A framework for Building Information Modeling implementation in engineering education

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Abstract

Universities are facing many challenges to their efforts to introduce Building Information Modeling (BIM) in engineering education. Many research efforts have been dedicated to the subject and addressed some specific aspects of the issue. Thus, there is no comprehensive framework to provide decision makers with practical and neutral guidelines. The framework proposed in this paper identifies the main challenges to address. A case study from a Canadian engineering school is used to evaluate and to validate the proposed framework, and to illustrate the challenges. The strategy of integrating BIM in engineering education should be based on the specific skills the students are expected to acquire. It is then possible to define the appropriate teaching approaches. An effective implementation strategy should be gradual in order to progressively raise community awareness, learn from mistakes and identify best practices. A particular emphasis should be placed on the needs of the local industry.

Keywords:

BIM; Engineering Education Research; Theoretical framework, Curriculum Development; Decision-making

1. Introduction

Building Information Modeling (BIM) is a disruptive approach which is dramatically changing the way construction projects are designed, managed and built. It uses a multidisciplinary object-oriented 3D model of the constructed facility in order to improve and to document its design and to simulate different aspects of its construction or its operation. Many research works (Eastman et al. 2011; Kreider & Messner 2013) have addressed BIMs potential to improve productivity in the industry. Traditionally, the construction sector is characterised by a low rate of productivity compared to other similar industries (automotive, aerospace, etc.) (Egan 1998; Haas et al. 1999; Pekuri et al. 2011). While many studies have shown the added value of BIM, Architecture, Engineering and Construction (AEC) firms are facing many challenges in their BIM implementation experience. Among the main challenges (mostly related to technologies, organisation and policies) is the lack of well-trained personnel that firms can rely on when implementing BIM (Sacks & Barak 2010). The truth is that the crisis in training is not really new in the construction industry (Egan 1998), and the face of the engineering education is being changed by the combination of two related movements: the technological movement (to overcome the related information flow and the physical barriers) and the ideological movement to remove the man-made and artificial barriers (Lowell Bishop & Verleger 2013).

With the rise of the BIM approach in the construction industry, a particular emphasis is being made on the technological movement, and the question of training and education has taken a new level of importance in the sector. Indeed, beyond the usual training needs, new needs arise with the arrival of this new technological approach and new operational roles in construction projects. Barison and Santos

(2010a) inventoried some of these new roles and responsibilities. Only a few years ago, these roles were very software-oriented, but they are gradually changing towards more emphasis on management needs (Boton & Forgues 2015). An interesting outcome from the work of Barison and Santos (2010a) is that these roles are not simply related to technical competencies, but they also involve integration and leadership-related aspects. For example, "the main function of a BIM Manager is to manage people in the implementation and/or maintenance of the BIM process" and a BIM facilitator has the responsibility of assisting other professionals and usually is charged with improving the communication between the engineer and the foremen or contractors (Barison & Santos 2010a).

As shown by the recent BIM Academic Symposium series (Issa 2016), for a successful BIM introduction in their curricula, universities are facing major dilemmas. One important dilemma is related to the fact that curricula in the AEC sector are based on today's practices, but "AEC education should be adapting, and structured to evolve to address present and future challenges" (Becerik-Gerber et al. 2011). While practices have evolved towards more integration in the aerospace and automotive industries, the construction sector continues to have very low rates of IT adoption (Attar & Sweis 2010; Jupp & Nepal 2014; Nikas et al. 2007). The processes are therefore very similar to those of the past. As it is based on these processes, AEC curricula seem to be looking backwards instead of looking forward. Moreover, people who are responsible for such curricula in the universities are generally not aware of what BIM is and the challenges it brings to the industry. It is usually considered simplistically that BIM is in contradiction with current practices, and deciding to implement it in curricula is equated to choosing between the present and a possible future. The most current decision consists of splitting the difference and to propose some isolated BIM courses. Another dilemma then appears: educating software specialists with advanced technological skills, or forming managers with procedural skills and less technical competencies. Indeed, due to the large variety of roles and responsibilities BIM specialists must be prepared to deal with (Barison & Santos 2010a) and the necessary balance between technology, organisation and processes (Boton & Forgues 2015), it is challenging for universities to find a middle ground.

