplines within the institution where the study is conducted. It is worth mentioning that the availability of resources such as high-end computers and software is important. Variants include learning in a combined environment or in a studio environment only, with or without participation of guest lecturers and, typically, without prerequisites. Example cases include Charlesraj et al. (2015), Bozoglu (2016), Pikas et al. (2013), Shanbari et al. (2016).

Approach Type 7: Mixed Level Single Discipline (*Course*) *– in a single institution*: In this category, teaching and learning take place among students of the same discipline within the same institution but who are at 2 or more different levels in their studies. For example, year 3 and year 4 students might be taught at the same time with the option of deferring the course to year 4 by year 3 students. This approach is typically carried out in a combined learning environment and variants include: the requirement for prerequisite courses, participation of guest lecturers and industry mentors, incorporation as a capstone project. Example cases include Wu and Hyatt (2016), Lewis et al. (2015), Wu and Luo (2016). Time and resources availability are important factors in implementing this type of approach as these can be beyond faculty capacities and thus reliant on national or institutional mandates to encourage this approach.

Approach Type 8: Mixed Level Multidisciplinary (*Course*) *– in single institutions*: This categorisation relates to the engagement of more than one discipline in different levels of studies but in the same institution. This arrangement is particularly practiced where the topic or course involved is either an elective or core course that is taken by different levels of students from different disciplines. To an even greater extent than approach Type 7, this approach relies on the organisational structure allowing for proper coordination and collaboration and institutional/national mandates for encouraging them. These approaches are typically carried out in combined learning environments either with or without prerequisites and mentors. Example cases include Chiuini et al. (2013), Rassati et al. (2010), Leite (2016).

Approach Type 9: Mixed Level Multidisciplinary (*Course*) *– in multiple institutions*: faculties and students from different institutions are involved in the teaching and learning of BfCE activities respectively. This approach usually take place at capstone level, where participants from both institutions combine their efforts to complement disciplines that are not available in both institutions. Additionally, this approach is suitable for the demonstration and teaching of the collaborative aspects of non-collocated participants in real or simulated construction projects. The amount of time allocated for such studies is usually not less than a semester due to the range of technical and academic activities involved. Only one example case of this approach was uncovered in the study (Becerik-Gerber et al., 2012) and this was conducted in a combined learning environment, involved the participation of software/industry mentors and required no prerequisite courses. The availability of suitable software and hardware to facilitate self-learning and communication was particularly important.

Approach Type 10: Mixed-MULTIPLE Levels Multidisciplinary (*Course*) *– in a single institution*: This approach involves the collaboration of different levels of students from one discipline with another set of students at different levels from another discipline but all being enrolled at the same institution. This is an expansion of approach Type 8 where the students from each discipline involved are usually representative of only one level, but which may be different to each other. Here, there is a lot of vertical and horizontal integration in the composition of the student group and this allows for simulating differential knowledge levels within an organisation and the diversity of focus areas while encouraging collaboration and learning. Practicing this approach requires considerable time coordination among levels and departments, access to training software and other technical resources and some level of software skill which could be compensated for by engaging industry or software mentors (see Zhao et al., 2015).

3. Discussion and interpretation of results

3.1. Open Coding

Open coding signifies the first level of data analysis. According to Corbin and Strauss (1990), during open coding, data are weighed against one another for the purpose of identifying what they have or do not have in common based on events/actions/interactions surrounding them. Categories and subcategories are formed when common concepts emerge that have been labelled a priori. Open coding was carried out for all the cases through reading the texts line by line and using NVivo Plus (v.12) to parse information for categorisation into themes and sub-themes after highlighting and extracting relevant indicators and incidents as codes. Further incidents and indicators that generally relate to the question of this study resulted in a total of 429-open codes that were subsequently parsed into 58-open code categories such as: causes of BfCE, advantages, disadvantages, the environment in which teaching and learning took place, teaching methods employed, stage of BIM education, delivery, learning foci, number of semesters for which the learning lasted; number of institutions combined in the cases, effects, limitations, challenges, etc.

3.2. Axial Coding

Axial coding involves identifying relationships among the properties and dimensions of the identified categories while relating them to the core phenomenon under study. The 58-open coding categories were rearranged to align with the given categories shown in the Axial Coding Paradigm of Figure 1, i.e. the causal conditions, core category or phenomenon, context, intervening conditions, strategies and consequences. These are expanded upon in turn below.

3.2.1. Causal conditions

The causal conditions include: leveraging BIM technology to educate students on designing, building and operating a net-zero energy prototype building culminating in capstone experience in some cases; understanding construction information management and storage platforms; perceived requirement by graduates to operate in a technologically driven world of work; ability of new employees to use BIM technologies and using 'a' BIM platform as 'a' conduit for the integration of complementary innovations e.g. laser scanning, photogrammetry, building inspection/surveillance and point cloud computing using unmanned drones. The causal conditions were understood, in a general sense, to be elements of the digitalisation of the construction industry.

3.2.2. Core phenomenon

BfCE was considered to be the core phenomenon for this study given its centrality to the whole process. In order to understand why construction educators engage in BfCE, varying indicators emerged that were grouped under this theme. From the Axial Coding Paradigm (ACP), this phenomenon is motivated by the causal conditions noted above. Faculties' specific responses take the form of different strategies or approaches to the implementation of BfCE and these are influenced by both context and intervening conditions. The strategy or approach adopted results in specific outputs or consequences.

3.2.3. Context

The contextual and intervening conditions governing the selection of specific strategies were considered in terms of factors at the macro, meso and micro scales. Macro conditions refer to international, national and community events that directly affect a study or institution to which the study is affiliated. Meso conditions relate to institutional factors and the micro level refers to sub-organisational and sub-institutional factors. Following the suggestions of Corbin and Strauss (1990), both macro and meso factors were regarded as contextual conditions whereas micro level factors were considered to be intervening conditions. Contextual conditions identified included:

Era: Era is a subtle factor and all the approaches are influenced by it as all the cases are in one way or another responsive to the 1987 launch of the BIM technology. Looking back to the launch of the first sets of commercially available BIM software in 1987 (Eastman et al., 2011; Quirk, 2019), and also giving consideration to technology shelf life of about 5 years, the time frame given for the implementation of key BIM guidelines in UK (Adamu & Thorpe, 2016) and global effort by public sector on BIM adoption, BfCE only began in 2006–2010 and has since then gathered momentum.

National or institutional mandate: National or institutional mandate is one of the identified factors responsible for two things in the development of BfCE. First influence was how fast this motivated the faculty in starting albeit faster than they probably would have started. Secondly, is the breadth of engagement. This influence is pronounced owing to the ability of the department to involve more than one discipline in most cases.

Industry demand: The surge in industry demand for graduates who are knowledgeable and well-grounded in BIM technology and processes (Deniz, 2018) has increased the sensitivity of academia towards BfCE. The advent of BIM has brought with it new industry roles such as BIM coordinator, BIM manager, etc. Training of these employees is considered economical if approached and addressed through academes such as universities (Palomera-Arias, 2015; Palomera-Arias & Liu, 2016). To meet industry demand, academia has in the past 5–6 years improved BIM awareness among university students and explored new didactics methodologies to use BIM in their teaching. However, faculties have been admonished not to focus teaching only on the present needs of the industry but on fostering well rounded graduates that would both be able to serve in the current industry and the industry of the future (Clarke, 2012; Underwood et al., 2019).

Environmental issues: Environmental issues such as sustainability, global warming, waste management, etc. have enjoyed better explication through BIM environments. Faculties have actively leveraged BIM capabilities e.g. visualisation, simulation, ability to organise data, etc. to both illustrate and teach the students about these issues.

Accreditation requirements: Accreditation bodies and their requirements have also impacted the level of BfCE development and delivery approaches. Formalising BfCE requirements is considered a forceful impetus in promoting BfCE in universities.

3.2.4. Intervening conditions

As noted above, intervening conditions were taken as referring to micro level factors. Intervening conditions identified from the cases included the following.

Resources: Resources refers to the assets that facilitate the delivery of BfCE. These include facilities such as classrooms, design/computer studios, etc. or more technical artefacts such as hardware and software. The presence (or absence) of these resources strongly influence faculties' approaches to BfCE as well as what is taught.

Time coordination: The amount of time available and its coordination is another factor influencing the BfCE approach adopted. The limited number of weeks in any academic calendar drives the prioritisation of what is to be taught within the available time. Time coordination is particularly important when collaboration between two or more disciplines and/or institutions are involved.

Skill level: Skill levels among both faculty and students influence the choice of didactical approaches. It was noted that a lack of skills discouraged or reduced the level of engagement with BfCE in some cases.

Organisational structure: Organisational structures affect the degree of autonomy that can be exercised by faculty members in modifying the curriculum and therefore have an influence on the ease with which BfCE can be incorporated into existing courses and curricula.

Guest lectures/External roles: The availability of guest lecturers and external role players including mentors, especially by alumni adds to the types of approach that may be adopted in any BfCE endeavour. These external forces may also impel faculty members to engage in BfCE when they share their industry experiences and express how important it is to have BIM-ready graduates.

3.2.5. Strategies

Strategies are the different approaches to BfCE that faculties adopt in response to causal conditions (the digitalisation of the construction industry) and which are influenced by both the context and by intervening conditions. These different ways and means of teaching different engineering concepts, processes, procedures, construction methodologies, etc. are reflected in the combinations apparent in Table 2, i.e. teaching basis, learning foci and delivery.

3.3. Typology of BfCE approaches

A typology of the different approaches to BfCE was derived by the authors and is presented in Table 3. Our analysis of the cases found that all the identified BfCE approaches can be conveniently described in terms of the level of delivery, whether it is mono- or multidisciplinary, the scope of the offering and whether one or more institutions are involved. The 44 cases involved 10 distinct types of BfCE approaches but further combinations (which were not found in the sample cases) are also potentially feasible.

3.4. Consequences

14 indicators relating to the consequences of different approaches, their advantages and disadvantages were identified. In addition, it was noted that the different approaches to BfCE also had effects that could be categorised at a higher level of abstraction as either meeting immediate or short-term industry needs in terms of producing BIM-ready graduates who can 'do BIM' or meeting long-term needs through the leveraging of BIM to create a collaborative and immersive educational environment for teaching and learning. Table 4 illustrates the identified consequences and how they relate to the different dimensions of the various BfCE approaches.

3.5 Selective coding

Selective coding is the final phase of the theory derivation process where an attempt to explain and synthesize the interactions between the different categories of the axial coding paradigm is made in order to derive an understanding of the BfCE processes. The authors propose a conceptual framework as shown in Figure 2.

Digitalization of the construction industry is driving changes in construction industry needs (both short-term needs – immediate skills requirements; and long-term needs – reorganisation of industry and ways of working) and in construction education. Construction education is, on the one hand, responding to these industry needs, e.g. through providing students with BIM awareness and skills, and, on the other hand, it is leveraging the opportunities that arise from the digitalization of the construction

Table 3. Typology of BfCE approaches with examples

Level			Discipline		Scope			Institutions		Examples found in the literature
Undergraduate	Postgraduate	Mixed	Single	Multiple	Topic(s) within course	Full course	Multiple courses / programme	Single	Multiple	
×			×		×			×		Sharag-Eldin and Nawari (2010)
×			×				×	×		Kim (2014); Palomera-Arias (2015); Zhang et al. (2017)
×			×			×		×		Pikas et al. (2013); Brioso et al. (2017); Wang and Leite (2014); Dougherty and Kevin Parfitt (2013); Mathews (2013); Sands et al. (2018); Shenton et al. (2014); Livingston (2008); Barham et al. (2011); Palomera-Arias and Liu (2016); Shanbari et al. (2016); Yi and Yun (2018)
×				×			×	×		Comiskey et al. (2017); Solnosky and Parfitt (2015); Wong et al. (2011)
×				×		×		×		Bozoglu (2016); Zhang et al. (2018); Pikas et al. (2013); Monson and Dossick (2014); Jin et al. (2018); Nawari et al. (2014)
×				×			×		×	Comiskey et al. (2017)
	×		×				×	×		Hijazi et al. (2018)
	×		×			×		×		Wang and Leite (2014); Suwal and Singh (2018); Sampaio (2015); Pikas et al. (2013); Nassar (2012)
	×			×		×		×		Bozoglu (2016); Charlesraj et al. (2015); Pikas et al. (2013); Shanbari et al. (2016)
		×	×			×		×		Wu and Hyatt (2016); Lewis et al. (2015); Hu (2019)
		×		×		×		×		Chiuini et al. (2013); Rassati et al. (2010); Leite (2016)
		×		×		×			×	Becerik-Gerber et al. (2012); Zhao et al. (2015)

Table 4. Consequences of adopting different BfCE approaches

ID#	Consequences	Level			Disciplines		Scope			Institutions	
		Undergraduate	Postgraduate	Mixed	Single	Multiple	Topic(s) within course	Full course	Multiple courses / program	Single	Multiple
1	Need for approval from higher authorities	Low	Low	High	Low	High	Low	High	High	Low	High
2	Time coordination difficulty			High	Lower	High	Low		High		Higher
3	Previous BIM knowledge requirement	Low	Low	Low	Low	Low	Low	High	Higher	Low	Low
4	Investment in hardware and software				Low	High	Low	High	Higher	High	Higher
5	Need for mentors						Low	High	Higher	High	Higher
6	Need for more than one faculty member				Low	High	Low	High	Higher	High	Higher
7	Suitability for teaching engineering concepts						High	Low	Lower		
8	Requirement for BIM mandate	Low	Low	High	Low	High	Low	High	Higher	High	Higher
9	Requirement for change in curriculum				Low	High	Low	High	Higher	High	Higher
10	Promotion of self-learning						Low	High	Higher		
11	Suitability for imparting a wide array of BIM concepts and ideas				Low	High	Low	High	Higher	High	Higher
12	Promotion of interdisciplinary learning / communication / collaboration	Low	Low	High	Low	High	Low	High	Higher	High	Higher
13	Time limitations						High	Low	Lower		
14	Promotion of communication skills in students						Low	High	Higher		

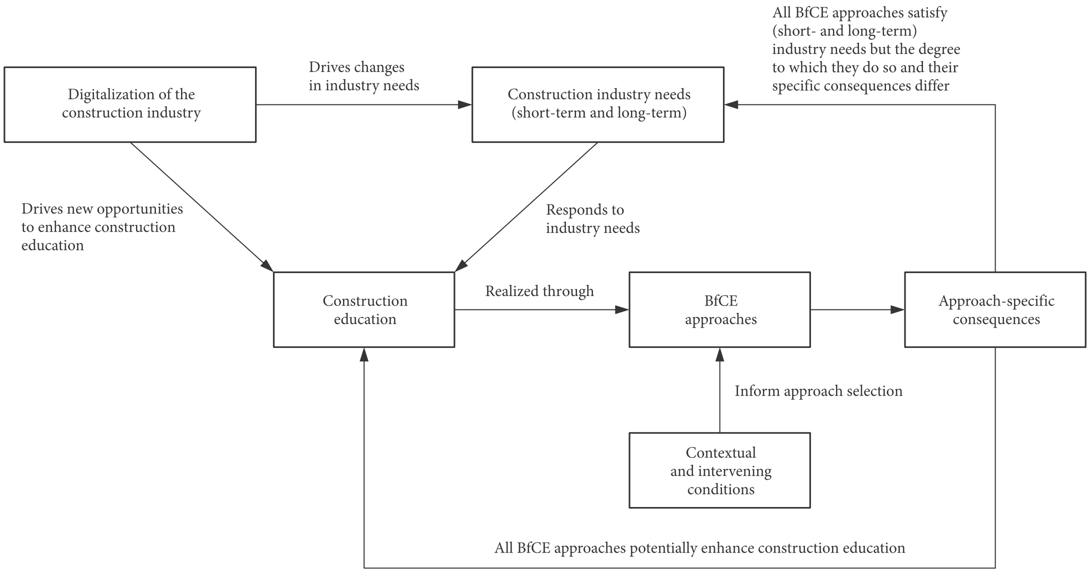

Figure 2. BfCE conceptual framework

industry to enhance construction education, e.g. opportunities for improved integration of curricula both within and between disciplines, closer correspondence of the teaching and industry environments through using real project data, etc. in the form of BIM-enabled education.

The changes to construction education are manifesting as different BfCE approaches which are enabled and constrained by contextual conditions (at the macro and meso levels) and intervening conditions (at the micro level) and these affect the selection of different BfCE approaches in any particular case.

All the different BfCE approaches are intended to satisfy the construction industry needs (both short-term needs and long-term needs) and to enhance construction education but they achieve these aims in differing degrees in accordance with their consequences.

Conclusions

This study set out to systematically synthesise extant cases of BIM implementation in universities' AEC-FM disciplines. A general awareness of the need to find and implement new strategies of educating professionals in the AEC-FM disciplines was found. This has been informed by recent changes in the digitalisation of the construction industry which are affecting the ways of working in the construction industry as well as giving rise to educational opportunities which could be useful in fostering graduates who would not just serve the short-term but also the long-term needs of the construction industry.

Universities are responding to these challenges with a diverse range of BfCE approaches which this study has recorded – going from a topical level to a whole curriculum level, with collaboration extending to multiple disciplines involving many institutions at the same time. As wide as the level of engagement so is the diversity in the topics focused upon under different circumstances – from the elementary introduction of BIM to more advanced conceptual teaching in a virtual BIM environment. The formalisation of these approaches and the contextual and intervening conditions that support them can assist in decision making for BIM for construction education implementation in universities.

In this study, a Grounded Theory (GT) approach, specifically, a Straussian Theory Model (STM) has been adopted to identify and define the different BfCE approaches reported in the literature, the contextual and intervening conditions which give rise to them and their consequences and to develop a conceptual framework which sets out the relationships between these and the digitalisation of the construction industry. In addition, we have derived a descriptive typology that depicts all possible BfCE approaches.

The implications of this study for current practice include the formalisation of the processual activities of most (if not all) current BfCE approaches in AEC-FM education. Apart from course design, the number of disciplines and institutions involved in categorising the approaches as considered by previous authors, this study has taken account of the human elements underlining these approaches along with the causes, contextual and intervening conditions that influence approach choice and their attendant consequences. This can assist construction educators to understand and determine suitable approaches for either starting or extending their current teaching practice and to conceptualise new approaches that have yet to be tried and reported.

With this understanding of BfCE approaches and processes, future studies will be geared towards the development and implementation of a pilot BfCE intervention within an action research framework. To enable this, we need to further investigate:

1. Specific university microenvironments including the one in which the pilot BfCE intervention will take place, their associated contextual and intervening conditions and how these shape BfCE approaches;
2. The mechanisms by which different BfCE approaches respond to perceived industry needs and how they are thought to enhance construction education.

This study is limited to peer reviewed journal articles and conference proceedings and searches conducted on only a few databases. We acknowledge that other approaches that may exist in other sources could have been omitted or unaccounted for in this study.

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Teaching Project Risk Management in a BIM-Enabled Learning Environment

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Abstract. Digitalization is driving changes in the architecture, engineering, construction and real estate (AEC+ RE) industry and a central feature of this digital transformation is Building Information Modelling (BIM) which refers to the integrated digital representation of all building-related information. A BIM-enabled Learning Environment (BLE) aimed at creating an experiential learning space and offering opportunities for immersive and integrated learning on the basis of real project data has been conceptualised in earlier research. This research addresses the need to design educational interventions using the BLE. On the basis of document analysis and lecturer observation, the current and proposed approaches to teaching project risk management are described and compared in terms of their activities, learning objectives, feedback and assessment strategies and contextual factors. The new approach is intended to leverage BIM in order to engage students in a learning activity that closely corresponds to industry project reality and ways of working. It also presents challenges in terms of ensuring adequate acquisition of theoretical knowledge and finding sufficient time for students to grasp the complexities of a realistic, industry project environment.

