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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.

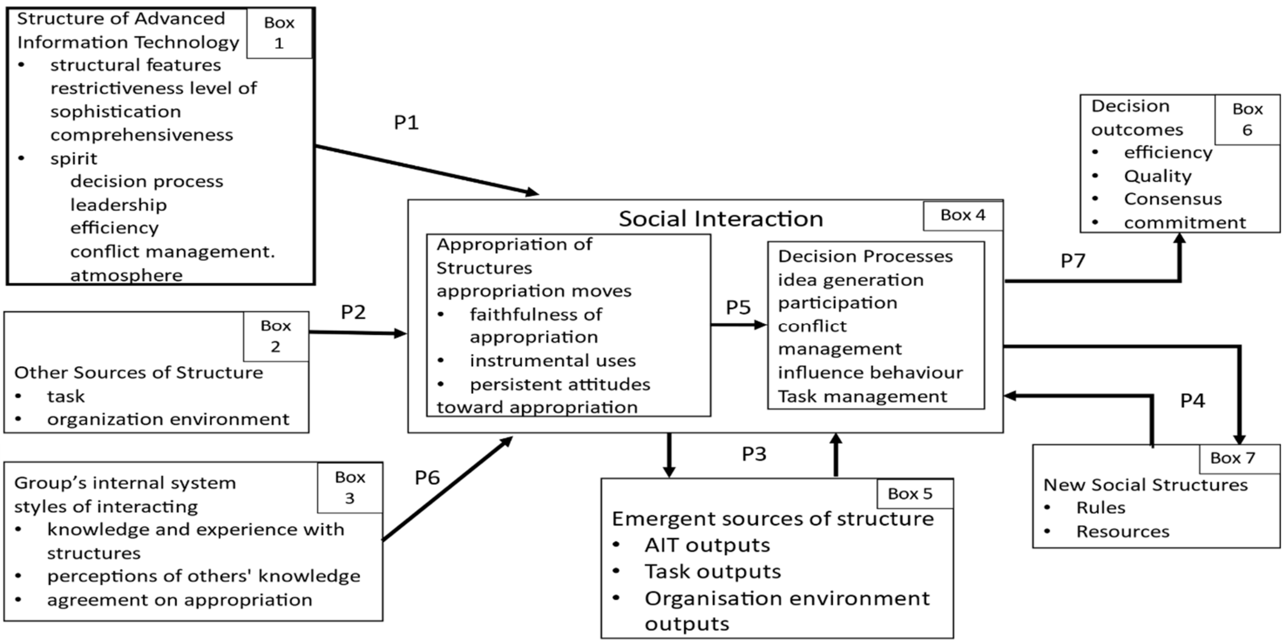

Figure 1. Adaptive Structuration Theory (AST) Framework (DeSanctis and Poole (1994)). Propositions: **P1**: AITs provide social structures that can be described in terms of their features and spirit. To the extent that AITs vary in their spirit and structural features sets, different forms of social 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.