Although many research works have been dedicated to proposing a framework for different aspects of BIM implementation in education (Kocaturk & Kiviniemi 2013; Macdonald 2011; Sacks & Pikas 2013; Shelbourn et al. 2016; Succar & Sher 2013), no comprehensive framework has been proposed to support BIM introduction in engineering universities, nor to assist researchers in their comparison work. This paper presents a framework of BIM introduction in engineering education. It first discusses the existing strategies and the skills expected from BIM in education. It then proposes a framework with its main constituting elements. Based on the case of an engineering university in Canada, it finally shows how such framework can be used to advance both education and research in BIM.

2. Which Approaches for which Skills in AEC?

2.1 Teaching approaches in engineering

The lecturer-centred “chalk and talk” format has remained the dominant pedagogy approach in engineering teaching, and many accreditation criteria are based on “what is being taught” (Mills & Treagust 2003). However, many criticisms have been raised about the effectiveness of such an approach (Char & Collier 2015) including the lack of integration with industrial practices, the lack of teamwork and communication skills necessary for graduates, the insufficient design experience provided to students, the low level of awareness of the reality of modern engineering practices, the inadequate relation between theory and practice, and the use of outdated learning strategies as identified by Mills and Treagust (2003). Moreover, according to Lowell Bishop and Verleger (2013), it is generally difficult to teach and assess many of the criterion required by the accreditation organizations such as the Accreditation Board for Engineering and Technology (ABET) or the Canadian Engineering Accreditation Board (CEAB) with "informative lectures and closed form questions".

To overcome these criticisms and limits, new approaches have emerged during the last decades, with a student-centred approach and more emphasis on "what is being learned". One of the most well-known is Project-Based Learning (PBL). PBL is defined as "a comprehensive approach to classroom teaching and learning that is designed to engage students in investigating authentic problems" (Blumenfeld et al. 1991). It encompasses subject courses and project-organised curriculum (throughout a curriculum), and should be differentiated from project-oriented studies (in individual courses) (Heitmann 1996). A variant of PBL is Problem-Based Learning. Very similar to Project-Based Learning, it originated at McMaster University in Canada and has been extensively used in medical education (Kilroy 2003). Problem-based learning uses a set of problems as the starting point of the process of learning, and skills training and lectures are designed to support the process (Perrenet et al. 2000). Perrenet et al. (2000) has explored how suitable this approach is for engineering education, and concluded that it can be a successful approach for engineering teaching. According to De Graaff (2013), different types of PBL exist, and in order to choose the most appropriate one and fully take advantage of it, it is important to clearly identify "the way the problem is presented to the students, the role of the teachers, the timespan allotted for working on the problem, etc." It is also crucial to determine if PBL "is concentrated in isolated projects or it is considered a leading principle throughout the curriculum" (Graaff 2013).

Another interesting approach is the Flipped (or Inverted) Classroom. In this approach, instead of giving lectures inside the class and practice exercises and problem-solving outside the class, "the events that have traditionally taken place inside the classroom now take place outside the classroom and vice-versa" (Lage et al. 2000). Practice exercises and problem-solving are then used inside the classroom and video lectures are proposed outside the class (Lowell Bishop & Verleger 2013).

Even though the discussion proposed by Mills and Treagust (2003) showed that the best approach to teach engineering should be a mix of "chalk and talk" and Project-Based Learning and Problem-Based Learning, it is still not clear for academia actors what is the best strategy and timing for introducing technology-based innovation such as BIM in their curricula. In addition to the implementation strategies, the question of the competencies students are supposed to acquire with regard to industry's needs is critical and constantly evolving.

2.2 What skills are we expecting students to learn from BIM?

Whatever these strategies are, the choice depends primarily on the need for training in the industry. Thus, the integration of new technologies in construction education should preliminarily be discussed among professional institutions (Horne 2006). In its report on Integrated Practice dedicated to integrative education, the American Society of Architects (AIA) identified BIM as "a catalyst to rethink architectural education" (Cheng 2006). The idea is to anticipate new demands while keeping core design skills which will remain of extreme importance. In this context, Barison and Santos (2010b) proposes three levels of BIM specialists to be trained: introductory (BIM modeller), intermediary (BIM analyst) and advanced (BIM manager). While this approach is clearly interesting to complement the strategies proposed by Horne (2006), it does not seem sufficient to cover the question of skills raised by the AIA's report. Indeed, the proposal seems too generic, lacking the appropriate level of detail required to serve as a helpful guideline for universities.