Keywords: Building Information Modelling (BIM) · BIM-enabled Learning Environment · Project risk management

1 Introduction

1.1 Background

Digitalization is driving changes in the construction industry and a central feature of this digital transformation is Building Information Modelling (BIM). BIM refers to the integrated digital representation of all building-related information from design through to demolition and it enables communication, coordination, planning, simulations, etc. to take place in a common, virtual environment.

The education of construction professionals has tended to lag industry in its deployment of BIM [1, 2] and this poses a challenge for the education of Architectural, Engineering, Construction and Real Estate (AEC+RE) students [3]. On the one hand, it must respond to the immediate industry needs by providing students with the knowledge and skills to carry out their professional tasks using BIM - this has largely been done in university AEC+RE programmes [4]. On the other hand, there are new

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opportunities arising from BIM which have the potential to enhance AEC+RE education and benefit the industry in turn [5]. These include opportunities for improving the integration of curricula within and between construction-related disciplines using real project data and creating learning environments that more closely correspond to industry realities.

1.2 BIM-Enabled Learning Environment

Earlier research [6] established the concept of a BIM-enabled Learning Environment (BLE) for creating a common learning space that spans both higher education and industry for immersive and integrated learning on the basis of real project data, as well as greater continuity between degree studies and professional development. The BLE concept draws on Dewey's notion that education requires a social environment that allows both communication (for learning) and application (for doing what is learnt) [7]. Further development of this idea through Kolb's Experiential Learning Theory introduces the concept of "Learning Space" which elaborates transactions between learners and their environments [8, 9]. In addition, Gidden's Structuration Theory provides a framework to describe this social environment in terms of the structures which allow it to be produced and reproduced in social activity. "Structures" in this sense are the properties, rules, resources and transformational relations which allow social practices to be reproduced across time and space and which give them the form of systems [10].

As shown in Fig. 1, the BLE is embedded within the systems of education and the AEC+RE industry. Both the structures of the education system (e.g. curriculum requirements, teachers and students, learning outputs, etc.) and the structures of industry (e.g. real project data, ways of working, professional roles, etc.) are appropriated and combined in order to create the BLE. For example, BLE roles must make sense both from the industrial BIM work flow point of view - e.g. Construction Manager, BIM Coordinator, Architect - and also from the educational point of view - e.g. Learner, Instructor.

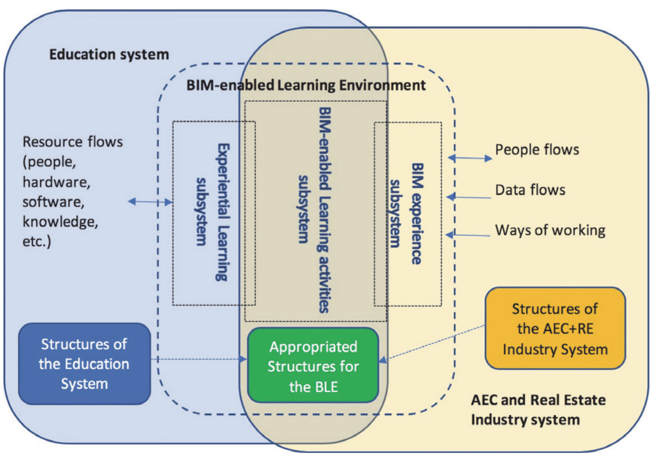

Fig. 1. The BIM-enabled Learning Environment (BLE) source: [6].

1.3 Teaching Project Risk Management

Risk in construction project management has been identified by several educational researchers as a concept that is not easily understood by students because of the difficulty in juxtaposing theory with practical reality [11, 12]. The concept of risk in construction projects originates from theoretical developments over centuries in many diverse fields including probability theory e.g. [13], economics e.g. [14], finance e.g. [15], insurance and actuarial science e.g. [16], sociology e.g. [17], etc. which has subsequently been built on by construction project management theorists. The result is a complicated concept for instructors to articulate to their students that variously relates to:

- uncertainty - having incomplete knowledge, particularly with respect to the future;
- probability - in the sense of 'rational belief' in the likelihood of a possible outcome with respect to a corpus of knowledge (evidence) which substantiates that belief;
- expectations - risk is experienced relative to expected outcomes;
- actions - in order to engage with risk, it is necessary to do something;
- time - there is a temporal dislocation between the consideration of risk and the outcome itself;
- profit/gain/loss [18].

In contrast, the practical application of risk management is relatively straightforward to understand and follows a logical process of: plan risk management, identify risks, perform qualitative and quantitative risk analyses, plan risk responses, monitor and control risks. This process, particularly the risk identification, risk analysis and risk response steps, is cyclical and repeats through the project [19].

The 'traditional' approach to teaching project risk management involves introducing the concept of risk and following this up with a (typically shallow and time-constrained) practical risk management exercise. However, the literature does report some innovations: for example, [11] developed a computer-based simulation game and applied mixed methods action research to demonstrate how both theory and practice of risk in project planning and control, using real life data, could be taught to a group of 33-students using an experiential learning approach. [12] designed and developed a similar game based on scenarios from a real-life land development. The Virtual Construction (VIRCON) simulation is another innovative development designed for educating students on project risk management. It integrates design and planning tools (with schedule simulator) for students to perform pre-contract activities including the production of a complete competitive bidding proposal [20].

BIM has also already been shown by numerous authors to be a powerful tool for enabling innovative approaches to construction education including project risk management. For example, [21] elucidate how BIM as a single repository for construction data and information can be used to eliminate the repetitive and redundant class exercises in project management courses. They argued that, with BIM, data and information relating to a particular project and context can be easily retrieved and manipulated for different class exercises and asserted that this facilitates quicker understanding and management of risk principles and applications in project execution.

1.4 Research Purpose and Paper Structure

The overall goal of this research is to fully leverage the educational opportunities of BIM in order to bring BIM-enabled construction education from concept into practice as this will offer more immersive and integrated learning experiences on the basis of real, up-to-date project data from industry. The BLE concept has been developed to achieve this but is still in the earliest stages of being applied in teaching practice. The purpose of this study is to find a solution to the question: How can project risk management be practically and advantageously taught within a BLE? Project risk management is an appropriate test learning activity because, although it is widely accepted as being important, it is often not applied systematically in the construction industry and, for good decision-making, project risk management must be based on accurate, historical project data (i.e. evidence). The greater availability and accessibility of project data with BIM raises the prospect of better project risk management provided that practitioners know how to use it effectively. Hence, experiential learning in a BLE offers opportunities to directly improve industry practices over existing project risk management teaching approaches.

In the following sections of the paper, the research methodology is outlined before two alternative pedagogical designs are presented - the case of the existing teaching arrangements and an alternative (proposed arrangement) in which the BLE concept is applied. The two cases are discussed, compared and contrasted and, finally, conclusions drawn in terms of the anticipated advantages and disadvantages of teaching project risk management in a BLE. This study is limited to the design of the new educational offering and does not extend to the implementation and evaluation of it in teaching.

2 Methodology

The study reported in this paper takes place within the broader context of a participatory action research project involving a five stage, cyclical process of Diagnosing, Action Planning, Action Taking, Evaluating and Specifying Learning [22]. The action research aims to introduce BIM-enabled education into the AEC curriculum and this study is focused on the Diagnosing and Action Planning stages, specifically the planning of an intervention with respect to teaching project risk management in a BLE.

“Diagnosing” refers to problem identification, data collection and data analysis resulting in solution proposals. In this study, the current approach to teaching project risk management within a particular project management in construction course is analysed by document analysis and lecturer observations/reflections in order to derive a baseline description which is framed in terms of its learning objectives, teaching and learning activities, feedback and assessment strategies and contextual factors.

The “Action Planning” stage relates to the detailed development of a proposed solution to the problem(s) identified during “Diagnosis”. In this particular case, it refers to the design of a novel, proposed way of teaching project risk management for the same course which takes advantage of the emerging opportunities of BIM-enabled learning and, specifically, employs the BLE concept. The new learning experience is designed on the basis of current, recommended learning experience design guidance and described in the same terms of learning objectives, teaching and learning activities, feedback and assessment strategies and contextual factors so as to enable comparison with the current teaching approach.

3 Findings

3.1 Case 1: Current Approach to Teaching Project Risk Management

Description of Teaching and Learning Activities. The risk management topic is currently delivered in an approximately 90-min classroom session comprising 2 parts - a 45-min presentation in lecture format which includes some interactive illustration of points during the presentation, followed by a facilitated class exercise for which a further 45 min of class time is assigned.
The lecture covers:

- The terms and concepts of risk management;
- The basic process of risk management in projects (plan risk management, risk identification, risk analysis, risk response, monitoring and control, documentation and record keeping/learning for future projects);
- Project risk management standards;
- Tools and techniques for achieving each stage of the risk management process;
- How risk and risk management link to wider ideas in construction, science and society (such as contracts as instruments of risk allocation and transfer, Integrated Project Delivery, statistical inference, climate change and disasters, societal risk and modernity, etc.)

The facilitated class exercise is aimed at demonstrating and reinforcing key steps of the risk management process - risk identification, (qualitative) risk analysis, recommending risk response actions. It is carried out in small teams of students who assume different construction industry roles (client, designers, contractor, etc.) as follows:

- A simple construction project scenario is given;
- Students work in small teams in the format of a risk management workshop to identify risks, analyse the relative significance of those identified (using a problility – impact matrix) and recommend actions to mitigate the most significant risks;
- Student teams report their findings;
- A general class discussion then takes place in which all teams' findings are considered and summarised and the key points of (practical) project risk management are reinforced.

Learning Objectives. The learning objectives are defined with reference to Bloom's Taxonomy as revised by [23, 24].

Table 1. Learning objectives for the current approach to teaching project risk management.

Bloom's Taxonomy (revised: [23])	Learning objectives
Remembering: Retrieving, recognizing, and recalling relevant knowledge from long-term memory	• Students are able to describe the process, tools and techniques of project risk management
Understanding: Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining	• Students understand the concepts of risk and project risk management
Applying: Carrying out or using a procedure through executing, or implementing	• Students are able to apply the project risk management process, tools and techniques in a given (simple) project scenario
Analyzing: Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing	• Within the given risk management process and project scenario, students are able to break up the scenario into constituent elements and analyse risks associated with each element
Evaluating: Making judgments based on criteria and standards through checking and critiquing	• Students evaluate the risks identified in terms of given (probablity and impact) criteria in order to reach a collective judgement (within their team) concerning the relative significance of each of the identified risks and what actions to take to mitigate them
Creating: Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing	• As a whole class, a common understanding of the most significant risks and suitable responses to them is created - but this does not take place at the individual student level

Feedback and Assessment Strategies. Given the short duration of this topic within the current project management in construction course, the opportunities for feedback and formative assessment are limited within it. Direct feedback (from their peers and from the lecturer) occurs as the student teams discuss and work through the risk management process steps. Towards the end of the class exercise, when the student teams' results are collated, it is typically the case that there is notable similarity between the most significant risks identified by the different teams and their proposals for mitigating these risks. This tends to give the students some confidence in the legitimacy of their results.

Summative assessment is limited to questions in the course final exam which require students to apply the same risk management process steps to a simple project scenario and also to recall appropriate tools, techniques and process stages of risk management.

Contextual Factors. Students taking this course are typically either in their 4th year of studies in an integrated, 5-year construction-related masters degree programme or taking a 2-year masters degree programme in the case that they have completed studies to bachelor's degree level previously, in a separate programme. Their industry experience varies from none at all to highly experienced professionals. By working in teams, their experiences can be pooled to an extent.

Primarily as a consequence of time constraints, the exercise scenario is highly simplified and minimizes the use of specific, real project data. This reduces its correspondence to industry reality but makes it easier to apply the recommended project risk management process steps to it. However, this leaves a significant gap between the exercise and practical application in real industry projects.

To date, quantitative risk analysis has been briefly introduced in this course but not included in the practical exercise because it would require considerably more time both to explain and for the students to apply (even in a highly simplified scenario).

3.2 Case 2: Proposed BLE Approach to Teaching Project Risk Management

Description of Teaching and Learning Activities. As noted above, the key idea of the BLE concept is to enable immersive and integrated learning experiences on the basis of real, up-to-date project data from industry. This experiential learning takes place on the basis of a realistic industry work flow that fully utilizes BIM (see Fig. 2).

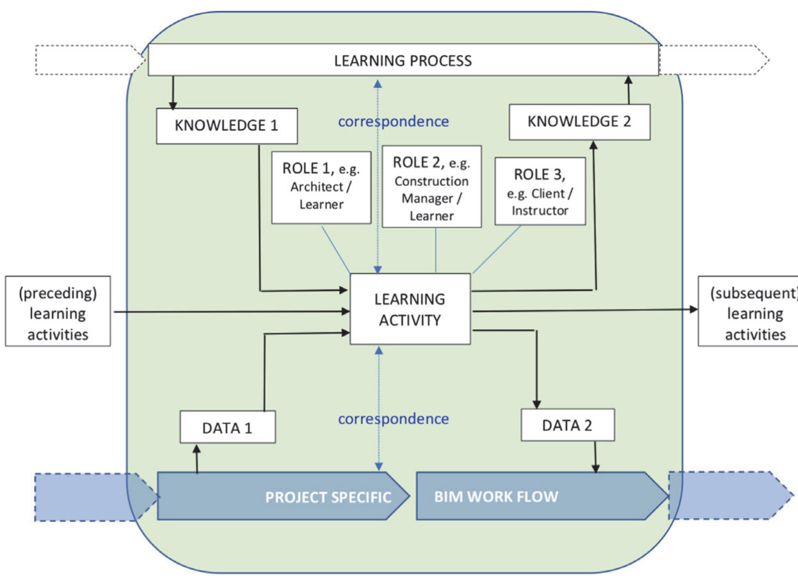

Fig. 2. The BIM-enabled Learning Environment (BLE) at the level of learning activity, adapted from [6].

BIM ensures comprehensive, organised and readily accessible project data. Much of this data is referenced directly to building objects (walls, beams, columns, windows, doors, floor slabs, pipes, etc.) which are represented in a virtual, 3D model of the building so that they can be easily viewed and understood. It therefore enables real, complicated project scenarios to be presented to and efficiently grasped by students. Using an industry BIM work flow ensures that the scenario on which the learning activity (project risk management, in this case) takes place corresponds to industrial reality and also that the data input to the learning activity (Data 1 in Fig. 2) is not contrived by the lecturer but rather exists as real project data and is drawn directly from the same sources as would be the case in industry. (It should be noted that this project data must be pre-checked and simplified to remove inconsistencies and unnecessary details which could confuse students.) Similarly, by carrying out the learning activity, the project data is further processed and the output data (Data 2 in Fig. 2) feeds directly back into the BIM work flow. The project is thus elaborated and progressed. In this way, the learning activity is intended to resemble a meaningful task in a genuine work context.

In order that students are suitably prepared and able to carry out the learning activity, they will need some pre-instruction (Knowledge 1 in Fig. 2). However, most of their learning occurs within the context of the learning activity itself (Knowledge 2 - Knowledge 1 in Fig. 2). In this way, the teaching and learning activities proceed as follows:

Initial instructions to (briefly) cover the essential pre-information necessary to commence with the experiential learning activity:

- Key steps in the process of project risk management;
- Instructions and information for participation in the learning activity.

The experiential learning activity - students work through a guided, detailed project risk management process (including both qualitative and quantitative risk analysis) on the basis of real project data within a BIM work flow. They do so in teams arranged according to typical industry roles and, in the course of the activity, they explore and discuss in detail:

- The terms and concepts of risk management;
- The process of risk management in projects (plan risk management, risk identification, risk analysis, risk response, monitoring and control, documentation and record keeping/learning for future projects);
- Tools and techniques for achieving each stage of the risk management process;
- Project risk management standards;
- How risk and risk management link to wider ideas in construction, science and society (such as contracts as instruments of risk allocation and transfer, Integrated Project Delivery, statistical inference, climate change and disasters, societal risk and modernity, etc.).

Learning Objectives

Table 2. Learning objectives for the proposed approach to teaching project risk management.

Bloom's Taxonomy (revised: [26])	Learning objectives
Remembering: (detailed description as per Table 1)	• Students are able to describe the process, tools and techniques of project risk management. With the BLE learning activity, this relates to a more realistic, detailed BIM-based process
Understanding: (detailed description as per Table 1)	• Students understand risk, project risk management concepts • As the learning activity takes place within a BIM work flow, students also acquire understanding of this work flow - which increases the learning value beyond the risk management topic
Applying: (detailed description as per Table 1)	• Students are able to apply the project risk management process, tools and techniques in a realistic project scenario based on real project data and an industrial work flow
Analyzing: (detailed description as per Table 1)	• Within the given risk management process and project scenario, students are able to break up the scenario into constituent elements and analyse risks associated with each element
Evaluating: (detailed description as per Table 1)	• Students evaluate the risks identified in order to reach a collective judgement concerning the relative significance of each of the identified risks and appropriate mitigation actions
Creating: (detailed description as per Table 1)	• Students reconsider the risk management process and the industrial work flow in order to recommend improvements

Feedback and Assessment Strategies. The intention of the BLE learning activities is that their successful completion and quality is assessed by the students themselves later in the course as the output data from each activity feeds back into the work flow and provides input data to later, subsequent activities. A poorly executed activity will lead to later process and implementation problems. The BLE thus seeks to reflect the default means of assessment of the industrial project process in the class room (see Fig. 2).

The learning activity presumes considerably more effort from students than the simplified project scenario in Case 1 does. This allows greater scope for feedback during the activity and also for formative assessment. It suggests that summative assessment should be linked to the learning activity itself as this cannot be repeated in a final exam.

Contextual Factors. Time is clearly a constraining issue for this approach. However, as the same real project data and underlying BIM work flow can be maintained throughout the course, the time for students to familiarise themselves with this learning environment may be spread across the whole course rather than impacting just a single topic.

The need for real project data presented in appropriate formats is critical to this approach and is not (yet) readily available. This requires initial investment to set up the project data and to 'clean' it of inconsistencies/errors and simplify it where necessary.

Industrial BIM work flows with respect to project risk management are by no means standardised - they are still under development and not yet widely adopted in industry. The learning activity processes are thus part of the development of BIM-based project risk management for the AEC+RE industry. On the one hand, this makes it more challenging to design the activities, on the other, the creative development of the process and work flow are currently important for industry. Although the students' industry experience varies from zero to highly experienced professionals, with respect to BIM-based project risk management, there is likely to be some novelty for all students.

4 Discussion

The two approaches to project risk management teaching described above differ fundamentally in their process. The current teaching arrangement (Case 1) focuses on explaining the concepts, terms and theoretical basis, and then engaging the students in a (simplified) scenario-based activity to demonstrate the application of theory to practice. In the proposed BLE-based approach (Case 2), the focus is on a realistic, experiential learning activity which corresponds closely to industry project reality and the theoretical consideration of the subject emerges as an extension of the practical application.