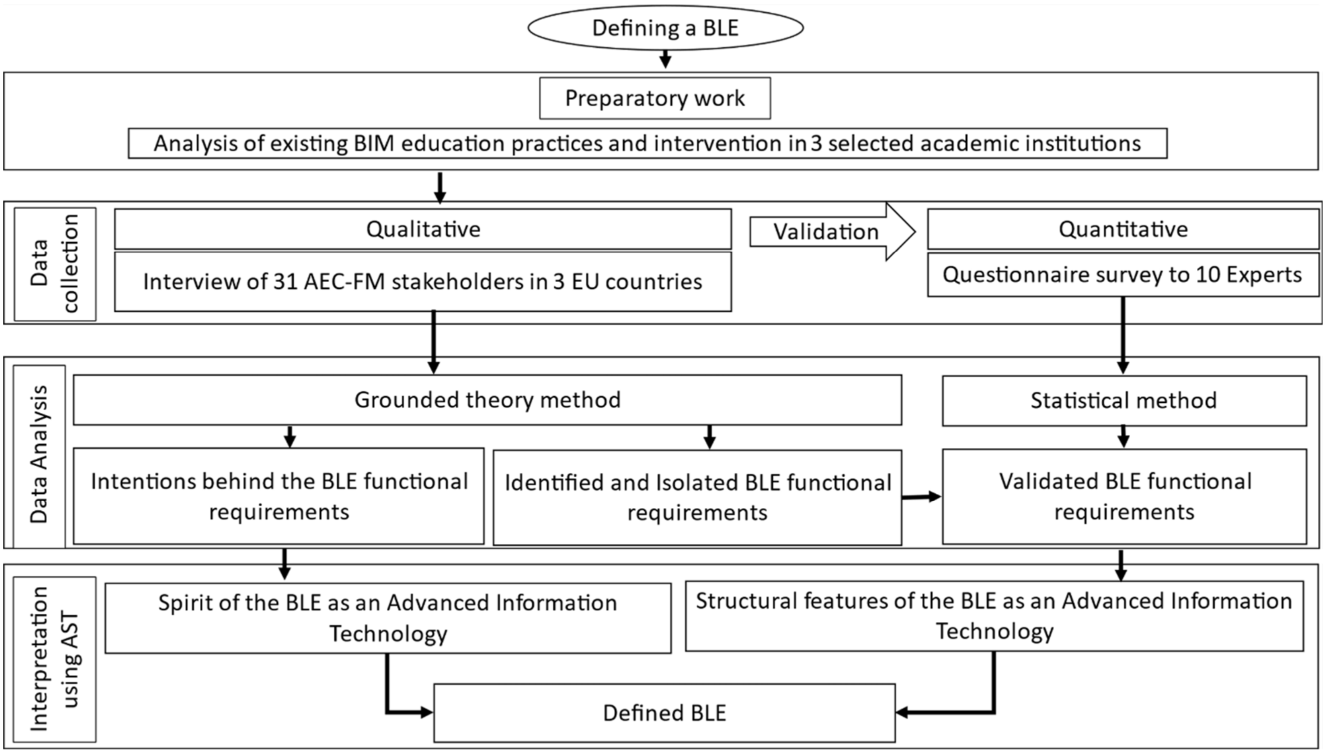

Figure 2. Research process adopted.

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).

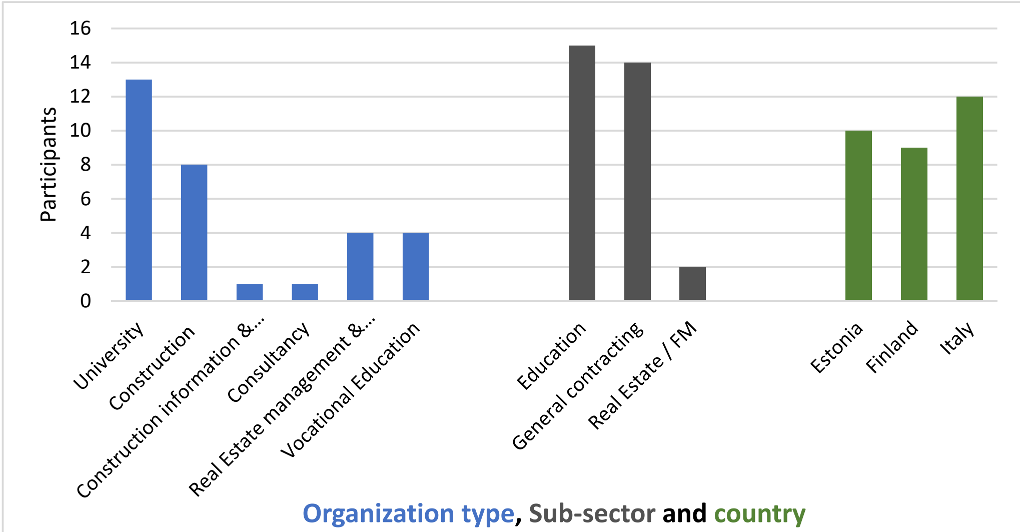

Figure 3. Characteristics of participants with respect to organization type, sub-sector, and location.

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.