In fact, "the short-term goals for the course can be stated in terms of the set of skills to be acquired by students, for engineering communication in general and for BIM in particular" (Sacks & Barak 2010). Based on a BIM course at Technion University, Sacks and Barak (2010) identified some specific skills that can be expected of students: modeling the structure of a building with relevant object selection, associating objects with the correct semantic relationships, production of views from the manipulation of the model, structural drawing production with all the required information, and model-based quantity take-off. Such skills are clearer and more in line with the generic skills expected from an engineering curriculum. Furthermore, while aiming to provide a comprehensive education, engineering bachelor degree programs are commonly facing the challenge related to the maximum number of credits (Sacks & Barak 2010). Introducing a new course is thus a complicated affair. The first approach to overcome such a situation is to propose optional courses while proposing new dedicated programs at the postgraduate level. However, in order to meet the industry's needs (see section 3.4.3) and to ensure a significant impact, it is imperative to find an intermediary way to progressively introduce the different aspects of BIM education by overcoming the main challenges they raise.

2.3 Main Challenges of BIM Integration in Engineering Education

With an architecture-oriented perspective, Kocaturk and Kiviniemi (2013) proposed a discussion of the challenges related to the integration of BIM in education. The discussion is about two major aspects to address: modeling and representation, and collaborative work. They identified some critical cognitive and pedagogical issues to address including new technology and working methods, and individual and distributed cognition. They also noted that BIM education should address the new services and specialisation currently high in demand in the industry, and the importance for education to not only follow BIM, but to "become one of the driving forces in this industry transformation" (Kocaturk & Kiviniemi 2013). Becerik-Gerber et al. (2011) identified the limiting factors for not incorporating BIM into education programs. It appeared that the primary reason was the lack of people qualified to teach BIM (55% of surveyed programs). The other reasons are related to the lack of adequate resources to make the change (45%), the lack of appropriate space (36%), the fact that BIM is not an accreditation criterion (27%), etc.

Based on multiple research efforts (Barison & Santos 2010b; Goedert et al. 2011; Horne 2006; Kocaturk & Kiviniemi 2013; Sacks & Pikas 2013), we can summarize the challenges related to BIM education into seven main groups: the skills to acquire, the teaching approach, the evaluation methods, the technological environment, the industrial partnerships, the implementation approach and the timing. Some frameworks have been proposed in the literature. Each framework addresses some of these challenges, as shown in Table 1. In 2010, Barison and Santos (2010b) proposed a review of the existing strategies for planning a BIM curriculum. Using a Content Analysis methodology, they analysed the reported experience of the leading schools in BIM education. The framework they propose categorizes BIM specialists, prerequisites, BIM course categories and each project's BIM model into one of three levels: introductory, intermediary and advanced. They also briefly discussed the schools' teaching and evaluation methods. Assuming that "BIM is not just a new topic to be added to the existing curriculum", the framework presented by Kocaturk and Kiviniemi

(2013) proposes a progressive and gradual integration of BIM, but is dedicated more to architecture schools. Their framework focuses on the model and the representation, and also on the tools, the issues and the methods for efficient collaborative work. The technological environment, the timing and the cognitive implications are particularly well discussed. Macdonald (2011) proposed the “IMAC” framework, dedicated to collaborative BIM education. The aim is to assist BIM teachers to benchmark their curricula and to find the best strategies to improve them. The IMAC framework consists of four stages corresponding to the identified levels of achievement in the use of BIM models. Macdonald’s framework proposes a mapping exercise of the existing courses in Australian universities, focusing on building technology, environment, management, IT and specialised aspects. Sacks and Pikas (2013) propose an elicitation of the requirements of BIM education requirements and the levels of achievement and topics that are necessary for each degree program. A total of 39 topics were identified and regrouped in three main topics. Succar and Sher (2013) tried to inventory the core BIM competencies that universities and engineering schools must teach in order to cover the needs of the industry. Thus, based on the same Australian context, they proposed a BIM education framework including a conceptual workflow with the identification, classification and aggregation of the different items of BIM competency. The framework proposed by Goedert et al. (2011) focuses on virtual construction education and game-based simulation. It applies automated inference principles as a means to provide situation-specific simulations. A residential project was used as proof of concept. Kim (2012) introduced an innovative and integrated approach for teaching BIM. That approach combines 2D drawings and 3D BIM models to present and understand the construction details, as well as for quantity take-off. The paper illustrates how BIM can be an effective “integrated learning tool in construction education.” Very recently, Shelbourn et al. (2016) developed a BIM education framework. Their proposed framework is intended to be international and is dedicated to the higher education sector. It is an improvement of the "IMAC" framework (Macdonald 2011) with a case study showing how it can be used.