In this way, Case 2 is representative of problem-based learning (PBL) approaches which have become increasingly popular in areas of professional education [25]. The emphasis on an experiential learning context also reflects the CDIO approach which stresses engineering fundamentals set in the context of real-world systems and products [26].

The digitalization of the AEC+RE industry is radically changing the way in which buildings are designed and constructed. [3] has pointed out that BIM enables the building design process to begin with a complete model of a building which can then be adapted to suit new conditions rather than always starting from abstract concepts and ending with the building. BIM enables a similar change for risk management as it provides a database relating to the current project and also historical projects. Thus making explicit all the evidence on which project risk management should be based.

A BLE-based approach to teaching project risk management is clearly more time-consuming (at the topic level) as it requires students to navigate in a much richer project data environment than would be the case for a simple example scenario. It also favours the acquisition of wider risk concepts and ideas through collective exploration and discussion. This offers more student-centred learning experiences but also takes considerably more time to deliver than a standard lecture format. In practice, course time constraints will determine the precise balance between traditional delivery and group exploration of risk concepts on the basis of the experiential learning activity. The learning activity will, in any case, provide students with a common reference with which to frame and make sense of the concepts.

A potential danger of such a strong emphasis on correspondence to industry and industrial work flows is an unintentional ‘vocationalisation’ of university education where relevance to current industrial practice is overemphasised at the expense of higher level conceptualisation, professional attitudes and principles. Again, an appropriate balance is sought where education does indeed correspond to industry needs but rather the wider, future needs than current, narrower needs.

5 Conclusions

The new, BLE-based approach to teaching project risk management is intended to leverage the opportunities offered by BIM to enhance industry performance and the effectiveness of education for AEC+RE professionals. The BIM work flow provides a data-rich, real project context in which to immerse students and engage them in a learning activity which closely corresponds to industry reality and enables experiential learning. It represents the emerging, industry ways of working which students must understand so that they can contribute to developing them in their future professional careers. However, it also presents attendant challenges in terms of ensuring the acquisition of a sufficient theoretical understanding of the subject so that students are prepared to contribute at higher levels of professional activity (e.g. policy formulation, standards development, etc.) than only the implementation and application of project risk management concepts to the project context. The realistic project context requires additional time for students to become familiar with and be able to effectively learn within.

Future work will focus on the next stages of the action research cycle: action taking, evaluating and specifying learning.

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Publication IV

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Evaluating Construction Education Interventions

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Abstract. The evaluation of engineering education interventions is important to gauge their impact and whether they achieve their intended objectives. Building Information Modelling (BIM) educational interventions are increasingly common at universities globally and their implementation is often accompanied by ad hoc evaluation practices and sometimes little evaluation at all. The aim of this study was to investigate existing evaluation practices among engineering educators, in particular technology mediated interventions and determine an appropriate evaluation methodology for BIM for Construction Education (BfCE) pilot initiatives. Academic articles and educational (non-research) guidance literature were reviewed to identify existing evaluation models. In addition, reported cases of BfCE were reviewed to identify specific approaches that have been applied to evaluate such initiatives. The study found that the use of evaluation models in engineering education is low. In addition, little evidence of the use of evaluation models in relation to BIM education interventions was found indicating a need to increase awareness among engineering educators on the importance of evaluation in promoting engineering education. An evaluation framework was derived to support engineering educators to more effectively evaluate their BfCE interventions.

Keywords: Educational evaluation · Building Information Modelling (BIM) · BIM education · Evaluation · Assessment · Construction education

1 Introduction

Studies have shown that introducing technology into didactics enhances learning and increases the motivation of students to learn (Wu and Kaushik 2015; Barham et al. 2011; Lopez-Zaldivar et al. 2017). “Building Information Modelling (BIM) is a process supported by various tools, technologies and contracts involving the generation and management of digital representations of physical and functional characteristics of” construction projects (“Building information modeling - Wikipedia,” n.d.). The desire to leverage the opportunities presented by BIM for engineering and construction education has led to efforts to design and execute pilot “BIM for construction education” (BfCE) pedagogical interventions (Olowa et al. 2019). Construction education has been criticized for the mismatch between graduate competencies and their professional roles in industry (Forsythe et al. 2013). By enabling the use of real

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construction project data and simulating more realistic, multidisciplinary workflows in the educational environment, BfCE offers opportunities to enhance construction education didactics to better align graduate's competences with emerging and future needs, particularly those arising from the digitalization of the construction industry. This has been generally recognized and initiatives to develop curricula to incorporate BIM have become widespread.

However, measuring and determining the effectiveness of such interventions have always been a challenge. The literature contains a plethora of models and approaches for educational evaluation and assessment proposed by various authors for both programme and course evaluations together with their attendant criticisms (for example, see Stavropoulou and Stroubouki 2014; Gordon 2018; Chinta et al. 2016; Anh 2018). Although Anh (2018) observes a spike in the attention given to evaluation among education practitioners in recent times, McCuen and Chang (1995) opine that most engineering evaluations are done retrospectively by the instructor in charge of the course with concentration on the implementation, and evaluation specifically based on the students' grade assessment. Little attention is given to the likely impact that the teaching style, institutional environment, teacher-student relationship, student-student relationship, classroom process and the general societal culture and values may have on the performance of the course. Additionally, most existing reports of BfCE trials lack clear descriptions of the evaluation methods adopted and the few reported evaluation activities suggest a focus on students' academic performances without adequate consideration of other, incidental and contextual factors that may have influenced the outcome of the interventions. Students' performances may be more objectively evaluated when there is a control group for comparison, but, in the absence of one, there is still a need for reliable approaches to evaluation. Behaviorist learning theory, which predicates evaluation on carefully established objective and learning outcomes along the societal, subject and student lines, suggests that such approaches can indeed be derived.

The purpose of this research is to investigate an appropriate evaluation methodology for BfCE pilot initiatives. To this end, a literature review has been carried out and the findings compiled into a generic framework for evaluation. This will contribute to the wider goal of a doctoral research project which seeks to determine how BIM can be leveraged to improve education in Architecture, Engineering, Construction and Facilities Management (AEC/FM) disciplines and to develop an effective BfCE module that enhances industry-relevant learning, increases students' motivation for (lifelong) learning and promotes this approach to teaching and learning.

We use the term "evaluation" here in relation to assessment and measurement as illustrated in Fig. 1 and described by Gandhi et al. (2017) thus: measurement is a construct that denotes giving a quantitative value to an attribute with no direction as to the impact of such quantitative value or interpretation of it. Assessment gives direction to the measurement without judgmental value while evaluation refers to a value judgement being applied to the assessment in order to inform action.

We acknowledge the broader purposes of evaluation which extend beyond students' academic performance (McCuen and Chang 1995) to the effect of the intervention on students' growth and behavioural output, educational decision-making, determining value in relation to resources invested, effectiveness of teaching/learning materials and techniques, encouraging and motivating students, etc. (Ogunniyi 1984).

Proponents of contextual considerations to evaluation such as Fry et al. (2015) argue that subtler considerations such as students' perceptions of the educator can also influence a students' attitude and performance in a course. The evaluation approach derived in this paper is intended to encompass all aspects of evaluation - achievement of learning objectives by students, content evaluation, delivery evaluation, learning environment evaluation, institutional impact evaluation/assessment, alignment of the learning content to industry needs, etc.

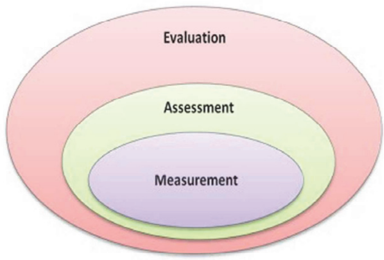

Fig. 1. Relationship between measurement, assessment and evaluation (Kizlik 2020)

This paper is arranged in five sections. The introduction is followed by a methodological description of the research approach which is a literature review. Findings are then presented followed by a discussion section in which an evaluation framework is proposed. A final section presents conclusions and recommendations from the study.

2 Approach

This research is part of a broader initiative in which an action research approach is employed for developing and testing the teaching of Construction Management topics within a novel, BIM-enabled education environment. Specifically, the action research methodology adopted follows a 4-step process of Diagnosing, Action Planning, Action Taking, Evaluation & Learning. For the present study, the focus is on the evaluation stage.

To establish the basis for evaluating the pilot BfCE action, a literature review was undertaken aimed at investigating existing guidance and experiences of evaluation of educational and training interventions. The review was carried out in two stages:

1. Reviewing the educational (non-research) guidance literature as well as articles in academic journals and conference proceedings to determine the suitability of existing evaluation models, whether evaluation of engineering education in a technologically mediated environment, at a topical level is feasible and the requirements for this type of evaluation.
2. Reviewing existing cases of BfCE reported in academic journals and conference papers to identify evaluation models and tools in use.

For the first stage, a Google Scholar search was carried out using the search term "evaluation of engineering education" anywhere in the text, in a search with no date restrictions but limited to English language sources. The search results were screened for relevance and a total of 24 sources (including textbooks, dissertations, journals, and conference proceedings) were selected for further content analysis using NVivo (v.12).

The second review drew on a comprehensive database of the BfCE cases reported in the academic literature which had been compiled in earlier research (Olowa et al. 2019). For this study, the cases contents were searched (using NVivo v.12) to extract all information pertaining to the evaluation models and tools used.

The results of these two reviews were then combined in order to derive a framework for evaluation to be applied in the evaluation stage of the wider action research.

3 Findings

3.1 General Evaluation Models

Evaluation models are specific frameworks or methodologies which assist evaluators in designing evaluation criteria and instruments. 15 examples of models were found in the literature (see Table 1: Evaluation models). Each model comes with its pros and cons and it appears that the criticism of any model may lead to the development of a new model. For instance, Illuminative evaluation model/ anthropological model was developed by Parlett and his colleagues (Stavropoulou and Stroubouki 2014) due to differences in ontological standpoints perceived in the Logic model of Weiss.

Table 1. Evaluation models

Evaluation model	Originator	Principles
	Edward Suchman	Evaluation as a scientific process
	Scriven	Need for both formative and summative evaluation
Countenance Model	Stake	Antecedents (innate abilities), Transaction (pedagogical intervention) and outcomes (products of the previous two). Emphasises evaluators' roles
Responsive Model	Stake	Level of involvement of educator
Context-Input-Process–Product (CIPP) model	Stufflebeam	Need for both formative and summative evaluation. External decision makers
Logic model	Weiss	Evaluation as a scientific process Level of involvement of educator
Illuminative evaluation model/ anthropological model	Parlett and Hamilton	Method of analysis Transparency in biases Flexibility/Rigidity
Utilisation-focused model	Patton	External decision makers

(*continued*)

Table 1. (*continued*)

Evaluation model	Originator	Principles
The teacher as researcher model	Stenhouse	Flexibility/Rigidity External decision makers
Connoisseurship model	Eisner	External decision makers
Goal-free and Goal-based model	Scriven	Flexibility/Rigidity
Case study model	Kenworthy and Nicklin	Flexibility/Rigidity
Process evaluation	Patton	Flexibility/Rigidity
Evaluation Planning Incorporating Context (EPIC)		External decision makers Flexibility/Rigidity
Balanced Score Card	Ho et al.	External decision makers
Outcome based evaluation (OBE)		Need for both formative and summative evaluation
Kirkpatrick's Model (four-step training evaluation)	Kirkpatrick	–

Sources: (Stavropoulou and Stroubouki 2014; Gordon 2018; Chinta et al. 2016; Anh 2018)

3.2 Processes in Evaluation Models

The models above include proposals for different steps or stages for the implementation of any evaluation exercise. The number of steps in the models are not uniform and they range from 3 to 10 steps or processes. Some models have their steps categorised into phases with each phase having sub-steps. For instance, the evaluation levels in Outcome Based Evaluation (OBE) are program, effectiveness, impact and policy while the framework levels in Kirkpatrick's Model are: Reaction, learning, behaviour and result. Furthermore, some authors argued that evaluation should not just be done at the end of a programme but should be comprehensive by starting right from the moment the programme is initiated (McCuen and Chang 1995).

3.3 Evaluation Models in Engineering Education

The literature reviewed suggested that the models in Table 1 above are not often explicitly considered in the evaluations of engineering education. Some authors have claimed the popularity of one or more of these models - for example, Anh (2018) stated that Stufflebeam's CIPP Model is widely used while McCuen and Chang (1995) opined that Kirkpatrick's Model is more common, but we found no evidence of this in our study even in relation to the evaluation of engineering education at programme or institutional levels.

A diverse range of methods of evaluating engineering education were found to be used by engineering educators for different purposes, lasting different periods, and involving varying complexities. Although most of the methods were not discussed fully by the authors, they include Accreditation Board for Engineering and Technology ABET, Baseline interview, longitudinal studies and portfolios, Web-based course for course evaluation questionnaires, Course panels and instructor reflective memos, QUESTE-SI (Quality system of European Scientific and Technical Education for Sustainable Industry), Student grades and SAPA (self- and peer-assessment). Many institutions ask their students for course feedback mostly by filling out questionnaires online which is used for general administrative purposes (for example see Palomera-Arias & Liu, 2016). This mode of data generation usually does not provide the information needed for effective course evaluation (id.). Somehow, the use of ABET seems understandable when applied to programme evaluation for it was designed for the purpose of accrediting engineering education (ABET, 2016b in Anwar et al. 2018). Whereas, QUESTE-SI on the other hand, which was initially designed for quality management in engineering education but at institutional and programme level now concentrates its attention on sustainability and environmental related issues though at the same level of application (Staniškis and Katiliute 2016). To what extent any of these methods could be applied to course and topical level of engineering education remain uncertain. Other methods applied at course levels are both for evaluation and assessment. Safe to recall that assessments carry with them no value judgement, to that extent Palmer and Hall (2011) adapted SAPA for course assessment. SAPA, the authors claimed could also be used for course evaluation. McCuen and Chang (1995) argue that evaluations based only on students' academic performance without contextual considerations such as the teaching style, institutional environment, teacher-student relationship, student-student relationship, classroom process and the general societal culture and values and which exclude the pre-implementation stages do not provide reliable evidence on what decisions could be made on intervention outcomes. Although this argument is the hallmark in the design of QUSTE-SI (Staniškis and Katiliute 2016), but its application is only at the institution or programme level.

Generally, engineering education seems to benefit only from the CDIO (Conceive – Design – Implement – Operate) standards, ABET, QUESTE-SI and other, educational board models. The developers of the CDIO in their justification for the supremacy of the model over other national and international standards e.g. UNESCO etc., claimed that it is more consistent, comprehensive and detailed. However, these standards or models are only applicable to programme wide application.

3.4 Evaluation in BIM Education

The second stage of the literature review considered evaluation models and tools reported in existing cases of BfCE. Out of 53 cases of reported BIM education activity, only 1 referred to any evaluation model at all and this was Comprehensive Assessment for Team-Member Effectiveness (CATME) for peer evaluation. 28 cases referred to the use of evaluation tools by BIM educators to assess the success or otherwise of their interventions. These are shown in Table 2 and include: (student/faculty/expert) interviews, questionnaire surveys, assessment rubric, test groups, student portfolios, focus groups and reflection.

Table 2. Evaluation in BIM education

Evaluation tool	Authors (cases)
Student feedback	Multiple authors/cases, e.g. Karshenas (2009); Peterson et al. 2011)
Questionnaire survey	Multiple authors/cases, e.g. Wong et al. (2011); Suwal and Singh (2018)
Assessment Rubric	Kim (2012)
Student Interview	Mathews (2013)
Questionnaire survey/Interview	Pikas et al. (2013)
Assessment rubric/questionnaire/interview	Kim (2014)
Informal discussion with students	Wang and Leite (2014)
Interview questionnaire of students, experts and faculty/test group	Park et al. 2016)
Questionnaire survey to industry experts	Clevenger et al. (2016)
Student survey/faculty reflection	Zhang et al. (2018)
student survey and focus group	ElZomor et al. (2018)
Student survey/student portfolio	Hu (2019)

The evaluation tools were also applied at different stages of the intervention. 6 out of the 28 cases of intervention in the study carried out a pre-implementation evaluation exercise, 5 conducted evaluation during the implementation of the intervention, i.e. formative evaluation (McCuen and Chang 1995), and all referred to post-implementation evaluations, i.e. summative evaluation (Ibid.).

The implementation stages of the evaluation tools varied among the cases. Some adopted pre-evaluation and post evaluation without formative evaluation during implementation. Others implemented formative evaluation during implementation with summative evaluation but with no pre-evaluation. Only one case (Clevenger et al. 2016) included evaluation at all 3 stages of intervention implementation.

The curriculum levels at which BIM education is carried out varied ranging from programme level to topic level. Only one case of programme and one of topic level curriculum implementations were reported with the remaining twenty-six cases referring to the implementation of new courses. At topic level, BIM-related learning is carried out within a course and the learning class session is usually between one and two. Course level involve dedicating a whole subject to BIM learning (usually with a course code) and/or relating BIM to the different aspects of other topics as they are offered in a subject (for example see Suwal and Singh 2018). Course level could also be a capstone project in which learners are required to exhibit the knowledge, skills and competencies that they have acquired over a certain period on a chosen academic project. BIM education at programme level involves introducing BIM education to the different academic levels in either a single or multiple discipline within the same department.

4 Discussion of Findings

The study found that the use of evaluation models in engineering education is generally low. In addition, little evidence of the use of evaluation models in relation to BIM education interventions was found with only one of the reported cases referring to any model at all being used in evaluation. This raises the questions: are models readily applicable in engineering education or in BIM education specifically? And, if so, is there a most appropriate model for engineering concept evaluation?

There are established evaluation models with similar process steps used for evaluating engineering education at institutional and programme curriculum level with only one for BfCE at course curriculum level and none at topic curriculum level. Noticeable is the prevalence of ad hoc models which are generally different from what are used outside engineering education. Methods and tools for evaluation are also diverse and the extent of knowledge sought by any of the methods is influenced by the subjective value of the evaluator or the educator.

Understanding the application of the models is an important prerequisite to their application under any circumstance for which they are anticipated, and even more understanding is needed if they are to be adapted. Whatever the choice of evaluation model to be adopted and/or adapted, there are merits and demerits associated with each. For this, evaluators are encouraged to weigh their purpose and balance it with the model anticipated.

Pre-implementation, implementation and post-implementation are the different stages at which evaluation could be carried out and authors, such as McCuen and Chang (1995), argue that evaluation should be carried out throughout the different evaluation stages (also advocated for post implementation even further long into the future after the intervention) to ensure maximum success of the exercise.

4.1 Development of BfCE Evaluation Framework

To inform the evaluation of our proposed BfCE intervention, we have attempted to draw together the key characteristics of the various evaluation models, tools and techniques reviewed. Figure 2 arranges these into 3 pillars of principles, process and tools on which a proposed evaluation framework in BIM for construction education (BfCE) is built. The principles relate to the main ideas behind existing evaluation models and include the axiological, ontological and epistemological values held by the educator that must be identified, acknowledged and consequently addressed for a robust evaluative outcome.

We have identified several principles that necessarily inform the implementation of evaluation in an intervention. These principles may be salient or unnoticeable and consideration of them would influence the choice of implementation process steps and how they are implemented.