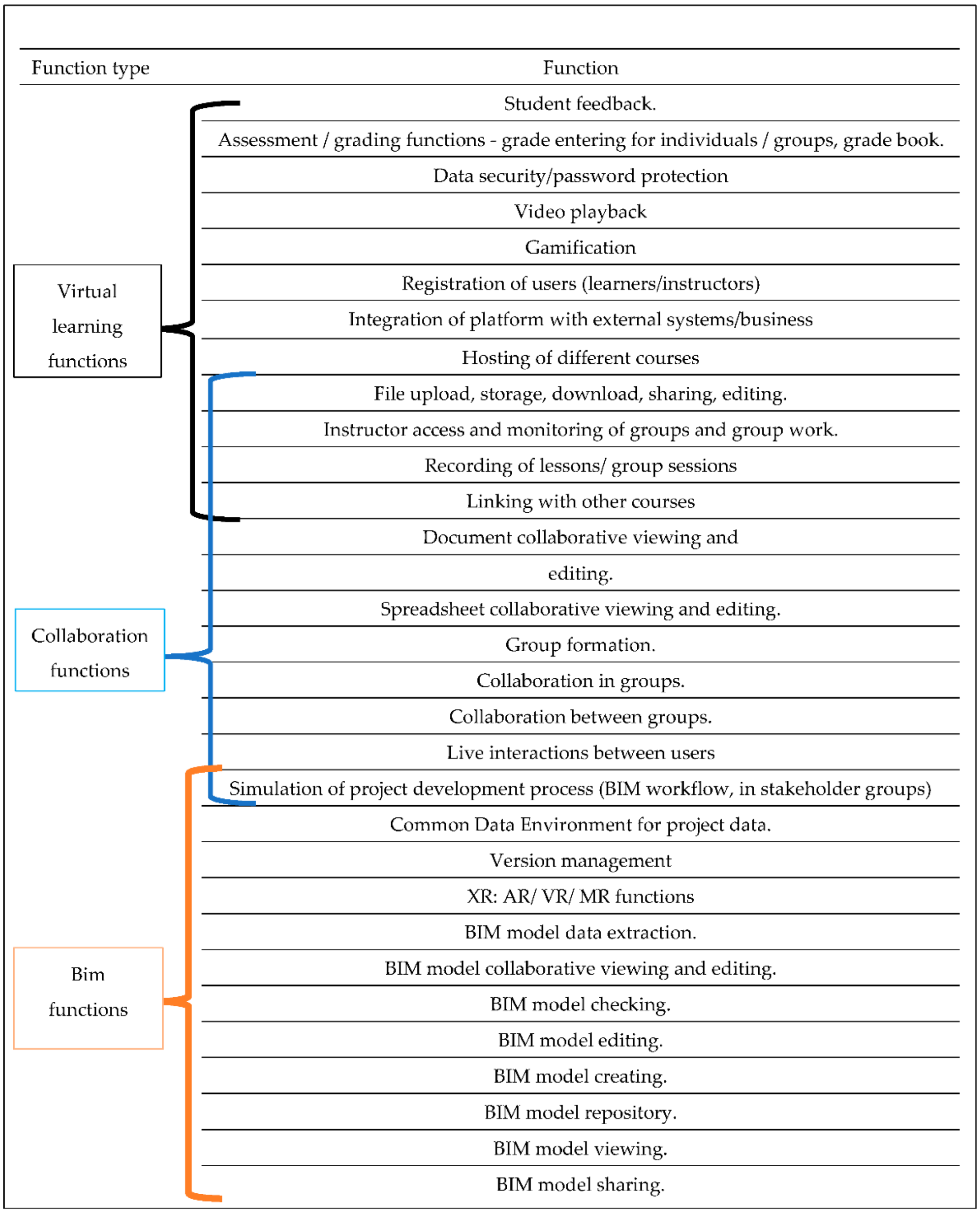

Figure 4. Matrix of functional categorization of BLE features.

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.

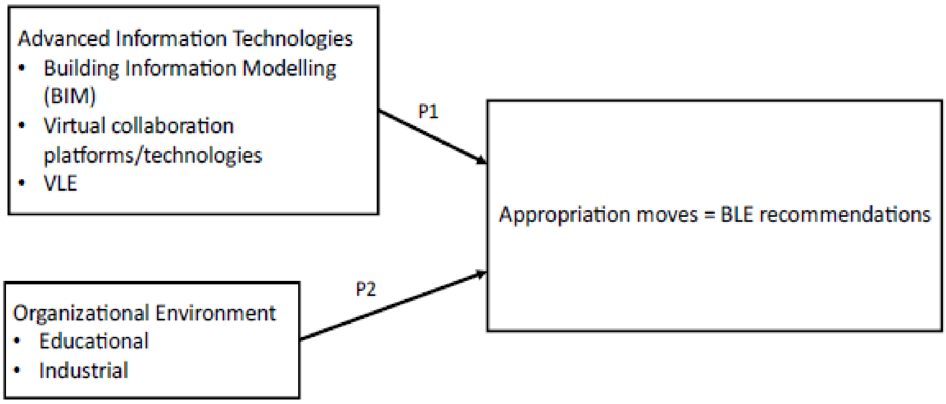

Figure 5. Concept map showing the sources of structures in a BLE.

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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