	SKILLS	TEACHING APPROACH			IMPLEMENTATION STRATEGY			
References	Skills to acquire	Teaching methods	Evaluation methods	Technological environment	Industrial partnerships	Implementation approach	Timing	**Formalized proposals**
(Barison & Santos, 2010b)	X	X	X					
(Kocaturk & Kiviniemi, 2013)	X			X			X	
(Macdonald, 2011)		X	X					X
(Sacks & Pikas, 2013)	X			X				
(Succar & Sher, 2013)	X				X	X		X
(Goedert et al., 2011)				X				X
(Kim, 2012)	X		X				X	X
(Shelbourn et al., 2016)			X	X			X	

Table 1. A comparison of existing frameworks for incorporating BIM in curriculum

As can be seen from Table 1 and from the overview presented above, none of these frameworks covers all the required aspects. However, it is important both for universities and researchers to provide a comprehensive framework that can enable them to incorporate BIM in education as well as to evaluate and compare the existing BIM programs.

3 A Framework for BIM Introduction in Engineering Education

3.1 Overview of the framework

The proposed framework considers the main challenges identified above. It is composed of three main dimensions representing the three main aspects to consider when introducing BIM in university curriculums: the skills to be acquired by students, the teaching approach to adopt and the implementation strategy. The main elements of the framework are depicted in Figure 1 and discussed in the following sections.

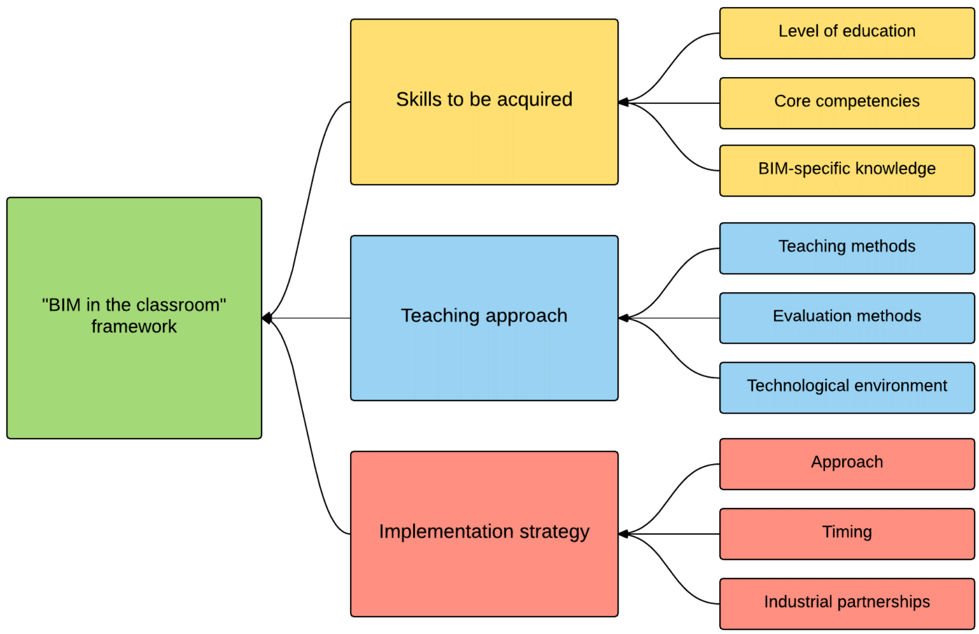

Figure 1: Main elements of the proposed framework

3.2 The skills to be acquired

The first element to consider when introducing BIM in AEC is the skills to be acquired by the students. In the proposed framework, the skills cover both the core competencies as developed in existing engineering competency models and the BIM-specific knowledge which encompasses the technologies, the processes and the policies related to BIM. The skills to be acquired also depend on the need for training in the industry, and for BIM introduction purposes, universities need to define the level of education, the core competencies needed, and the targeted BIM-specific knowledge.