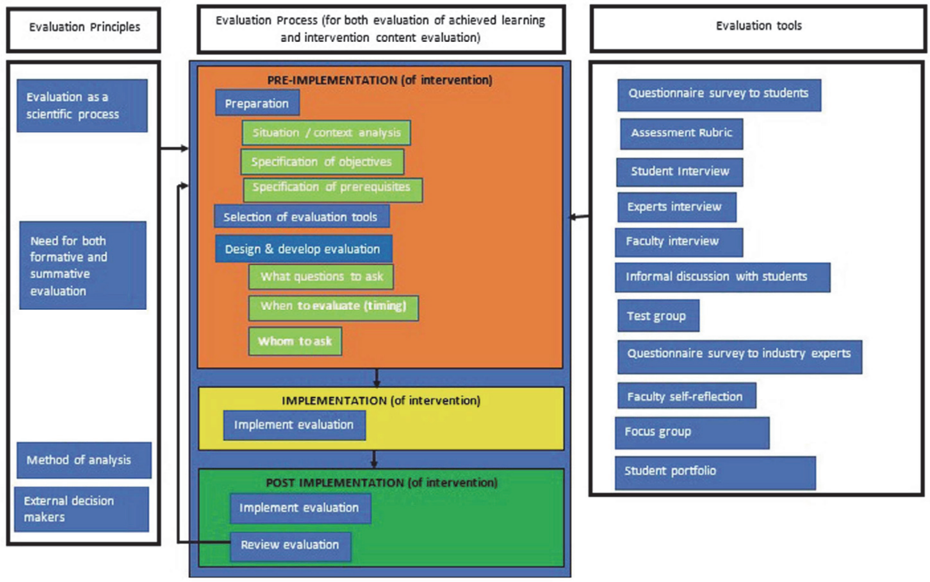

Fig. 2. Evaluation framework in engineering education

The implementation processes for evaluating BfCE (which could be for either one or a combination of content evaluation, delivery evaluation, learning environment evaluation and institutional impact evaluation/assessment) should include 3-broad stages for a rigorous and wholistic evaluation viz: pre-implementation, implementation and post-implementation. The first step of pre-implementation stage involves preparation activities such as situation and context analysis, specification of objectives and specification of prerequisites. The second step is the selection of evaluation tool(s). These tools (for example, questionnaire survey to students; assessment rubrics, etc.) could be used separately or combined in any suitable form to achieve the specified objectives. After the selection of the appropriate evaluation tool(s), the evaluation methodology can then be designed and developed in detail by asking the what, when and whom questions.

The second stage of the evaluation process is the implementation stage at which the pre-implementation decisions are carried out and implemented. If formative evaluation is required, then the educator or evaluator would constantly review the evaluation process at this stage for monitoring, control and possible improvement of the intervention environment and tool(s) for evaluation. However, the formative evaluation may be difficult to implement at topical level of intervention especially if the intervention is carried out over a single class session.

The third stage of the evaluation process is the post-implementation stage. This stage requires further implementation of the evaluation design and the review of both the second stage implementation and the third stage implementation. The post-implementation stage includes summative evaluation where the evaluation tool(s) designed and developed are administered at the end of the intervention for evaluation.

For the purposes of continuous improvement of the evaluation process, a review of the whole evaluation implementation should also be carried out to inform future evaluation cycles.

5 Conclusion

This study set out to investigate an appropriate evaluation methodology for BfCE pilot initiatives and interventions. Having reviewed and analyzed the extant literature on educational evaluation, evaluation models and approaches, in particular those related to engineering education, a framework for the evaluation of BfCE interventions has been derived to assist educators to evaluate their interventions. The proposed evaluation framework is intended to improve professionalism in the delivery of engineering education, and, specifically, improve the quality of BfCE implementations especially in universities. The benefits of utilizing a formal approach to evaluation are obvious, but further research is necessary to test its efficacy and outline in more detail the specific aspects of the methodology to make it more accessible and useful to potential users.

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Building information modelling (BIM) – enabled construction education: teaching project cash flow concepts

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ABSTRACT
This research explores the practical feasibility and effectiveness of BIM-enabled education in teaching the topic of project cash flows to construction management students. Using a participatory action research methodology, a BIM-enabled cash flow exercise was developed, carried out and refined in a construction investment course to simulate integrated practice. The results of the implementation demonstrate that BIM-enabled education can promote and infuse both BIM collaboration and professional practice experiences within an architecture, engineering, construction, and facilities management (AEC-FM) curriculum. Additionally, the teaching practice and method in this intervention demonstrate the capability to accommodate all levels of knowledge in Bloom's taxonomy which is a standard requirement for educational module design. This study recommends that BIM-enabled education be embraced and explored by faculties in AEC-FM courses to improve teaching and learning of construction management concepts.

KEYWORDS
Building information modelling (BIM); AEC-FM education; project cash flow; construction investment; construction management; engineering education; BIM exercise; problem-based learning

Introduction

Innovations and improvements in didactics arising from the digitalisation of the construction industry are being continuously witnessed in Architecture, Engineering, Construction and Facilities Management (AEC-FM) programmes. Building Information Modelling (BIM) is a central feature of this digitalisation, and it presents multiple opportunities for teaching practice improvements. BIM provides a collaborative system of construction that enables the digital representation of physical and functional properties of construction assets with which stakeholders can interact and it ensures comprehensive, organised and readily accessible project data. Much of this data is referenced directly to building objects (walls, beams, columns, windows, doors, floor slabs, pipes, etc.) which are represented in a virtual, 3D model of the building so that they can be easily viewed and understood. BIM therefore enables the simulation of real and complicated project scenarios in the classroom in a way that is both efficient for students to grasp and which promotes students' familiarity with BIM workflows and technology. In addition, numerous studies have shown that learning can be enhanced and students' motivation increased by introducing technology into didactics (Barham et al. 2011a; Wu and Kaushik 2015; LóPez-Zaldívar et al. 2017; Shanbari and Issa 2019).

This research explores the practical feasibility and effectiveness of BIM-enabled education through an action research case study focused on the topic of project cash flows as taught to construction management students. It is motivated by the potential for a new, BIM-enabled educational approach that moves away from dividing projects between specialist areas and toward integrating work and information flows for whole projects (Forgues and Becerik-Gerber 2013; Shanbari and Issa 2019) and which embraces the opportunities of BIM as a learning environment (Witt and Kähkönen 2019; Zamora-Polo et al. 2019). This offers solutions to the perceived mismatch between graduate competencies and their professional roles in industry (Forsythe et al. 2013; Lim et al. 2015), the need to integrate students' learning in the context of real projects (Alshanbari and Issa 2014) and, in doing so, to promote experiential, student-centred learning methods such as problem-based learning, etc. (Becerik-Gerber et al. 2012; Park et al. 2016; Wu and Luo 2018).

Project cash flow as a learning topic for this intervention is based on the experience of the facilitators and its relevance in professional practice as an aspect of project cost management. In learning topic selection, Ahn et al. (2013) suggest that the learning topics should comprise and reflect a selection of knowledge, skills, values, and attitudes relevant to and valued by the profession, subject disciplines, and by the wider society. Although cash flow concepts are common in construction management education, the way they are taught is predominantly by the traditional method of talk and chalk (Mills and Treagust 2003). Mills and Treagust (2003) reveal the inefficiencies of this method and the calls for change by engineering accreditation bodies. BIM-enabled education is a way of answering this call for change, but the number of documented BIM-enabled education is sparse, and thus suggests that this mode of knowledge propagation is still in its infancy. Using an industry BIM workflow ensures that the scenario on which the learning activity (project cash flow management, in this case) takes place corresponds to industry reality and that the data input to the learning activity is not contrived by the lecturer but rather exists as real project data and is drawn directly from the same sources as would be the case in industry. For the topic of project cash flows, the appropriate data input (time and cost) relies on a relatively detailed (5D) BIM

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model, and this helps to emphasize the role of BIM in organising all project data while also associating that input data with the spatial/physical aspects of the construction project which students can easily relate to. This enables closer alignment between the taught topic and the contemporary, digitalized industry workflows which are emerging in the construction industry globally. As a result, the experiences acquired and recounted here, as well as the analysis and conclusions of this effort, can benefit a large number of institutions all over the world.

This study is an initial step in developing an innovative, BIM-enabled curriculum that integrates construction management concepts in experiential learning on the basis of real construction project data, which is now, with the digitalisation of construction, increasingly possible in a classroom setting. This paper describes a BIM-enabled education intervention developed through action research, its objectives, organization, development, and instructional approaches. It provides details of the learning outcomes and contextual evaluation of this new approach and summarizes the lessons learnt. In the next section, this research is set in the context of existing BIM-enabled education initiatives reported in the extant literature. This is followed by a description of the action research methodology applied and then of the case context in which it was applied. The findings at each stage of the action research process are then presented before a discussion of their implications for educational practice and, finally, conclusions are drawn.

Literature review

Construction education

The current educational system has functioned with reasonable success for decades, however, the needs of the current generation of students are distinct, necessitating a unique strategy in order to achieve similar or even better results. Instructors around the world are aware of this and have recommended other methods of conducting university classes (Hanford 2011). Using a driving lesson example, Alshanbari and Issa (2014) give a succinct picture of the relationship between the learner and the industry. They opine that it is difficult for an intending driver of a car to develop the required driving skills without getting behind the wheel and driving. The practical part is necessary to complement lectures and tests which in themselves are not enough to produce a good driver. Therefore, they suggested that higher education should operate in a similar manner by encouraging students to engage in discussion and hands-on experimentation (Alshanbari and Issa 2014). By this, they canvass for a shift from a purely behaviourist based educational approach to a more constructivist based educational approach.

According to Barfield et al. (1995) learners can be classified as auditory, visual, tactile, or kinesthetic based on their learning preferences. Auditory, visual, and kinesthetic learners learn through hearing, seeing, and doing respectively (Roark 1998). Teaching AEC-FM classes while considering students' various learning styles is a difficult task (Barham et al. 2011b). Barham et al. observe that traditional lecturing is prevalent in delivering AEC-FM courses with occasional visits to construction sites sometimes used to complement the lecturing approach. This teaching style provides an auditory and visual learning environment. However, site visits are not always possible to include in the course schedule due to factors such as the lack of construction sites that match the class's demands, class scheduling conflicts, and safety concerns (Haque 2007). The typical lecture teaching method can often fall short of serving as an effective instrument for communicating knowledge to learners (Barham et al. 2011b). AEC-FM students are now unable to develop the necessary abilities to tackle real-world problems due to the lack of a favourable learning environment that stimulates aural, visual, and tactile senses. To improve students' learning capacities, a user-friendly interactive information repository with a conducive learning environment is required.

Innovations in construction education

Since the launch of "Cyclone" in 1976, using computers to simulate building jobs has been the subject of numerous research articles (AbouRizk and Shi 1994). Researchers now have more resources to run more accurate simulations because of the advances in technology. Modelling a full construction project, on the other hand, is far more difficult than simulating one or two components of it separately. Construction projects include an excessive number of activities and unpredictable variables, such as weather conditions, that can radically alter the outcome. Furthermore, one task can influence and be influenced by the others. The intricacy of construction projects is one of the key reasons why proper simulation is so challenging. As a result, numerous researchers have turned their attention to simpler simulation for instructional purposes (Nikolic et al. 2011).

BIM makes it easier to create knowledge libraries and learning settings that are favorable to learning. For data management, BIM is a wonderful tool. Through the 3D spatial model of the construction object, it enables easy and quick access to information contained in a single centralized database or in multiple databases kept at separate places. Auditory, visual, and kinesthetic learning environments occur as a result of BIM qualities such as simple access to information, visualization, and simulation capabilities. Access to the repository at any time and in real time via a 3D model creates a learning environment that is free of time and space constraints, allowing students to learn at their own speed (Barham et al. 2011b).

BIM as an innovative concept in construction education – The evolution of BIM education

BIM emerged from origins in "Building Description System" through several incarnations (such as Building Product Model, Product Information Models, Virtual Display Model, etc.) between 1975 and 1992 (Eastman et al. 2011). Through the introduction of policies, standardization, and improved accessibility in the early and mid-2000s the construction industry has witnessed a surge in BIM adoption and this has generated the need for new skills and competency requirements for graduates and industry professionals (Hooper 2015; Govender et al. 2019). Construction education has struggled to keep pace with industry BIM innovations and this has created a gap between graduate competencies and their expected professional roles in the industry (Barison and Santos 2018; Bozoglu, 2016).

The evolution of BIM education has been conceptualized into 3-progressive stages (Underwood et al. 2013):

1. BIM-aware, where graduates are made aware of the uses and exigencies of BIM relating to its implications for both digital and cultural transformation of the construction industry.
2. BIM-focused, involves graduates' abilities to use and manipulate BIM software in performing specific tasks such as modelling, clash detection, simulation etc.

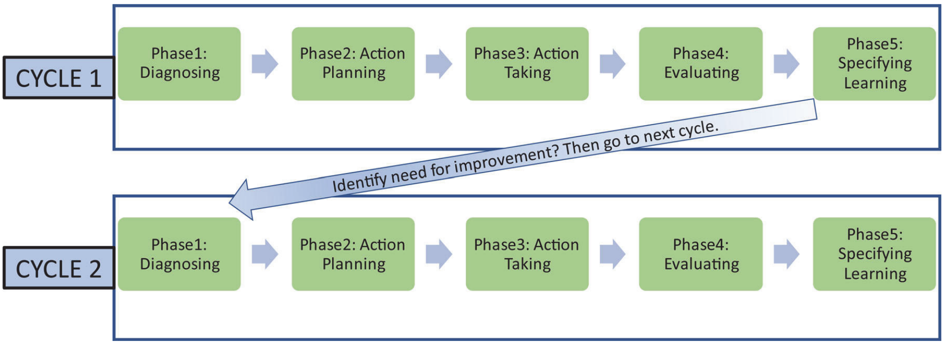

Figure 1. The action research process applied.

3. BIM-enabled, where education takes place in a BIM-mediated virtual environment and BIM acts as a platform for learning (Underwood et al. 2013).

Evidence suggests that both BIM-aware and BIM-focused education have been generally recognized and initiatives to develop curricula to incorporate BIM have become widespread. For instance, Peterson et al. (2011) reported how they introduced BIM to students (BIM-aware) and subsequently used it to demonstrate project management techniques (e.g., line of balance), integrated design and design optimisation (BIM-focused). Several studies over the past decade and a half (including Guidera, 2007; Dupuis et al., 2008; Rassati et al., 2010; Yan et al., 2011; Becerik-Gerber et al. 2012; Irizarry et al., 2012; Mathews, 2013; Nawari et al., 2014; Charlesraj et al. 2015; Andrea Gutierrez-Bucheli et al. 2016; Zhang et al. 2018) have all reported similar approaches at different scales and we may consider BIM-aware and BIM-focused education to be firmly established in construction education.

Some examples of BIM-enabled education also exist. Wei and Wang (2018) reported BIM-enhanced safety training within a BIM-enabled environment for occupational awareness improvement. Hu (2019) transformed a traditional Building Materials and Construction Methods course using a BIM-enabled pedagogical approach and teaching platform to help students understand fundamental concepts. Witt and Kähkönen (2019) asserted that by enabling the use of real construction project data and simulating more realistic, multidisciplinary workflows in the educational environment, BIM-enabled education offers opportunities to enhance construction education didactics to better align graduate's competences with emerging and future needs, particularly those arising from the digitalization of the construction industry. However, in contrast to BIM-focused learning, the number of documented cases of BIM-enabled education is relatively few, suggesting that this stage of BIM education is still emerging.

This study therefore investigates the potential for applying BIM-enabled education, specifically, in the construction management curriculum in higher education institutions and to the topic of project cash flows.

Methodology

An action research design was selected as this offers a systematic procedure to address teaching improvements in their educational setting (Creswell 2012). Within BIM education, action research approaches have been applied effectively in contexts where there is a need to concurrently assist in implementation while interacting with staff and students to determine what works, what doesn't and to trial improvements (e.g., Williams et al. 2004; Puolitaival and Forsythe 2016). In this research, the five-phase process recommended by Susman and Evered (2016) was followed as listed below and represented in Figure 1:

1. Diagnosing – identifying or defining the problem under study;
2. Action planning – selecting and developing a research strategy to implement the intervention;
3. Action taking – identifying potential solutions to the problem and selecting and implementing the most appropriate of them.
4. Evaluating – analysing and assessing the results of the actions taken;
5. Specifying learning – recognising and documenting the outcomes of the research in order to understand what problems are solved, which objectives are met, and/or what theories are supported or require revision.

This study comprised two iteration cycles of the five-phase process and this enabled the educational intervention to be further refined. The first cycle was conducted in the Autumn semester of 2019. After reflection and identifying the need for further improvement, a second cycle was carried out with a different group of students but within the same course in the Autumn semester of 2020.

Educational intervention (case) description

The education intervention is a BIM-enabled Cash Flow Exercise which was implemented in 2 cycles of an action research process at Tallinn University of Technology within a Construction Investments course. The Construction Investments course objectives are:

1. to introduce students to investments, investment appraisal methods, and the bases for making investment decisions in the built environment;
2. to explore the current global, regional, and national contexts in which construction investments are being made;
3. to make students aware of the policies, programmes, and incentives/disincentives which influence investment in the built environment;

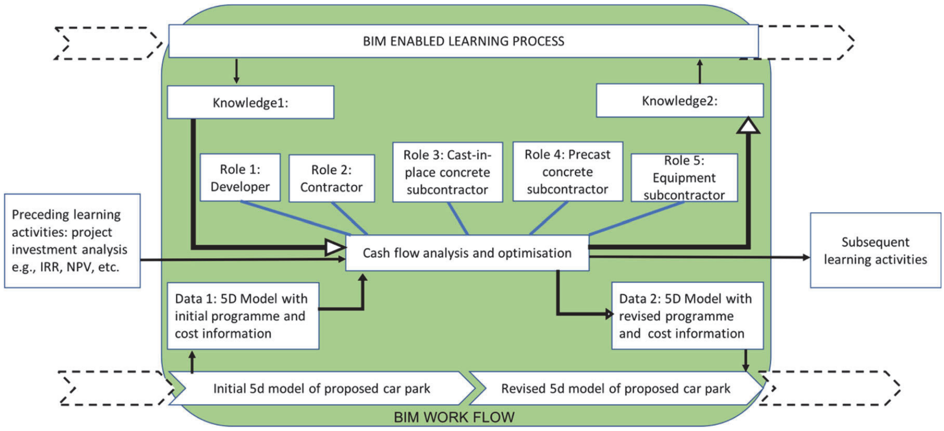

Figure 2. BIM-enabled learning environment (BLE) framework for Cash flow analysis and optimisation adapted from Witt and Kähkönen (2019).

Table 1. Cycles attributes.

Cycle attribute	Cycle 1	Cycle 2
Semester	Autumn 2019	Autumn 2020
Number of groups	5	5
Number of participants in groups	G1 = 3, G2 = 3, G3 = 3, G4 = 2, G5 = 2	G1 = 6, G2 = 6, G3 = 6, G4 = 6, G5 = 6
Time allocated for the exercise	1 h and 30-min in one class session	3 h and 40 min in 3-class sessions: 2 of 1 h & 30 min each and an additional 40 min from a 3rd class session
Data collection	Post-implementation questionnaire, observation, and facilitators' self-reflection.	Pre- and post-implementation questionnaire, observation, and facilitators' self-reflection

4. to give students an appreciation of the nature and motivations of investors and types of construction-related investment projects;
5. to raise students' awareness of the social and environmental aspects of built environment investments; and,
6. to familiarise students with project finance concepts and recent developments.