3.2.1 The level of education

The level of education here is similar to the "level of a BIM course" introduced by Barison and Santos (2010b). It determines the level at which BIM is taught in a course or a curriculum and identifies three levels: introductory, intermediary and advanced. The introductory level corresponds to BIM modelers' training, while BIM analysts and BIM managers are trained respectively at the intermediary and advanced levels. They also proposed three BIM course categories for the three levels: "digital graphic representation", integrated design studio and interdisciplinary design studio. While this is a very interesting starting point, the proposal does not seem sufficient to provide a good understanding of what should be the content of each level. Moreover, these authors implicitly suggest project-based learning as an appropriate strategy for all three levels. Finally, the BIM specialists to be formed at each level do not seem consistent according to the findings of the same authors about the role of BIM specialists (Barison & Santos 2010a). We will see in the next sections that defining the level of education and the types of specialists to be formed is more complex and should comprise an appropriate balance between modeling skills, management skills and theory/standards knowledge.

In this framework, we consider that the level of education is related to the academic level. Universities have to decide whether they will integrate BIM in bachelor or postgraduate degree programs, or both. The objective is not the same for each level. Based on the definition and the roles of the different BIM specialists identified by Barison and Santos (2010a), it seems consistent for universities to train BIM modelers, BIM facilitators and BIM software developers at the bachelor degree level. BIM managers, BIM analysts and BIM consultants can be trained at the master degree level.

Finally, Ph.D. and other doctorate and post-doctorate degrees would be the best programs to form BIM researchers or BIM-specialized consultants.

3.2.2 Core competencies

In Canada, the engineering programs' accreditation system introduced by the Canadian Engineering Accreditation Board (CEAB) uses 12 graduate attributes including Knowledgebase for engineering, problem analysis, investigation, design, use of engineering tools, individual and team work, communication skills, professionalism, impact of engineering on society and the environment, ethics and equity, economics and project management, life-long learning (Canadian Engineering Accreditation Board 2017). The recent engineering competency model proposed by the United States Department of Labor identifies different tiers of competency (Employment and Training Administration, 2015): personal effectiveness competencies (PEC), academic competencies (AC), workplace competencies (WPC), industry-wide technical competencies (IWTC), and Industry-sector technical competencies (ISTC). The first three competencies (PEC, AC, and WPC) are referred to as "foundational competencies". PEC refers to "soft skills", generally personal and learned at home, while AC are thinking styles and cognitive functions that are useful for all occupations and industries. WPC are related to self-management and interpersonal skills applicable to many industries and occupations. The fourth (IWTC) and the fifth (ISTC) competencies are industry-specific. IWTC cover the competencies that are useful for actors across the industry, while ISTC are specific to an industry-particular sector. BIM education should prioritize these last two competencies; depending on the level of education, the level of importance of BIM is not the same. Accordingly, its role in the core competencies will vary.

The bachelor degree level is where engineering core competencies are expected to be acquired, both foundational and industry-specific competencies. At this level, a particular emphasis should be placed on how BIM is taught as a support to industry practices. Each use of BIM should be carefully related to the traditional practices it is designed to improve. For example, 4D simulation should not be taught as a stand-alone course but as a part of a construction planning and scheduling course. In the same way, 5D costing applications should be integrated in budgeting and costing lessons in order to show the underlying links with the outcomes expected by industry practices such as quantity take-off, bill of quantities, invoices, etc. A list of BIM uses and their associated project phases has been proposed by Pennsylvania State University (Kreider & Messner 2013). The recurrent collaboration issues and how BIM can help in addressing them should also be taught to students, without going deeper in the understanding of complex BIM underlying theoretical concepts. At the master degree level, emphasis should be placed on stand-alone BIM modules, with particular attention to the interdisciplinary aspects of construction projects and recurrent collaboration issues. The aim is to deepen particular aspects of BIM, while also stimulating the interest of students in the search for sustainable solutions. The underlying theoretical concepts of BIM and the current technological barriers should be taught to student in order to provide them with a good understanding of the state of the art of the development of the BIM approach and the main issues in the industry.

It is important to note here that the universities cannot define the core competencies needed on their own. Indeed, advancements in construction processes are led by the industry, not the academia. Therefore, core competencies need to be set in close collaboration with industry. The necessary bi-directional interaction between the industry and universities is discussed below (section 3.4.3).

3.2.3 BIM-specific knowledge

Unlike Computer-Aided Design (CAD), BIM is considered as a disruptive technology (Eastman et al., 2011). Indeed, while CAD has merely reproduced on computers the traditional practices and accelerated their realization, BIM is supposed to change the paradigm of construction projects' organization. Therefore, if it is important to integrate BIM as a support of the core competencies identified above, it is also important to teach BIM-specific knowledge. These competencies can be categorized into three main groups: technology-related, process-related and policy-related competencies (Succar 2009). According to Succar (2009), technology encompasses BIM software, model servers, equipment and peripherals, database technologies, geographic information systems and other communication systems. The process-related competencies include the information exchange processes between the different project actors in order to build the BIM models or to extract and reuse the drawings', documents' or other components' information. The policies deal with regulations, guidelines and contractual arrangements, as well as building standards, educational programs and best practices (Succar 2009). From a technological point of view, Sacks and Barak (2010) offer a list of BIM-specific knowledge expected from a bachelor degree BIM course, including the ability to: accurately model the structure of a building and to select the adapted objects; create the appropriate semantic connections and other relationships between the model's objects; generate different views for different purposes by manipulating the model; extract drawing with all the required information; and to extract a quantity take-off and other documents from the model.

In the proposed framework, we consider three main BIM-specific knowledge: modeling skills, management skills and theory/standards knowledge. Modeling skills are technology-related competencies, management skills are linked to process-related competencies, and theory/standards skills are related to policies. These skills are not expected in the same proportion for all BIM specialists. Based on the BIM specialists' roles identified by Barison and Santos (2010a), Figure 2 proposes a distribution of the weight of the different BIM-specific knowledge expected for the different roles.

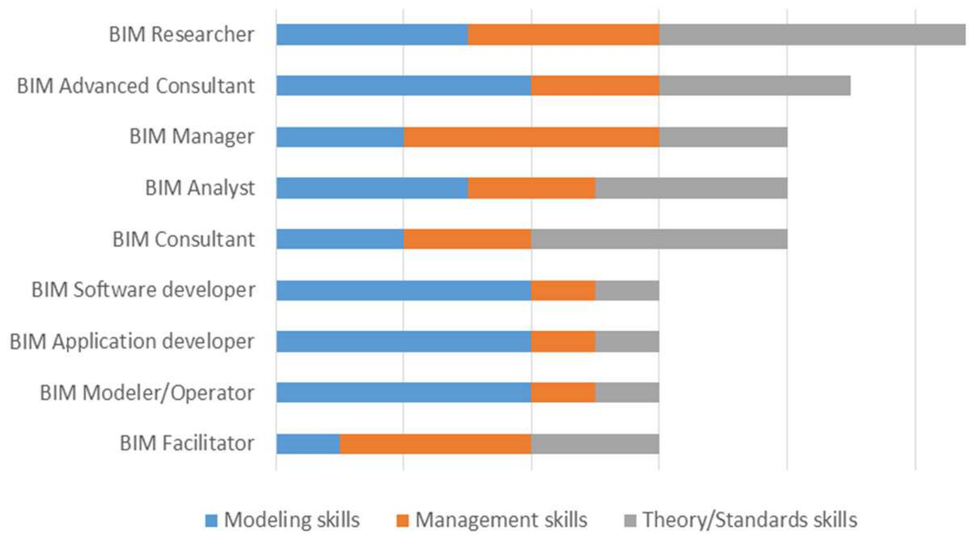

Figure 2: A distribution of the weights of BIM-specific knowledge expected for different BIM specialists

3.3 The teaching approach

The teaching approach includes the teaching methods, the evaluation methods and the technological environment.

3.3.1 The teaching methods

The teaching method is critical for the success of BIM education. To ensure the effectiveness of BIM education, it is important to find a good balance between teacher-centred and student-centred learning approaches. This means that interactive classroom activities should be mixed with the classic "chalk and talk" approach. For example, at the bachelor degree level, "chalk and talk" can remain preponderant, but only with a good dose of Project-Based Learning methods. These activities can encompass case studies, modeling exercises, and thematic discussions. According to Bishop & Verleger (2013), PBL methods can be very effective at achieving the ABET criteria, but flipped classrooms should also be encouraged to ensure a good balance between theory and practice. To successfully introduce PBL, it can be very helpful to follow the ten checkpoints proposed by De Graaff (2013). These checkpoints include starting the learning process with a problem, which can take the form of a project, a phenomenon or a case. Skills and knowledge from different disciplines should be integrated into the problem. This can be especially useful for illustrating the interoperability issues and the need for collaboration in BIM processes. Each student is encouraged to formulate his/her learning objectives and processes, but the collaboration of students regrouped in teams is also necessary. It is especially valuable for students to learn from their failures and utilize continuous feedback from the teacher to improve their learning experience.