Students of this course are typically either fourth year students following an integrated, 5-year Master of Science in Civil Engineering degree programme or taking a 2-year master's degree having completed their studies to bachelor's degree level previously, in a separate programme. Their industry and BIM experience varies from none at all to a high level of professional practice. In addition, as the course is one of few in the Structural Engineering and Construction Management study programme that is delivered in English at this university, it attracts international exchange students who may be from other disciplines.

The BIM-enabled Cash Flow Exercise is a learning experience in which students develop, analyse and optimise company cash flows in the context of a construction project scenario. A "5 D" (3 spatial dimensions + time + cost) BIM model serves as the learning object around which the learning activities take place. The exercise is arranged as group work where teams of participants assume different company roles (Developer, Main Contractor, Subcontractors) akin to those typical in the construction industry. The specific aim of the exercise is to collaboratively negotiate a global cash flow solution which enables all the companies to meet their (cash flow) objectives. This is achieved in 4 steps:

1. development of the project cash flows for each of the companies involved in construction;
2. analysing the developed cash flows and whether they meet specified (cash flow) objectives for each company (in terms of adequacy of return/profitability, credit limits, etc.);
3. negotiating a global solution which enables all the companies to meet their objectives and requirements; and, if this solution requires any changes to the (time scheduling) information in the 5D BIM model, then;
4. specifying the changes necessary to the BIM (see Figure 2 for context).

Table 1 summarises the attributes of both cycles of the intervention. The number of registered students for the courses in both cases exceeded the number of student participants in the exercise as exercise participation was not a direct pre-requisite for passing the course. In cycle 1, data collection was limited to a post-implementation questionnaire for students as well as recording the observations and reflections of staff. This was further developed in cycle 2 to include a pre-implementation questionnaire for students as well as development of the post-implementation questionnaire.

Cycle 1

Cycle 1 of the action research began in late 2018 with the initial conception of the BIM-enabled Cash Flow Exercise which was subsequently implemented in the Autumn semester of 2019.

Diagnosing

Earlier research, including Witt and Kähkönen (2019), Olowa et al. (2021), had established the importance and potential

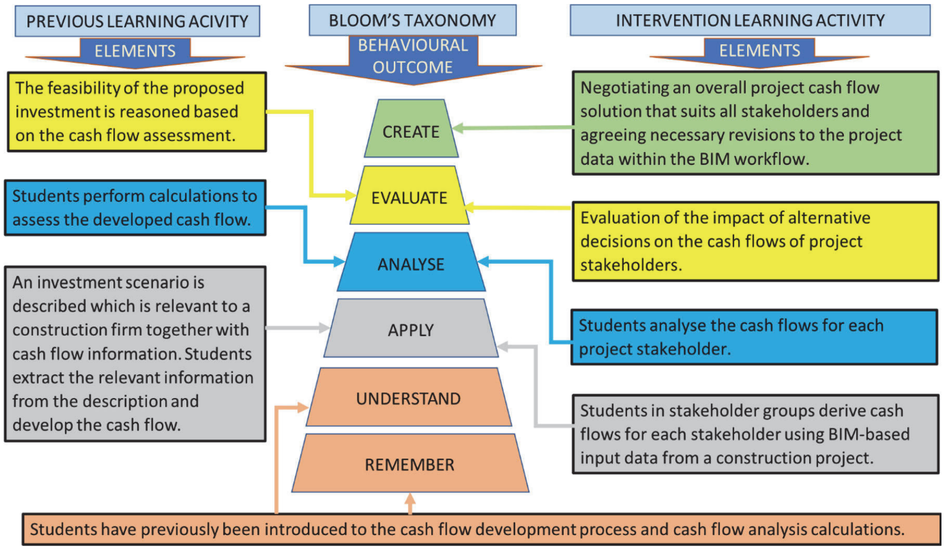

Figure 3. Learning activities and outcomes for the BIM-enabled intervention.

benefits of BIM-enabled education and the cash flow topic appeared to offer a suitable and conveniently bounded opportunity to trial a BIM-enabled education intervention at the topical level. The previous method of cash flow teaching, as analysed through document analysis and lecturer observations/reflections, saw the application of cash flow calculations to a simple investment example which was relevant to a construction firm. In contrast, a BIM-enabled approach to cash flow teaching allowed the application of cash flow concepts to a scenario which was fully embedded within a construction project.

Action planning

Action planning involved the definition of learning outcomes, teaching and learning activities, feedback and assessment strategies for the intervention. The teaching and learning activities were premised on the principles of BIM-enabled learning as recommended by Underwood et al. (2013) where the focus is neither on informing students on the existence and the changes that BIM is bringing to the construction industry nor on how to use BIM as software applications but rather in deploying and leveraging BIM in classrooms to educate students of AEC-FM disciplines on construction management and engineering concepts to improve efficiency in both teaching and learning, increase students' motivation and encourage lifelong learning. The learning activities and anticipated behavioural outcomes were defined with reference to Bloom's taxonomy (Bloom 1956) and are shown in Figure 3.

Action taking

The intervention was implemented in the Autumn semester of 2019. The learning activity focused on collaborative learning and students worked in groups representing 5 different construction industry stakeholders, namely: developer, contractor, cast-in-place subcontractor, precast subcontractor and equipment subcontractor. A 5-D BIM model of a multistorey car park (Figure 4) was used as the *learning object* (Torrente et al. 2009). It was important for the model to have both time and cost data so that students could extract, process and then feed-back the processed data into the model. With reference to Figure 2 (above) *Knowledge 1* and *Knowledge 2* represent what the group members knew before and after the exercise, respectively. *Data 1* represents all the data in the BIM model and in the additional instructional materials provided to students to enable them to undertake the exercise. Once their tasks were successfully complete and a global solution to the project cash flow had been found that satisfied all stakeholders' cash flow objectives, the resulting *Data* 2 could then be fed back into the BIM model. With that, the learning activity in the form of one iteration of the BIM workflow was completed.

Evaluating

The evaluation of this cycle of the study was based on a short questionnaire survey, facilitator's reflection notes and outcome of the exercise. The questionnaire was an online "google form" with 6 questions requiring short text responses and the link was sent to all students who had participated in the exercise. From the 17 student participants, 6 questionnaires were returned. For the purpose of comparative analysis, the responses to the 5 closed questions have been quantified using the following subjective categories: 5 = Absolute Yes, 4 = Qualified Yes, 3 = Neutral, 2 = Qualified No and 1 = Absolute No. The summary of results is shown in Table 2.

The 6th question was an open question that asked participants how the exercise could be improved, and the comments received related mainly to increasing the time allocated for the exercise. For example, "There should be a longer class if it's possible", "Reserve enough time so that everyone could have time to understand the whole process".

Specifying learning

This section reports on some of the important lessons learnt in the first iteration of the intervention. Firstly, it was found that the exercise instructions were clearly understood by the

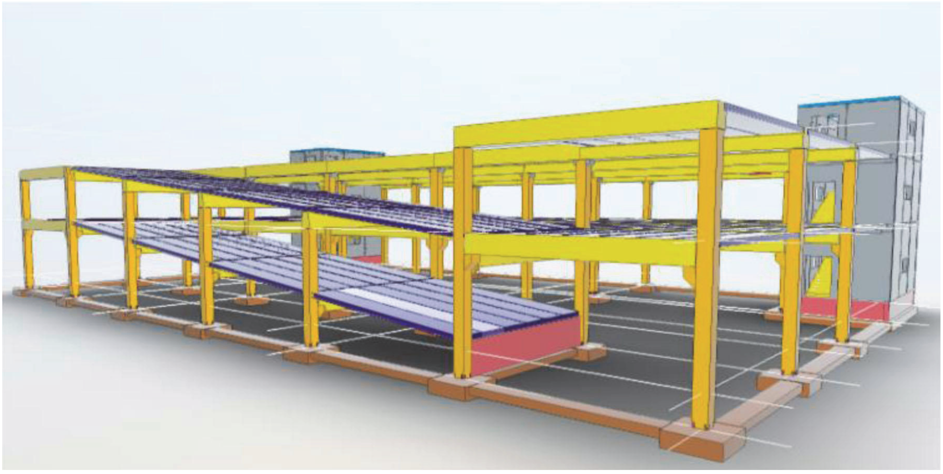

Figure 4. 5-D BIM model of a multistorey car park.

Table 2. Implementation survey result of students' satisfaction in Cycle 1 ($N = 6$).

Question	Mean	Std. deviation
Was the purpose of the exercise clear?	4.50	0.548
Did you find the exercise interesting?	4.33	1.211
Was it helpful to link the exercise to 'real' project data?	4.33	0.816
Was it helpful to link the exercise to the BIM workflow?	3.50	1.378
Did the exercise complement previous course materials or lessons?	4.33	0.816

participants although one participant did suggest that the exercise could have been introduced in an earlier class to allow for greater familiarity with the instructions before the actual exercise was carried out. Secondly, that the learning approach to the exercise was preferred by the participants compared to traditional classroom teaching. The participants further appreciated the linking of the exercise to the (near-to-real-life) 5-D BIM project model. Although the exercise demonstrated the BIM workflows related to project cash flow calculations, analysis, and negotiations, the correspondence of the exercise tasks with industry BIM work flows was not obvious to some participants.

The most important lesson drawn from Cycle 1 related to lesson plan improvement with respect to time allocation. The time allocated for the exercise was inadequate and this resulted in participants being unable to fully complete it. Only a few groups were able to complete their information input into the shared spreadsheet. This corresponds to completing step 2 of the 4-step exercise process as described above. This input into the shared spreadsheet by all groups was prerequisite to negotiating a global cash flow solution (step 3) and then updating the BIM model information (step 4). Thus, in its first cycle, the exercise ended with an almost complete shared spreadsheet. The lecturer did, however, demonstrate in the first minutes of the subsequent class how all stakeholders' cash flows could meet their requirements if the works were rescheduled and that this rescheduling would then need to be reflected in a revised 5 D BIM model.

Cycle 2

Diagnosing

The lessons learnt and challenges encountered in the first iteration provided useful insights into conceptualising, designing, and implementing topical level BIM-enabled education and they informed the next phase of action planning.

Action planning

The proposed learning experience and standard within the existing contextual factors were maintained with a few adjustments. Notable refinements were to the time allocated to the learning activities and to the data collection and evaluation arrangements.

Following from the experience of the first iteration, the overall activity time for the actual intervention was increased from 1-h and 30-min in a single class session to 3-h in 2-class sessions of 1-h and 30-min each. Having 2 class sessions greatly improved the likelihood of exercise completion and also introduced a 1-week time gap mid-exercise which allowed additional catching up time if the target half-way point had not been achieved within the first class. In addition, a desktop study was conducted to explore how best to comprehensively evaluate BIM-enabled education at a topical level.

The group size was left fluid for two major reasons: firstly, students were offered the option of virtual participation in this cycle due to COVID-19 which prevented some students from being physically present in the classroom. Secondly, student groups had been formed at the beginning of the semester and it was convenient to maintain these groups for the BIM-enabled Cash Flow Exercise, particularly as the groups contained physically present, virtually present and non-participating students and these could change at short notice. For these reasons, it was difficult for the facilitators to accurately determine the number of active student participants for each stakeholder group and led to larger group sizes than would be considered optimal.

Action taking

Cycle 2 was carried out in the Autumn of 2020 with a maximum participation of 30 students in 5 groups of 6 members each. As previously, in the lead up to the exercise, students were introduced to topics (e.g., cash flow development principles and investment appraisal methods such as net present value (NPV), internal rate of return (IRR), etc.) which were basic to them carrying out the cash flow exercise. Additional information and understanding required to carry out the exercise (stakeholders' financial status and project cash flow objectives, relevant conditions of contract relating to payment terms, retention and defects liability periods, etc.) were explicated by the facilitators at the start of the exercise.

Evaluating

The feedback and assessment strategies used followed the evaluation framework recommended in an earlier study (Olowa et al. 2021) for evaluating BIM for Construction Education (BfCE) interventions. The evaluation of this iteration was approached more methodically and systematically than that adopted for Cycle 1 and followed the processes of: (i) preparation, (ii) selection of evaluation tools, (iii) design and develop evaluation, (iv) implement evaluation and (v) review implementation (under both pre- and post-implementation). The strategy of designing and hosting the questionnaire survey as a Google form was maintained from Cycle 1, however, for Cycle 2, a pre-implementation questionnaire survey was included. While responding to the questionnaires was still not compulsory for participants, it was strongly encouraged and the number of returned questionnaires: 17 and 18 for pre- and post-implementation, respectively, represented an increase in response rate compared to Cycle 1. The lessons learnt in this cycle are based on the analysis of the responses to the questionnaires as shown in Table 3, in conjunction with class observations and facilitator's reflections in the *specifying learning* section. (The same numerical scale of responses applies as per the responses to Cycle 1 questionnaire: 5 = Absolute Yes, 4 = Qualified Yes, 3 = Neutral, 2 = Qualified No and 1 = Absolute No.)

Specifying learning

Important learning to be specified from Cycle 2 includes that, although this intervention was not designed to directly teach students about BIM models, it was still considered necessary to find out if the students had any previous knowledge of BIM. This questioning revealed that approximately equal numbers of participating students had prior BIM knowledge as didn't have any prior BIM knowledge. Notwithstanding the discipline of most of the student participants being civil engineering, this was not a very surprising result because almost half the students were Erasmus exchange students and many of them came from different disciplines but took the course because it was in English. By introducing some control questions in both the pre- and post-implementation questionnaires, the exercise also seemed to have shifted the students' understanding of cash flow and how cash-flow calculations relate to construction projects in a positive direction. The same observation in knowledge shift was made concerning the relationship between cash flow, BIM workflow and project cash flow optimisation. The exercise was perceived to be understood and considered as interesting by the students. The impact of the current COVID-19 pandemic was that the possibility of virtual participation was taken by some students whereas, in the first iteration, all students participated physically.

Table 3. Implementation survey results in Cycle 2.

	Pre-implementation		Post-implementation	
Questions	Mean	Std. deviation	Mean	Std. deviation
Have you been taught about Building Information Modelling (BIM) in any previous courses?	2.83	2.007	NA	NA
If yes, how would you rate your current understanding of BIM?	1.64	1.391	NA	NA
Do you enjoy working in groups/teams?	4.56	0.856	4.59	1.004
Do you find it useful for your own understanding to discuss problems/calculations/solutions with your peers?	4.56	1.149	4.82	0.728
Do you understand how cash flow and cash flow calculations relate to construction projects?	2.94	1.097	3.92	0.493
Do you understand how cash flow relates to a BIM workflow?	1.69	0.910	3.33	0.924
Do you understand how different companies involved in a construction project can collaborate in order to optimize the project cash flow?	2.28	1.239	4.14	0.660
How important are cash flows to companies involved in construction projects?	NA	NA	4.56	0.482
Would you be interested if a similar BIM workflow is used to explain other subjects (concepts) apart from cash flow?	NA	NA	4.06	0.906
Was the purpose of the exercise clear?	NA	NA	4.28	1.074
Did you find the exercise interesting?	NA	NA	4.83	0.707
Did the exercise complement previous course materials or lessons?	NA	NA	4.94	0.243
Did the exercise improve your overall knowledge of cash flow?	NA	NA	4.56	0.856
Was it helpful to link the exercise to 'real' project data?	NA	NA	5.00	0.000

*NA = Not applicable.

This demonstrates that such an exercise could also be carried out (entirely) virtually, if necessary.

Results

Evaluation of the intervention was based on the participants' feedback from questionnaire surveys in conjunction with the facilitators' observations and reflections. These indicate that the intervention accomplished its intended learning objectives and that the intervention itself and instructional strategies employed were favourably assessed by participants. Specifically, as shown in Tables 2 and 3, students' understanding was seen to improve as a result of the exercise.

Cycle 1 outcomes

This cycle was more or less to establish a proof of concept and, as such, little emphasis was placed on the evaluation of the exercise as a whole. Nevertheless, the facilitators asked the participants to express their opinions on the exercise's clarity, interest generation, relation with reality, association with BIM workflow, and reinforcement of previous knowledge.

Was the purpose of the exercise clear?

The participants' response to the above question gave a mean score of 4.50 when measured on a 5-point Likert scale using 5 = Absolute Yes, 4 = Qualified Yes, 3 = Neutral, 2 = Qualified No and 1 = Absolute No. This indicates that all the participants' agreed that the individual group's tasks, purpose and objectives in arriving at a globally negotiated and agreed project cash flow in the exercise were clear and understood.

Did you find the exercise interesting?

The participants' average response to this question was 4.33. This means that most students agreed that the exercise was engaging.

Was it helpful to link the exercise to 'real' project data?

The ability to access and work with real project data is pivotal to this study and the majority of the participants, with an average score of 4.33, agreed that working through the exercise based on real project data was helpful.

Was it helpful to link the exercise to the BIM workflow?

This response had a lower mean score of 3.50 compared to the rest of the questions asked from the participants but still received an overall positive (yes) score. This may reflect the large number of participants who were not familiar with the BIM workflow and suggests a need for them to be educated in some BIM skills before the exercise.

Did the exercise complement previous course materials or lessons?

The researchers were curious to know if the exercise was helpful in reinforcing and integrating previously learned concepts - this being one of the goals of the intervention. The responses received show that majority of the participants, with mean score of 4.33, agreed that the exercise complemented previous course materials or lessons.

Cycle 2 outcomes

Do you understand how cash flow and cash flow calculations relate to construction projects?

Average rating before: 2.94; after: 3.92; statistically significant at p = 0.00. Based on the subjective categories earlier assigned i.e., 5 = Absolute Yes, 4 = Qualified Yes, 3 = Neutral, 2 = Qualified No and 1 = Absolute No; this infers that majority of the students were more or less *neutral* when first asked the question "*Do you understand how cash flow and cash flow calculations relate to construction projects?*" Whereas their response to the same question at the end of the exercise tended toward "*Qualified Yes*" which cannot be attributed to random chance after conducting statistical significance test with a p value of 0.00.

Do you understand how cash flow relates to a BIM workflow?

Average rating before: 1.69; after: 3.33; statistically significant at $p = 0.00$. Following similar classification of the responses into the five categories as in the previous question, the pre-implementation perception of the respondents tended toward "*Qualified No*" when asked the question "*Do you understand how cash flow relates to a BIM workflow?*" However, it tended toward "*Qualified Yes*" at post implementation with the difference in result not being due to random chance as confirmed by the statistical significance testing.

Do you understand how different companies involved in a construction project can collaborate in order to optimize the project cash flow?

When asked the question: "*Do you understand how different companies involved in a construction project can collaborate in order to optimize the project cash flow?*" Generally, the participants' responses were toward a "Qualified *No*" before the intervention and toward an "A*bsolute Yes*" after the intervention. Statistical test of significance showed that the observed change in knowledge was not due to random chance but rather because of the intervention.

It is also notable that the participant evaluations show an improvement from Cycle 1 to Cycle 2 (when Tables 2 and 3 values are compared) in terms of:

- students finding the exercise interesting (average rating Cycle 1: 4.33; Cycle 2: 4.83; not statistically significant, $p = 0.19$).
- the helpfulness of linking the exercise to 'real' project data (average rating Cycle 1: 4.33; Cycle 2: 5.00; statistically significant at $p = 0.06$).
- the exercise complementing previous course materials or lessons (average rating Cycle 1: 4.33; Cycle 2: 4.94; statistically significant at $p = 0.05$).

Though one indicator did appear to drop slightly from Cycle 1 to Cycle 2:

- clarity of exercise purpose (average rating Cycle 1: 4.50; Cycle 2: 4.28; not statistically significant, $p = 0.26$).

However, it should be taken into consideration that, for both cycles, participants rated all these indicators highly and, from the facilitators' reflections, Cycle 2 was definitely an improvement on Cycle 1 but there remains room for further improvement. Opportunities for improvement may be categorised into:

- Time considerations;
- Stakeholder group sizes and comparative workload issues;
- BIM model quality improvements;
- Learning environment.

Time allocation for the first iteration (1 ×90-min class) was clearly insufficient and this led to the exercise not being completed. The second iteration, in 2 ×90-min classes with a week's break between them, was a considerable improvement and allowed groups space to reflect and to catch up if they were behind after the first 90-min class but time was still insufficient and a further 40 min had to be added in order to achieve completion.

Discussion

BIM-enabled learning activities involve understanding project contextual characteristics through the BIM model and other associated project information (contractual arrangements, etc.) which are all incorporated into the activity (as inputs, boundary conditions, etc.) as these relate to the core of learning (Senaratne and Pasqual 2011). Students require time to explore and absorb this information and, particularly for pilot interventions at the topical level, such as the BIM-enabled Cash Flow Exercise, the relative amount of time needed for this is considerable. However, where numerous learning activities covering several topics can utilise the same project contextual information, the time needed will diminish proportionately and be relatively minor for course-level interventions and almost negligible if the approach were adopted for whole programmes. This later strategy is prevalent in BIM education as observed in the study of over 304 BIM education cases by Barison and Santos (2018) with the aim of providing students with clarity on conceptual issues through BIM visualisation thereby creating the advantage of not having to re-create BIM models for every curriculum in addition to fostering a valuable learning environment (Macdonald 2012; Lee and Hollar 2013).

A second set of time-related problems arose as a consequence of the stakeholder groupings and the difficulty in achieving a balanced workload. The concept of the grouping was intended to serve several pedagogical purposes. Firstly, to simulate the industry workflow by aligning students to specific industry roles and that working in groups would promote collaboration and active learning thus adding value to the exercise. Secondly, and in alignment with the observation by Hu (2019), instead of a step-by-step, piecemeal method that is characteristic of traditional learning styles, the new pedagogical strategy increased students' drive by presenting an all-inclusive and sophisticated view of the topic. Because of the steep learning curve and the availability of new technologies, the new generation of students are able to seek aid in a variety of ways on their own. This not only boosted learning confidence but also motivation (Hu 2019). The value of group working was largely confirmed by the students themselves in their positive responses to questioning about their group work (refer to Table 3). However, the group arrangements also led to time problems as some groups (the Developer and Main Contractor) had more complex calculations to perform than others (Subcontractors), some groups experienced calculation problems which took time to resolve and the mutual dependence for each other's calculation outputs ultimately meant that some groups had to wait for others before they could finalize their calculations. This situation had been anticipated by facilitators in the preparation of both cycles and, to some extent, it was mitigated by selecting student groups perceived to be stronger to the more demanding roles and also providing more support to these groups during the exercise. However, more can and should be done to bring about workload balance between groups. For example, one alternative would be to have multiple projects in which each group undertakes a different stakeholder role thus enabling balance and a more even learning experience.

In addition, group sizes affected their performance, and, from the first iteration, it was understood by facilitators that the number of group members should ideally be limited to 2 or 3 where 3 is the optimal group size and 2 is preferable to 4. Establishing the optimal group size has always been a critical factor for consideration by project-based learning researchers. Davis and Miller (1996) recommended a group size of five, Henke (1985) group sizes of 3–5, while Barab et al. (2000) and Peterson and Myer (1995) report problems with group sizes of three and five. This suggests that group sizes of 4 or even number sizes are preferable (Helle et al. 2006). However, similar to the group size reported by Becerik-Gerber et al. (2012) and in contrast to the understanding gained from Cycle 1, there were up to 6 members in each group for the second iteration though the actual number of active participants in each group throughout the exercise was not possible to determine given the blended (face-to-face and virtual) nature of the groups under COVID-19 restrictions. The possibility of having two sets of 5 groups with a maximum of 3 members in each group could have been preferable, following the recommendations of Henke (1985), but such a strategy would have increased the risk of having a stakeholder group with 1 or no active members and that would have caused considerable disruption.

The 5-D BIM model was designed using Tekla Structures but, for the purpose of the exercise, only a free viewing tool was required and Tekla BIM sight (now Trimble Connect for Desktop) was used. Since the inauguration and subsequent development of Industry Foundation Classes (IFC) by the buildingSMART (former International Alliance for Interoperability — IAI) between 1995 and 2000 (Barison and Santos 2018), it should be noted that the .ifc file could also be opened with any other BIM software but this gave rise to interoperability issues in that data relating to cost and time were missing when the ifc file was opened in non-Tekla applications like Autodesk Revit and Navisworks Manage. This experience accentuates the argument of Zhang et al. (2013) that IFC is a complex and redundant data-modelling framework that requires precise implementation guidelines. The data from the BIM model needed to be 'cleaned up' after extraction from the industry foundation class (ifc) file format into the comma separated values (csv) file formats so that student participants could directly use it in spreadsheet applications with minimal (formatting and editing) effort especially since the intervention was time constrained. This underlines the need for high quality (error free, sufficiently and correctly detailed) BIM models in open, compatible formats that are fully readable with multiple software applications in order to support BIM-enabled learning activities.

Virtual instruction and participation were fundamental to this intervention, particularly in Cycle 2, and from the societal point of view, this is a trend that may well persist and should be further developed and promoted with time. Several authors have argued that the ability to use technologically supported simulation, and discussion forums are significant characteristics of e-learning environments (Fowler 2015; McGrath et al. 2018; Cai et al. 2019). Barari et al. (2020) re-affirm this position by stating that virtual teaching platforms with adequate facilities contribute to students' collaborative teaching and peer learning. The present exercise employed multiple platforms in its delivery – for BIM model viewing and data extraction (Tekla BIM sight), for collaborative spreadsheet development (One Drive) and, in Cycle 2, virtual group work (MS Teams). This brought with it challenges in terms of accessibility and interoperability. Although virtual instructions have been reported by some studies to be beset with student frustration especially in BIM-focused learning (Becerik-Gerber et al. 2012), this was not the case in this study. As such, the authors opine that, for BIM-enabled learning to function efficiently, there is a need for a purpose-built, integrated BIM-enabled learning environment where all necessary capabilities are available in one place. Such a platform should enable model viewing, editing, storage, retrieval, etc. together with learning activity-specific operations (for the cash flow exercise, these primarily involve collaborative spreadsheet calculation capabilities).

Conclusion

Building Information Modeling (BIM) has significantly changed architectural, engineering, construction and facilities management (AEC-FM) practices and how the AEC-FM sector functions. Whereas, in industry practice, BIM has already become commonplace, how this important development might be applied effectively in higher education is still being determined.

This study sets out to explore how BIM can be leveraged to incorporate project-based experiential learning in construction management education and to evaluate students' and facilitators' perceptions of a BIM-enabled pedagogical intervention. A two-cycle, participatory action research study was carried out to pilot and refine an intervention at the topical level: the BIM-enabled Cash Flow Exercise. The responses received from student participant surveys and facilitators' reflections at the end of each cycle confirm the value of this type of BfCE approach. The topical level of the intervention has the advantage that there is no need for a drastic change in the existing curriculum, but the time needed for introducing the project contextual information is relatively high. Both the BIM-enabled learning activity design and the descriptive evaluation methodology used in this study will serve as a guide for researchers and future curriculum development of BfCE within AEC-FM education.

There are limitations relating to the generalizability of these results. The evaluation and conclusion on the success of this intervention are both premised on a short-term, cross-sectional study and a longitudinal study is required for more objective evaluation. Other contextual factors such as teacher–student and student–student relationships were not considered in this study. The possibility of introducing a control group exists and this was considered as an alternative to the use of a pre-implementation survey questionnaire which may have sensitised students to the purpose of the intervention and thus affected their (post-implementation) responses.

With the existing time constraints, the exercise scenario is very simple and the use of specific, real project data is quite limited. While making it easier to apply the recommended cash flow management process steps to it, this does reduce its correspondence to industry reality and thus it leaves a gap between the exercise and practical application in real industry projects.

To support this and other, similar BIM-enabled learning activities, particularly in distance learning and blended learning contexts, there is an emerging need for the specification and development of a BIM-enabled learning environment or platform in which the functionalities required to carry out BIM-enabled learning activities (e.g., BIM model viewing, data extraction, editing, etc. as well as activity-specific functions – collaborative spreadsheet applications for cash flow calculations) would be available. Future research, therefore, will focus on identifying these functional requirements and their corresponding technical requirements in order to derive a specification for an open, accessible and compatible BIM-enabled learning environment.

Disclosure statement

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Defining a BIM-Enabled Learning Environment—An Adaptive Structuration Theory Perspective

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Abstract: Digitalization of the AEC-FM industry has resulted in the reassessment of knowledge, knowledge management, teaching and learning, workflows and networks, roles, and relevance. Consequently, new approaches to teaching and learning to meet the demands of new jobs and abilities, new channels of communication, and a new awareness are required. Building Information Modelling (BIM) offers opportunities to address some of the current challenges through BIM-enabled education and training. This research defines the requisite characteristics of a BIM-enabled Learning Environment (BLE)—a web-based platform that facilitates BIM-enabled education and training—in order to develop a prototype version of the BLE. Using a mixed-methods research design and an Adaptive Structuration Theory (AST) perspective for interpreting the findings, 33 features and 5 distinct intentions behind those features were identified. These findings are valuable in taking forward the development of the BLE as they suggest a BLE requires the integration of functions from three existing types of information technology application (virtual learning environments, virtual collaboration platforms, and BIM applications). This study will inform the design of a web-based BLE for enhanced AEC-FM education and training, and it also provides a starting point for researchers to apply AST to evaluate the use of a BLE in different educational and training contexts.

Keywords: BIM; BIM-enabled learning; BIM education; virtual learning environment; AEC-FM

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1. Introduction

Digitalization of the construction industry is driving changes in the required knowledge, skills, and attitudes of construction industry professionals, thus motivating the adaptation of their education and training. Building Information Modelling (BIM) is central to this digitalization, and it offers opportunities to address some of the current challenges through BIM-enabled education [1], i.e., using BIM as a vehicle for knowledge creation, sharing, transmission, and evaluation. In earlier research, the authors analyzed extant cases of BIM education and investigated the difficulties faced in designing and implementing BIM education curricula generally and BIM-enabled education curricula specifically. In doing so, the need for an integrated, BIM-enabled Learning Environment (BLE) in which educators and trainers can effectively carry out BIM-enabled education and training was identified [2,3]. A BLE is expected to provide a web-based platform through which new and existing BIM-enabled approaches can be conveniently deployed for teaching and learning activities for the Architecture, Engineering, Construction, and Facilities Management (AEC-FM) disciplines. This study aims to define the characteristics of a BLE and applies an Adaptive Structuration Theory (AST) perspective to achieve this.

AST is a development of Anthony Gidden's Structuration Theory to the context of Advanced Information Technology (AIT) use in organizations [4]. Structuration Theory aims to understand social systems through their structures—the properties, rules, and resources or sets of transformational relations that allow similar social practices to be reproduced across time and space and give them the form of systems [5] (pp. 16–25). AST considers the types of structures that are provided by AITs, i.e., structures that are embedded within the technologies themselves, and the structures that emerge in human action as people interact with these technologies [5].

DeSanctis and Poole [6] define AITs as information technologies that not only enable the accomplishment of organizational tasks but also support coordination among people and provide procedures for interpersonal exchange. As an educational and training platform, the proposed BLE must clearly achieve both—it must enable BIM-enabled educational/training tasks and also mediate interpersonal exchanges between teachers/trainers/students—and thus may be considered an AIT in the AST sense.

DeSanctis and Poole [6] propounded the theory for understanding technology-induced organizational change and proposed a comprehensive framework to this end, which is shown in Figure 1. By applying this AST framework to the problem of BLE development, the authors' intention is to first understand and define the characteristics of the BLE as an AIT in order to develop the BLE and then, later, to study its use and impact in the organizational contexts where it is utilized for education and training. This article reports the first of these steps: research to define the BLE characteristics with reference to the AST framework in order to subsequently facilitate research, in which the AST framework is applied to study the effects of BLE implementation.

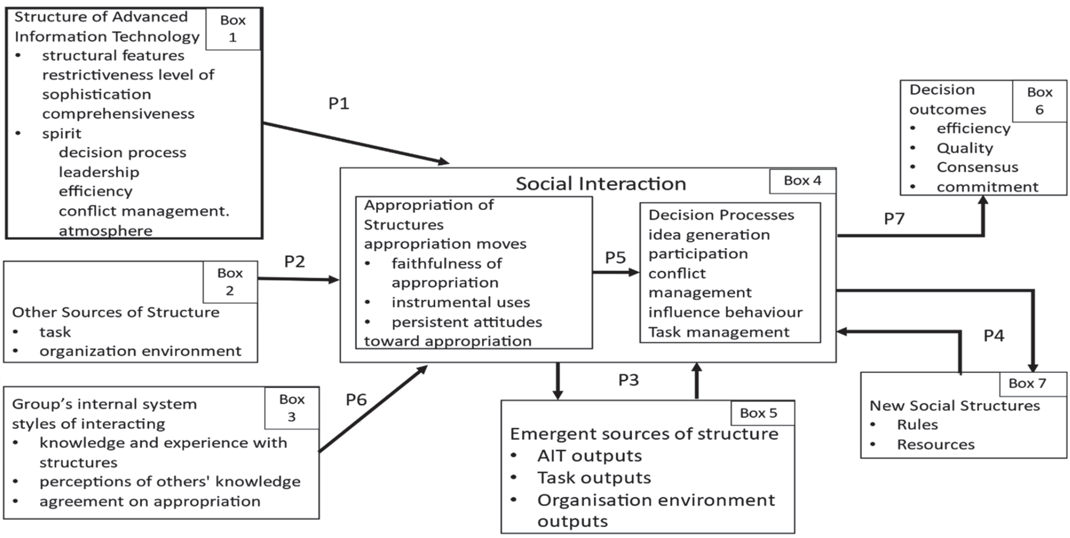

Figure 1. Adaptive Structuration Theory (AST) Framework (DeSanctis and Poole (1994)). Propositions: **P1**: AITs provide social structures that can be described in terms of their features and spirit. To the extent that AITs vary in their spirit and structural features sets, different forms of social interaction are encouraged by the technology. **P2**: Use of AIT structures may vary depending on the task, the environment, and other contingencies that offer alternative sources of social structures. **P3**: New sources of structure emerge as the technology, task, and environmental structures are applied during the course of social interaction. **P4**: New social structures emerge in group interaction as the rules and resources of an AIT are appropniated in a given context and then reproduced in group interaction over time. **P5**: Group decision processes will vary depending on the nature of AIT appropriations. **P6**: The nature of AIT appropriations will vary depending on the group's internal system. **P7**: Given AIT and other sources of social structure, ideal appropriation processes, and decision processes that fit the task at hand, then desired outcomes of AIT use will result.

AST maintains that the structure of an AIT may be characterized in terms of its set of structural features and its spirit. The structural features relate to the rules, resources and capabilities offered by the AIT, and they control and bring meaning to the social interactions mediated by the AIT. The spirit of an AIT refers to the overall intentions behind its set of structural features in terms of value propositions and goals for which the AIT was designed (cf. [7]). It also embraces what DeSanctis and Poole [6] referred to as the "status quo", i.e., the current interpretive account of the technology's values and purposes based on the numerous ways by which the technology is appropriated over time by different users under different conditions. As Orlikowski [8] puts it: "While technologies may appear to have objective forms and functions at one point, these can and do vary by different users, by different contexts of use, and by the same users over time". Similarly, DeSanctis and Poole [6] argue that the use of any structure in an AIT is not sacrosanct since humans, as reflective agents, may use any aspects of the technology structures in any way they wish—they referred to these as appropriation moves. The decision to appropriate a particular structure and its continuance is dependent on how favorable and satisfying the actual outcome is. An appropriation move is considered faithful, if it is in line with the design intent for which it was created, or unfaithful, if used differently from the spirit of the technology (which is not necessarily a bad thing).

This study defines the structural features and spirit of the proposed BLE as an AIT through a qualitative, interpretivist, pragmatic approach. As previously noted, this will enable BLE development in the first place and, subsequently, facilitate the study of a BLE in use. Moreover, identifying both the structural features and the spirit of a BLE will assist in categorizing the existing sources of BLE structures into domains that would enable both a comparative and gap analysis of users' requirements in delivering BIM-enabled learning. The latter is particularly necessary since the expected output of this effort is the development of a web-based BLE that will afford geographically dispersed users the opportunity to access learning materials without the constraints and limiting issues associated with hardware devices, encourage independent and lifelong learning, and also promote adaptive and personalized learning. Lastly, it will offer researchers, educators, and trainers a means to evaluate empirically, and, possibly, address the consequences arising from, teachers' and learners' appropriation moves with respect to a BLE.

In the next section, we provide a brief review of the related literature. This is followed by a description of the methodology adopted to define and specify the attributes of the proposed BLE through a series of case studies and interviews carried out in three countries. The findings of these case studies and interviews are then presented before their implications for theory and practice are discussed. Conclusions are drawn in the final section.

1.1. Literature Review

1.1.1. BIM-Enabled Education

BIM education has seen an upsurge in interest in the last two decades among teaching faculty and researchers with authors emphasizing different aspects of educational skills, attitudes, and knowledge. Conversely, the presence of COVID-19 globally in the past 2 years has also brought to focus the importance of digital technologies, virtual and augmented realities, and other tools that are valuable in construction engineering education [9]. BIM educational programs start with creating awareness and educating students and trainees on how to use different industry-specific BIM software packages (e.g., Revit, ArchiCAD, Navisworks, Rhino3D, Aconex, etc.) for modelling, viewing, simulating, scheduling, or data sharing (see [10–16]). Courses often begin by highlighting the benefits and barriers of BIM, including the reasons for BIM adoption in the AEC-FM industry (e.g., [17–27]) and the progress on BIM knowledge and authoring/manipulation skills (e.g., [28–31]).

Beyond developing BIM software skills, BIM technology has also been used to impart other learning such as coordination, collaboration, communication, and interpersonal relationships among students, etc. (see [16,32–34]). For instance, Barham et al. [35] experimented with BIM as a visualization tool in teaching structural detailing. Several other studies have demonstrated how researchers and practitioners are pushing the boundaries in the ways that BIM can be leveraged in construction engineering games for educational purposes (e.g., [36–42]). This mutual influence between BIM technology and BIM agents—teaching BIM technology and using BIM technology to teach—is a defining characteristic of BIM education.

Underwood et al. [1] categorized the evolution of BIM education into three progressive stages:

1. BIM-aware, where graduates are made aware of the uses and exigencies of BIM relating to its implications for both digital and cultural transformation of the construction industry.
2. BIM-focused, which involves graduates' abilities to use and manipulate BIM software in performing specific tasks such as modelling, clash detection, simulation, etc.
3. BIM-enabled, where education takes place in a BIM-mediated virtual environment, and BIM acts as a platform for learning [1].

Both BIM-aware and BIM-focused education have been generally recognized and initiatives to develop curricula to incorporate BIM have become widespread. A comprehensive account of BIM-enabled education cases has been documented in Abdirad and Dossick [43] and more recently updated in Olowa et al. [2].

1.1.2. BIM-Enabled Learning Environments

COVID-19 has significantly underscored the demand for distributed, collaborative, self-paced, and adaptive learning. Already a decade ago, Ku et al. [40] identified these challenges and experimented on what they referred to as a BIM interactive Model (BiM)—a platform that combines a virtual environment with BIM for learning purposes and proposed a theoretical web-based virtual world for engaging construction stakeholders in real-time social interaction using the Second Life virtual environment. They contended that integrating 2D and intelligent 3D BIM models would supplement construction education to overcome the limitation of location-based learning and make it accessible to anyone with an internet connection. Recognizing the benefits of promoting distributed training opportunities, as suggested by Ku and his colleagues, further studies have been carried out and reported in support of this initiative (e.g., [44–49])

Acknowledging the general consensus among previous developers and authors on the ability of a virtual learning environment (VLE) to promote off-site training and education, Shen et al. [50] used the 3D-UNITY game engine to create a web-based training environment for HVAC rehabilitation and improvement using a BIM model. In contrast to Ku et al. [40] and the Second Life platform, the authors argued that game engines have been sufficiently developed for BIM interoperability, thereby making game creation cheaper and easier with little to no need for programming skill. With their research, Shen et al. [50] were able to demonstrate how BIM could be leveraged for teaching at the topical level.

1.1.3. Application of AST to BIM-Enabled Learning Environments

AST is used in this study as it emphasizes the importance of social structures in the development of new technologies and in the use of those technologies by people [6,51]. As Turner et al. [51] note: "AST explains the complications associated with the technology–organization connection and provides . . . information on how to develop new technologies or design educational curriculums that encourage adapting new technologies". Although we have not come across any study that has applied AST in the development of a new, innovative technology (in this case, a BIM-enabled Learning Environment), AST has been extensively used in evaluating AITs relating to group decision support systems [7] and, more recently, to explore value creation at the business process level through BIM in the construction industry [52]. AST has also been used to investigate socio-technical changes that are brought about by AITs, such as social media interaction among researchers [53], understanding the relationship between agile methods and organizational features [54], and understanding the influence of ICT infrastructure on student teachers' use of Student Information Management System [55].

2. Materials and Methods

According to Ma et al. [56], there are 3 steps involved in defining the functional requirements for an AIT. These include identifying and isolating relevant processes of intended users; formulating functional requirements based on the isolated processes; and revising and validating the relevant processes that correspond to the formulated functional requirements through inquiries from prospective users. With these processes in mind, an exploratory sequential mixed-methods research methodology [57] was applied in this research with the aim of specifying a BIM-enabled Learning Environment (BLE).

In preparatory work to this study, an initial, theoretical BLE concept developed by Witt and Kähkönen [58] had been applied in a BIM-enabled learning intervention that was trialed at Tallinn University of Technology within an existing course taught to fourth year civil engineering students (reported in [3]). In addition to this Estonian case, two further cases of BIM-enabled learning activities carried out at the University of Bologna, Italy and Tampere University, Finland were analyzed in order to develop an initial list of requirements for a BLE. A desk study was also conducted to review existing academic and grey literature to find relevant materials related to existing BLE type initiatives so as to understand the general characteristics of a BLE. These preparatory activities enabled the design of the semi-structured interview data collection strategy and instrument elaborated below.

2.1. Data Collection

2.1.1. Interview Participants

For the interviews, participants were purposively selected in 3 European countries: Estonia, Finland, and Italy. These 3 countries were selected for convenience in the context of an ongoing research collaboration between the Tallinn University of Technology, Tampere University, and the University of Bologna. The relevance criteria for participants were that they should be actively engaged with AEC-FM training and/or AEC-FM education and/or BIM-training and/or BIM-education in any (e.g., academic, industry, etc.) setting irrespective of their mode of delivery in teaching practice. The selection of interviewees was intentionally directed towards achieving representation from as wide a range of relevant stakeholders as possible. A total of 31 participants (10 from Estonia, 9 from Finland, and 12 from Italy) were interviewed with interviews in each country conducted by 2 or 3 different facilitators. All interviewees read and signed an informed consent form prior to their participation.

2.1.2. Interview Schedule

A semi-structured interview schedule was used to elicit information regarding the ideal characteristics of a BLE based on the educator's/trainer's lived experiences and aspirations. The interview schedule commenced with an overview of the purpose and context of the research and confirmation of the interviewee's data (name, position, and affiliations). As the interviewees were expected to comment on a concept (the BLE), as opposed to an existing artefact with which they could have direct experience, it was important to establish a common understanding of the general idea of the BLE among all interviewees. For this purpose, a short (1 min) video outlining the BLE concept with commentary in the local language (Estonian, Finnish, or Italian) was played to them before a series of open-ended questions were asked as follows:

1. Please describe the teaching/training that you/your organization give (Including subject(s), target audience).
2. Do you currently use BIM for delivering your teaching/training? (Alternative if organization only arranges training: Is BIM currently used in the delivery of training arranged by your organization?)

   If YES:

3. How do you use BIM in the delivery? (e.g., for visualizations, project data, communication, etc.)

(Alternative if organization only arranges training: How is BIM used in training delivery?)
If NO:

4. Could you use BIM to help deliver your teaching/training and for what? (e.g., for visualizations, project data, communication, etc.)

(Alternative if organization only arranges training: Could BIM be used in training delivery?)

5. Beyond your present area(s) of teaching/training, how do you think BIM could be used in BIM-enabled learning?

(Alternative if organization only arranges training: Beyond the areas of training arranged by your organization, how do you think BIM could be used in BIM-enabled learning?)

6. What functions would you like to see in a BIM-enabled Learning Environment?

2.2. Data Analysis

2.2.1. Grounded Theory Method

The analysis of the interviews was based on a Grounded Theory (GT) model because of their acclaimed usefulness in the development of process-oriented, context-based descriptions and explanations of information system phenomena [59]. GT is a method of data analysis and theory generation propounded by Glasser and Strauss [60] that is based on induction. Since the pronouncement of their initial concept, it has metamorphosed with different authors suggesting additional nuances on how it should be applied leading to different GT versions. According to Urquhart, the major models used in the literature are those suggested by Glasser, Strauss, and Charmaz [59]. Despite their differences, they all agree on iteratively sampling data to generate themes (at a high abstract level) that are useful for developing theories grounded in the collected data. This study adopted the Straussian Theory Model (STM) with the unit of analysis being predominantly segments of the interview transcripts that convey a particular meaning. In line with the Straussian approach, extracting these segments of texts is the first step of analysis referred to as open coding. This was followed by axial coding in order to identify major categories. However, this methodology was applied as a tool for discovering associations within the data rather than as a rigid set of rules [59]. The data collection and analysis were sequential. Interviews were mostly carried out virtually (online) using MS Teams, Zoom, etc. as maybe agreed by both the facilitators and the participants. Where possible, face-to-face interviews were also conducted. In both circumstances, interview sessions were audio recorded and transcribed. As interviews were conducted in local languages as well as in English, interview transcription and analysis were carried out by different analysts and this necessitated coordination in the form of a commonly agreed analysis template with four predetermined coding categories: demographics; subjects taught; target audience; and functional requirements. Additionally, emergent categories were then continuously added as analysts found them. These included method(s) of teaching/training, BIM uses, level(s) of BIM awareness/competency, and challenges. The structural coding was achieved using NVivo qualitative data analysis software in some cases and, in others, the MS Word text editor was used, as not all the facilitators were familiar with NVivo software. Analysis of all interviews was then aggregated using NVivo software for further and final analysis. As part of this aggregated analysis, all interview references to the "spirit" attributes of the BLE were also captured through theoretical sensitivity.

2.2.2. Validation of BLE Features by Focus Group

The results of the interview analysis were then presented to a focus group of AEC-FM education experts for validation. For the focus group, the researchers took advantage of an online workshop in which BIM educators and enthusiasts from 5 countries participated and discussed the BLE concept and the proposed BLE features that had emerged from the interviews. Focus group participants were then asked to rate the level of importance of each proposed BLE feature identified from the interviews using an online questionnaire containing both closed- and open-ended questions. The closed-ended questions presented each identified feature with a 5-point Likert-type scale for importance ratings: "1-Not important", "2-Slightly important", "3-Moderately important", "4-Very important" and "5-Critically important". The open-ended questions were intended to elicit comments, suggestions and recommendations for additional features that would be important for a BLE but were missing from the list identified from the interviews.

2.2.3. Statistical Methods

The questionnaire was fully completed and submitted by 10 respondents. Analysis of the online questionnaire by the focus group was carried out using descriptive statistics, viz simple mean score and a relative importance index for each of the identified BLE features. Figure 2 illustrates the research process adopted for this study.

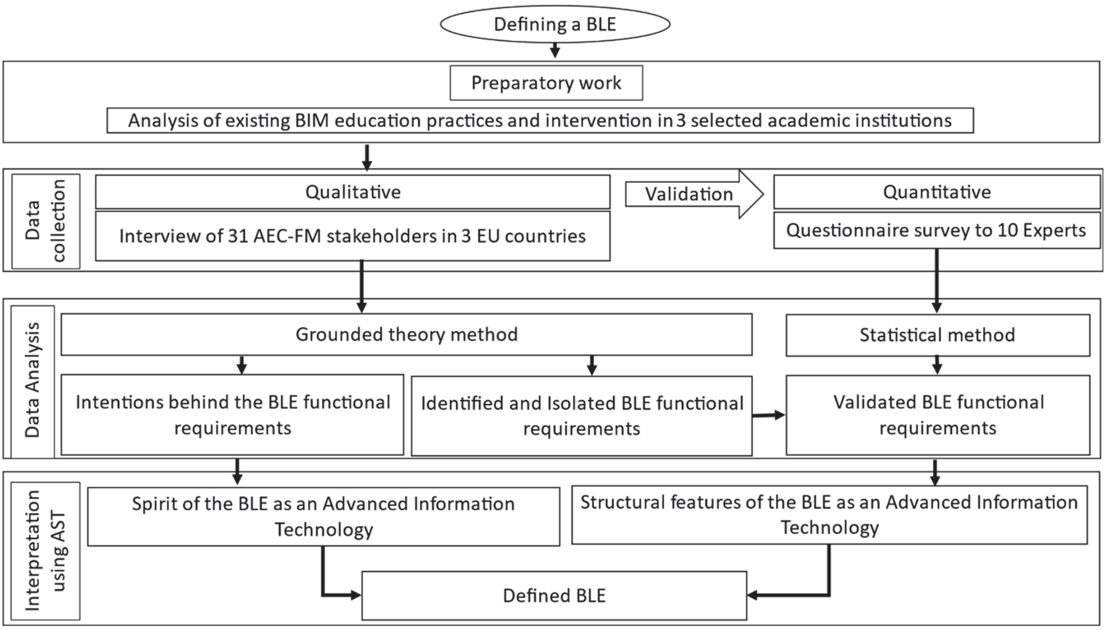

Figure 2. Research process adopted.

3. Results

3.1. Characteristics of Participants

The interviewed participants were from diverse backgrounds in terms of the type of organization that they belonged to, actual sub-sector in which they operate, and their geographical location. Figure 3 shows three clusters of bars, which depict the distribution of the participants according to their organization type, sub-sector, and country. From the three countries where the interviews were conducted, i.e., Estonia, Finland, and Italy, a total of six sub-categories emerged from the organization type with the highest participants coming from the university (13), construction (8), and vocational education (4) sub-categories. Other sub-categories are Construction information and training NGO (1), Consultancy (1), and Real Estate management and maintenance (4).

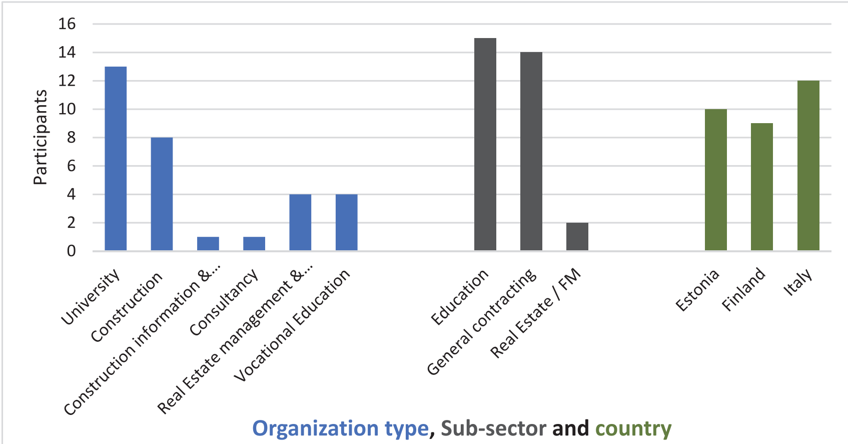

Figure 3. Characteristics of participants with respect to organization type, sub-sector, and location.

The sub-sectors to which the participants belong were also identified as education (15), general contracting (5), and real estate/facilities management (2). The individual characteristics of the validation questionnaire of respondents within the focus group could not be isolated because, while it was expected that all validation workshop participants who had not been engaged in developing the research findings would complete the online questionnaire, this did not turn out to be the case.

3.2. Identifying and Isolating Functional Requirements/Structural Features of the Proposed BLE

Table 1 shows the list of 33 identified and isolated functional requirements emerging from the preparatory desk study (literature review and three case study analyses), the 31 interviews and the focus group suggestions for additional BLE features together with an explanatory commentary on the corresponding structural feature for the proposed BLE.

Table 1. Processes based on BIM structures.

#	Identified and Isolated Functional Requirements	Explanation of Corresponding Structural Feature of BLE
1	BIM model viewing	BLE should enable BIM model viewing to allow learners to visually explore the object of their learning experiences.
2	BIM model data extraction	Input data for any learning task should be available in the model and be accessible to and conveniently extractible by learners.
3	BIM model sharing	Ability to share models and thus communicate around models.
4	BIM model version management	Ability to track and manage different BIM model versions.
5	BIM model editing	Ability to edit BIM models. If a meaningful learning task is performed, it will generate further data, which needs to be input back into the model (for example, scheduling tasks will elaborate a model from a 3D to a 4D model).
6	BIM model collaborative viewing and editing	Ability to collaboratively view and edit models. The abovementioned functions of viewing and editing should, ideally, be collaboratively performed in groups.
7	Repository of example BIM models	The BLE should include a repository or library of high quality, consistent, and error-free models.
8	Common Data Environment (CDE) for project data	Ability to host project data consistently and persistently. The learning objects are projects, and project data is not limited to that which is incorporated into the BIM model. Thus, a Common Data Environment is a necessary attribute.

Table 1. *Cont.*

#	Identified and Isolated Functional Requirements	Explanation of Corresponding Structural Feature of BLE
9	Simulation of the project development process (realistic BIM workflow, key stakeholder roles, etc.)	Ability to simulate a realistic project development process. Learning experiences will attempt to simulate real life projects, so realistic stakeholder roles and BIM-based workflows will need to be supported by the BLE.
10	BIM model creating	Ability to create BIM models. Although most BLE tasks are envisaged as starting with an existing model already created, it could be useful to have access through the BLE to model creating tools also.
11	BIM model checking	Ability to check BIM models—incorporating/integrating checking functionality within/with the BLE.
12	Extended reality (XR) functions: Augmented Reality (AR)/Mixed Reality (MR)/Virtual Reality (VR)	Ability to integrate extended reality functions. To improve visualization and communication, additional XR functionality could be useful.
13	BIM object creation and editing	Ability to create BIM objects.
14	Group formation	Ability to create groups. The BLE must enable group formation and group work, as learners will typically work in stakeholder groups.
15	Collaboration in groups	Ability to communicate and work together in groups while engaged in learning.
16	Collaboration between groups	The possibility for groups to communicate and interact with one another, since learner groups will tend to represent stakeholders and stakeholders need to interact for project development.
17	Instructor access and monitoring of groups and group work	Ability to create instructor privileges for both access and group work monitoring. Instructors will need to interact with groups (as well as with individuals).
18	Collaborative viewing and editing of documents and spreadsheets	The collaborative viewing and editing of documents and spreadsheets (not only of BIM models) is essential in carrying out learning tasks in groups.
19	Live interactions between users	Ability to engage in live interactions among users. To improve the convenience and time efficiency of instruction and group work.
20	Recording of group sessions and lessons	Ability to record group sessions and lessons. This functionality would be useful to both learners and instructors (and is increasingly essential in mitigating COVID-19-related learning constraints).
21	Registration of users (learners/instructors)	Ability to register and deregister users. As the BLE is a learning environment, this is an essential administrative feature.
22	Data security/password protection	Capabilities for securing users' data and information especially in relation to registered users and their activities.
23	Hosting of different courses	Capable of hosting multiple courses. Learning experiences will be provided as modules/courses in the BLE.
24	File upload, storage, download, sharing, editing	Ability to upload, store, download, share, and edit files for course content and access to materials.
25	Video playback	Ability to playback videos—for course content as well as enabling access to external (video) materials.
26	Linking to extra learning materials	Ability to link to additional learning materials—for course content and access to (all kinds of) materials.
27	Individual learners' storage for learning materials	Ability to store individual's learning materials. Ideally within the BLE and on individual learners' devices.
28	Links between courses.	Ability to link multiple courses to build on previous courses' results and to track impacts on/inputs to future courses. This would encourage/enable continuity and connections between different/contiguous learning experiences.

Table 1. *Cont.*

#	Identified and Isolated Functional Requirements	Explanation of Corresponding Structural Feature of BLE
29	Assessment/grading	Ability to assess and grade learners—grade entering for individuals/groups, grade book. Needed for learning administration, quality, and learner assessment purposes.
30	Questionnaire creation, completing, submission	Ability to create and analyses questionnaires, quizzes, and polls. As part of a formative and summative assessment of learning.
31	Student feedback	Ability to obtain feedback from users and learners. For quality assurance and improvement purposes.
32	Gamification support	Capable of integrating gamification functions. Incorporating competition enhancements as a way of motivating learners—high scores/leader boards, etc.
33	Integration of platform with external systems/business	Ability to integrate with external platforms—for example, with institutional study information systems.

3.3. Validating and Revising the Structural Features of BLE

Table 2 shows the list of structural features for a BLE based on the focus group ranking. The mean was calculated based on the 5-stage Likert scale ranging between 1 and 5, 1 being "Not important" and 5 representing "Critically important". Using the relative importance index (RII) where the most important has the least value (1 in this case) and the least important has the highest value (i.e., 30). Three of the functional requirements (#13, #26, #27) were identified by the focus group as suggestions for additional BLE features and were therefore not included in the validation questionnaire and consequently, not ranked by the focus group.

Table 2. Revised and validated structural features.

Structural Feature	Mean	RII
Ability to obtain feedback from users and learners (#31)	4.54	1
Ability to input, access, and extract learning task data (#2)	4.47	2
Ability to create and manage within groups (#15)	4.47	2
Ability to simulate project development process (#9)	4.44	4
Ability to link multiple courses to build on previous courses' results and to track impacts on/inputs to future courses (#28)	4.44	4
Ability to integrate with external platforms or going concerns (#33)	4.44	4
Ability to host project data in persistently (#8)	4.35	7
Ability to secure and protect users' data and information (#22)	4.35	7
Ability to collaboratively view and edit BIM models (#6)	4.28	9
Ability to visually explore learning objects in BIM models (#1)	4.27	10
Ability to share and communicate around models (#3)	4.27	10
Ability to upload, store, download, share, and edit files (#24)	4.25	12
Ability to create instructor privileges for both access and group work monitoring (#17)	4.13	13
Ability to host multiple courses (#23)	4.13	13
Ability to check BIM models against process and regulatory standards (#11)	3.94	15
Ability to collaboratively view and edit different document file formats (#18)	3.92	16
Ability to create and analyze questionnaire, quizzes, and polls (#30)	3.92	16
Ability to playback videos (#25)	3.92	16

Table 2. *Cont.*

Structural Feature	Mean	RII
Capable of integrating gamification functions (#32)	3.75	19
Capacity to accommodate a repository or library of high quality, consistent, and error-free models (#7)	3.74	20
Ability to create and manage between groups (#16)	3.71	21
Ability to create groups (#14)	3.67	22
Ability to edit BIM models (#5)	3.62	23
Ability to engage in live interactions among users (#19)	3.62	23
Ability to register and deregister users (#21)	3.58	25
Ability to integrate extended reality functions (#12)	3.40	26
Ability to evaluate learners (#29)	3.40	26
Ability to manage different BIM model versions (#4)	3.33	28
Ability to create BIM models (#10)	3.22	29
Ability to record group sessions and lessons (#20)	3.05	30
Ability to create BIM objects (#13) *	*	*
Ability to store individual's learning materials (#27) *	*	*
Ability to link to additional learning materials (#26) *	*	*

* Items not included in the focus group questionnaire as these emerged from focus group suggestions for additional BLE features.

3.4. Spirit of the Proposed BLE

Qualitative content analysis of the interview data also revealed insights into the attributes of the spirit of the proposed BLE. Table 3 shows the spirit attributes or intentions that were expressed by the participants and which informed their defining of structural features for a BLE. These attributes include collaboration, active learning, integrated learning, adaptive and personalized learning, and project process improvement

Table 3. Spirit of the proposed BLE.

#	Spirit Attributes	Interview Quotations Implying Spirit of Proposed BLE	Participant (P)/Country (E = Estonia; F = Finland; I = Italy)
1	Collaboration	" . . . the involvement of stakeholders"	P.6/E
		" . . . I hope that our school colleagues . . . will join us because they can use our e-course objects too for their learning subject material for showing and explaining"	P.4/E
2	Active learning	" . . . more involvement by the students"	P.6/E
		" . . . for people who're just joining the company . . . they haven't really seen any . . . situations on site."	P.8/E
3	Integrated learning	" . . . that they understand the impact of various decisions at the early phases of the project."	P.6/E
		" . . . possibilities to take the quantities of the volumes . . . "	P.7/E
		" . . . for architectural definition and building package analysis for teaching activities"	P.13/I
		" . . . to teach data visualization including some analysis."	P.9/E
		" . . . to use BIM in an integrated way by all the actors involved in the process."	P.10/I
		"Viewing the model of job site and impact of future decision of site safety."	P.17/I
		"Quantities and other information-take-offs from digital models"	P.22/F

Table 3. *Cont.*

#	Spirit Attributes	Interview Quotations Implying Spirit of Proposed BLE	Participant (P)/Country (E = Estonia; F = Finland; I = Italy)
4	Adaptive/Personalized learning	" . . . students need related knowledge, and it does not matter which specialty is discussed because all the information is separated . . . and BIM is very good example of how we can join different line subject with one another and how it will be done for student."	P.9/E
		" . . . need some. Interactions with the courses so if one course finishes with some stage then they will use the same . . . "	P.6/E
5	Improvement (of project processes)	" . . . improve our [training] process"	P.8/E
		" . . . to use a 3D visualization"	P.7/E
		" . . . see the clashes or the mistakes that are in the design"	P.7/E
		" . . . exploring and evaluating key areas of innovation and skills through the BIM methodology."	P.11/I
		"Marketing with visualizations and interactive 3D Product design (design management)"	P.26/F
		"Project planning and management (cost estimating, scheduling, purchasing, task planning, project control)"	P.26/F
		"Compliance checking of BIM models as a part of quality assurance"	P.28/F

4. Discussion

The interview transcripts and emergent recommendations for BLE features, to an extent, appear to reflect the participants' positive and negative experiences in relation to their own education/training activities. For instance, the popularity of collaborative learning in groups and problem/project-based learning approaches is reflected in the numerous recommended features that relate to groups and collaboration (features (refer to Tables 1 and 2 above): #3, #6, #14, #15, #16, #17, #18, and #20) and generating realistic project learning contexts (features: #2, #7, #8, and #9). In addition, participants complained of problems with managing software for students and interoperability (reflected in features #7 and #18) as well as the need for effective integration between systems (reflected in features #12, #32, and #33). Further challenges expressed by participants included the limited BIM skills of educators and trainers themselves, and there was some skepticism regarding educators'/trainers' motivation to welcome new modes of training using BIM models. These challenges have been identified by several researchers as impediments to BIM education generally (e.g., [1,61,62]) and, it seems, could not be addressed by specific feature recommendations for the proposed BLE.

The recommended BLE features can also be understood as corresponding to three distinct categories of function: "BIM" functions, "collaboration" functions, and "virtual learning environment" (VLE) functions, and Figure 4 depicts these categories together with their associated BLE features.

The BIM functions relate to features typically associated with BIM software such as the creation and editing of BIM models, BIM model viewing, common data environments for project data, etc. Collaboration functions allow for virtual communication, coordination, and collaboration in groups and can be readily recognized as including features commonly associated with existing virtual collaboration/video conferencing platforms such as Zoom, MS Teams, etc. Similarly, the VLE functions aggregate those features (learning progress tracking, performance monitoring, assessment and testing, feedback to learners, associated security and data protection, and so on), which would be associated with typical VLE or learning management system (LMS) platforms such as Moodle, Blackboard, etc. There are also some recommended BLE features that relate to more than one of these categories. For example, the ability to be able to upload, store, download, and edit files is common to both VLE and collaboration categories. Similarly, the ability to simulate project development processes and associated stakeholder interactions relates to both collaboration and BIM function categories. Importantly, we note that these three functional categories are required to be incorporated into the proposed BLE if it is to properly support and facilitate AEC-FM training and learning.

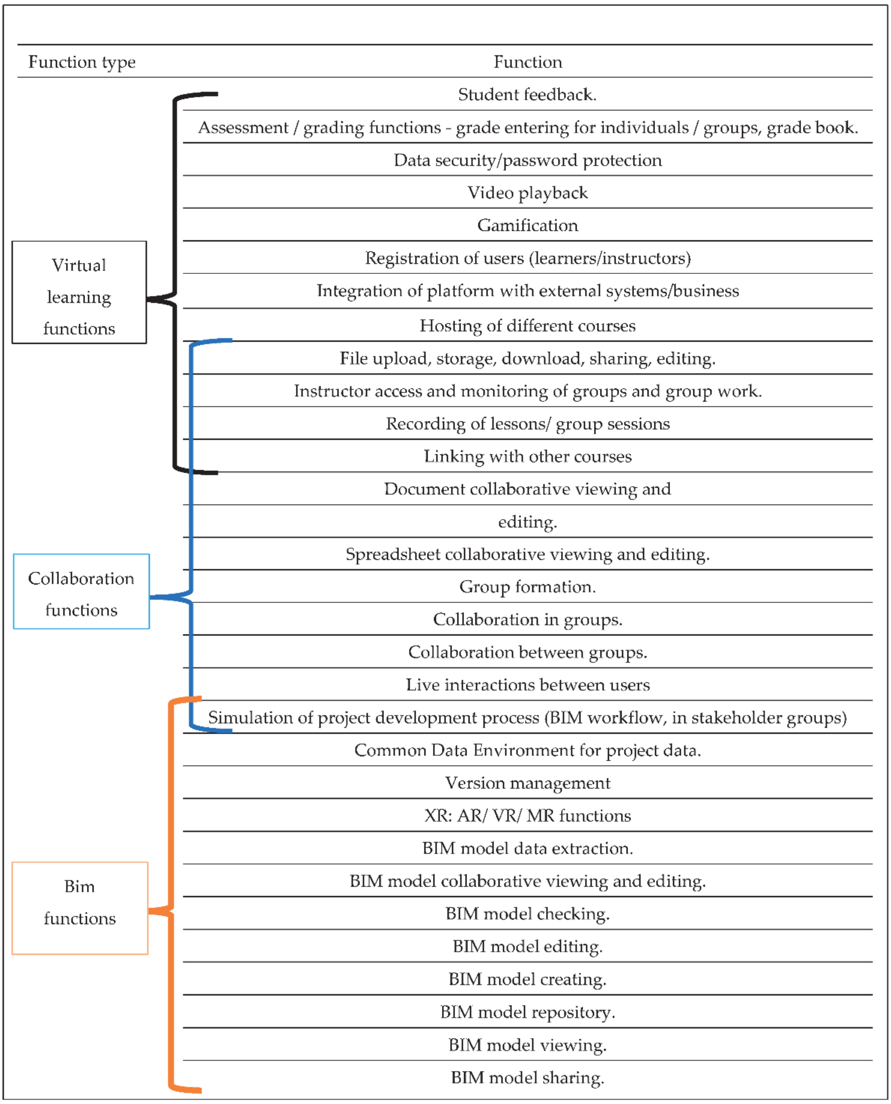

Figure 4. Matrix of functional categorization of BLE features.

These findings suggest that, when asked to specify the functionalities that would be necessary in a BLE, the interview participants have collectively drawn on their educational/training experiences of existing AITs (specifically BIM, virtual collaboration, and VLE technologies) and identified relevant functionalities from these familiar AITs to then incorporate into the new, proposed AIT (the BLE). This process closely resembles the "appropriation of structures" as conceptualized by DeSanctis and Poole [6]—see boxes one and four and proposition P1 in Figure 1. The same types of social interactions enabled by certain structures embedded within these existing AITs are considered by the interviewees to be desirable for BIM-enabled learning, and therefore similar social interactions should also be enabled by the BLE. In order to replicate these desired social interactions among and between learners and teachers using the BLE, the same enabling structures must therefore be appropriated and incorporated into the BLE specification.

DeSanctis and Poole's [6] conceptualization also points to other sources of structure in the organizational environment and task (Figure 1, box two) as well as the (AIT user) group's internal system and styles of interaction (Figure 1, box three). Whereas at the stage of designing the BLE, both user groups and tasks are as broadly defined as possible so as to allow the greatest and widest potential utility of the BLE, the organizational environments in which the BLE will be used and from which the interviewees have been drawn may be readily identified as being of two distinct types: educational and industry. It follows that the structures of the BLE will also reflect the structures from these two organizational types: structures from the education system and structures from the AEC-FM industry system. The structures embedded in education systems have been delineated by Witt and Kähkönen [58] to include the rules, resources, and roles relating to learning and teaching, and it is clear that participants' interactions and relationships with these structures have informed their suggestions offered for defining the structures of a BLE.

The contributing structures from the AEC-FM industry system relate to industry-specific roles and ways of working. The nature of the construction industry is such that it involves different stakeholders, with different responsibilities and liabilities even when they have the same product as a goal. The industry workflow demands that suppliers come in at different points in the execution and delivery of projects with clear deliverables and targets. The structures enabling these activities are reflected in the interviewees' recommendations of related structures that a robust BLE must exhibit to effectively deliver project-based learning to graduates, trainees, and professionals for industry relevance. Within the AEC-FM industry environment, its digital transformation and, specifically, its adoption of BIM is particularly important, as the BLE is predicated upon the latent benefit of BIM for the industry and also for education. BIM structures dictate how work and project data should flow with different levels of definition, how they should be shared, etc.

The emergent conception is one in which the structural features recommended by participants for the proposed BLE are those which they have identified as enabling the social interactions they consider could support BIM-enabled learning. Additionally, when we consider from where (the organizational environments from which) those participants are drawn and the types of AITs (BIM, virtual collaboration technologies, and VLEs) with which they are already familiar, it becomes clear that these (environments and AITs) are the sources of the structures that are being appropriated for incorporation into the BLE.

DeSanctis and Poole [6] consider the structure of AITs to comprise both structural features and also spirit—the overall intentions behind the set of structural features. While our data collection and validation rather emphasized the definition of the structural features (for the practical reasons of interviewees and focus group members' ease of understanding), the intentions that drive these features have also been extracted to some extent from the interview transcripts (summarized in Table 3). It is notable that many of the intentions (spirit attributes in Table 3) among educators in higher education institutions (HEIs) reflect what have previously been documented and described as educators' strategies in BIM for construction education [2]. These include integrative teaching, promoting active learning or constructivist education, promoting accessible education, and creating adaptive and personalized learning experiences. Further spirit attributes (intentions) captured included collaboration and (project process) improvements, both of which appear to reflect current intentions (particularly relating to BIM adoption) within the AEC-FM industry, thus reinforcing the notion that the recommended structures (both structural features and spirit) for the proposed BLE are indeed selected structures appropriated from existing AITs and organizational environments with which the interviewees were familiar. This is illustrated in Figure 5: concept map showing the sources of structures appropriated to define the BLE.

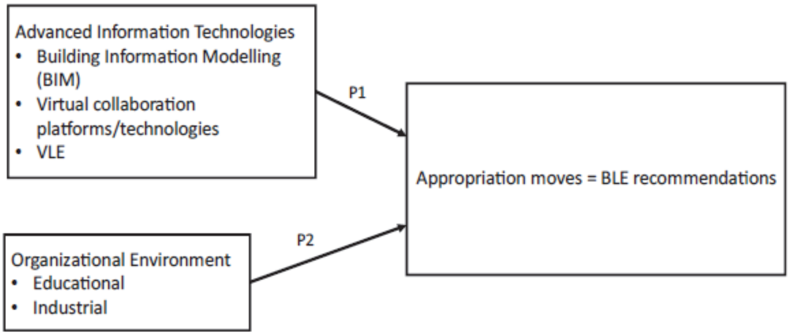

Figure 5. Concept map showing the sources of structures in a BLE.

The notion of appropriation of structures from existing AITs and organizational environments, in itself, is a useful insight for the further development of the BLE as it may be thought of as representing an integration of these AITs and environments. This phenomenon of adapting available resources underscores the need to have a defined structural starting point that will promote the delivery of BIM-enabled education in an efficient way. The development of a prototype BLE on this basis will enable a new pedagogical strategy capable of increasing students' motivation by presenting a more inclusive and sophisticated view of any AEC-FM BIM-related topic or course. Going forward, the defined structures must now inform technical system design in order to develop a prototype BLE.

Whereas DeSanctis and Poole [6] originally designed AST to assess and evaluate the outcomes of AIT use in social settings, this study has shown how it can also be employed to define an AIT (the BLE) in terms of the desired social structures (structural features and spirit) that the proposed AIT is intended to enable. We have also found AST to be a useful theoretical lens through which to interpret and understand the emergent BLE definition that has been derived. Once the BLE is developed, even in prototype form, then it will be possible, and it is intended to deploy the full AST approach to investigate how it is used by (different) social groups and thus evaluate its effectiveness in delivering BIM-enabled learning.

Regarding the limitations of this study, it should be noted that we have concentrated on defining the structural features and the spirit of a BLE using a structured set of interview questions among a few interviewees and respondents in three European countries. While we consider the findings robust, they are geographically and developmentally specific, and a larger, more geographically dispersed sample size would be beneficial for a more comprehensive identification and definition of the structures of a BLE, particularly if it were to be utilized in non-European contexts.

5. Conclusions

The digitalization of the AEC-FM industry has resulted in a demand for the reassessment of knowledge, knowledge management, teaching and learning, workflows and networks, individual roles, and relevance. Consequently, new teaching and learning platforms to cater to the requirements of new jobs and abilities, new channels of communication, and a new awareness are all required. BIM is a central feature of this digitalization, and it also offers opportunities to address some of the current challenges through BIM-enabled education and training. While BIM has become standard in industry, it is still being determined how it can be fully leveraged in training and education. To facilitate BIM-enabled learning, a platform—the BIM-enabled Learning Environment (BLE)—through which new and existing BIM-enabled approaches can be conveniently deployed for teaching and learning activities in the AEC-FM disciplines is needed.

This study aimed to define the characteristics of the proposed BLE. Within an exploratory sequential mixed-methods approach, preliminary data were collected through the qualitative analysis of three case studies as well as a study of the academic and grey literature. This led to a series of 31 semi-structured interviews being carried out in three European countries (Estonia, Finland, and Italy). A qualitative, grounded theory inspired, content analysis of the interview transcripts was applied to identify and isolate the desired functionalities of the BLE and the broader intentions behind these functionalities. The identified and isolated features of the BLE were then validated and added to in a focus group validation exercise using a quantitative, questionnaire with a Likert-type scale for importance ranking. Thus, a comprehensive list of BLE features was defined and validated, and each feature's ranking in terms of its relative importance was determined. In addition, the general intentions underlying the set of identified features were described.

Adaptive Structuration Theory (AST) was applied as a theoretical lens through which to interpret and understand the emergent findings in terms of the BLE's structural features (functionalities) and spirit (intentions behind the recommended functionalities). While, to the authors' knowledge, the application of AST for the design of an Advanced Information Technology (AIT) (the BLE) is a first, the AST lens did enable us to appreciate that the structures of the proposed BLE (its structural features and spirit) were not new in themselves but were rather being appropriated from other, existing AITs (BIM, virtual collaboration technologies, and VLE platforms) with which the interview participants were already familiar. In addition, and, in a sense, providing the sources of structure to the existing AITs, structures were also appropriated from the organizational environments that the participants came from. These insights are valuable in taking forward the development of the BLE into an actual, usable prototype as they suggest the functional integration of features from three defined AIT sources. The AST framework also provides a sound basis for future investigations of the BLE in use—which would be the typical application of the AST framework to study AIT use in a given social/organizational context.

Plainly, there are remaining challenges and doubts about how best to implement BLE in training and whether the new processes will be worth the effort among the stakeholders. This skepticism is understandable when we remember that change is turbulent and not easily embraced by all. This situation gets more complicated when trainers envisage putting in disproportionate additional efforts to bring a new learning style to bear. However, this is one way the development of an easy to use, open, and accessible platform with a repository of example BIM-enabled exercises could prove valuable.

The findings of this study have a wide range of implications for both theory and practice and in guiding future research direction. First and foremost, from a practical point of view, it provides the basis for the actual development of a prototype BLE. It also provides decision makers in software development organizations (especially those relating to the development of BIM applications for industry) insights and improvement opportunities to develop products that can be more easily integrated into AEC-FM education. Additionally, educational policy decision makers at relevant governmental levels should consider promoting more collaboration between developers of technologies for industry, users of technology, and educators/trainers—not only from the point of view of preparing industry workers with appropriate technology knowledge and skills but also in order to maximize the degree to which the technologies can be used to enhance education and training. Future research will focus on

1. Further investigation among more diverse and geographically dispersed stakeholders especially in the developing countries to ensure context-wide requirements are captured.
2. Investigating the technical integration of all the identified functions into a user-friendly, web-based platform for optimized AEC-FM education (the BLE).
3. Exploring the implementation of the BLE and evaluating its effectiveness using the AST framework.

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