In the case of BIM stand-alone courses, it is important to ensure that the teacher has BIM Teaching Knowledge (BTK). As shown in Figure 3, BTK is at the intersection of three interlocking knowledge areas: BIM software knowledge, BIM standards and policies knowledge, and pedagogical knowledge. According to the competencies expected by students from the course, priority should be put on BIM software and pedagogical knowledge or BIM standards and pedagogical knowledge.

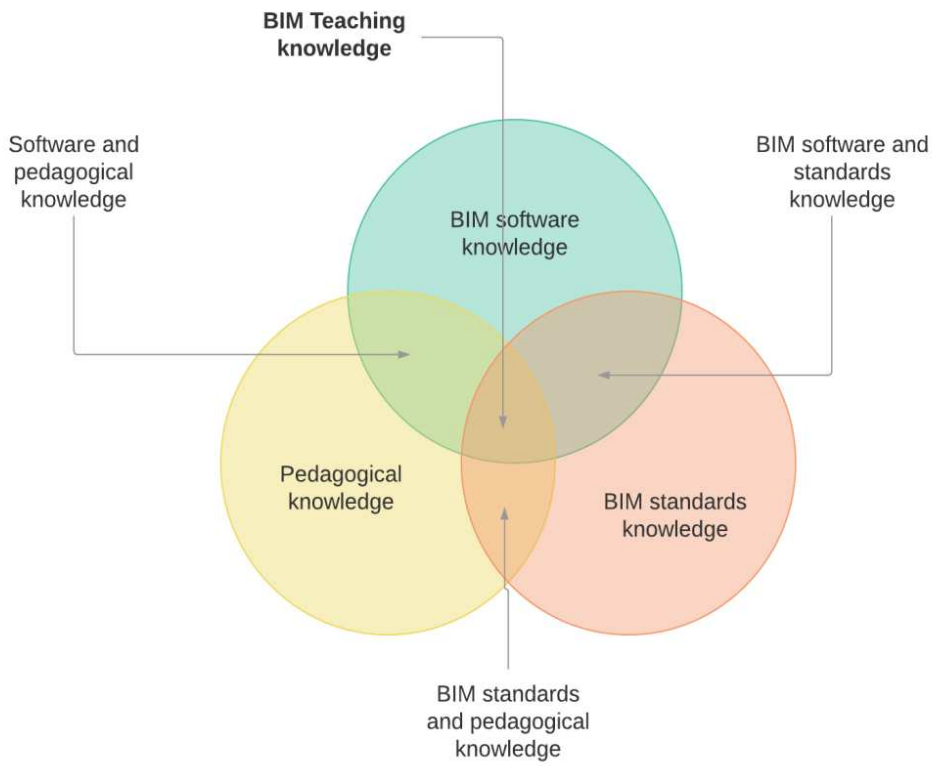

Figure 3: Venn diagram of BIM Teaching Knowledge

3.3.2 The evaluation methods

To assess students' learning, two main approaches are used: summative evaluation and formative evaluation (Bloom et al. 1971). In summative assessment, which generally takes place at the end of an instructional section (in the form of a final project, judgement or exam, with a high point value), the students' learning is evaluated in order to compare it to some defined standards. Among the existing methods for summative assessment, we can cite testing, observation report, students' interview or survey, multiple-choice questionnaire, and oral presentation or final project. Formative evaluation aims at providing some useful feedback in order to improve both the teaching and the learning processes.

The assessment procedures should be "designed to stimulate the learning" (Graaff 2013) while evaluating the skills gained by the students. But, evaluation is particularly challenging in BIM education, because unlike other subjects, it is not easy to test the competence gained by students with an exam in which software are operated (Sacks & Barak 2010). However, determining which skills have been acquired by students is crucial (Barison & Santos 2010b). Modeling exercises and tests could be complementary to the exam itself as a means to evaluate the level of learning (Barison & Santos 2010b; Sacks & Barak 2010). According to the main course objective (BIM technology or BIM management) and the number of students, appropriate evaluation methods should be used, as proposed on Figure 4. For example, an emphasis can be put on modeling exercises when BIM technology learning is the main aim and the number of students is not very high.

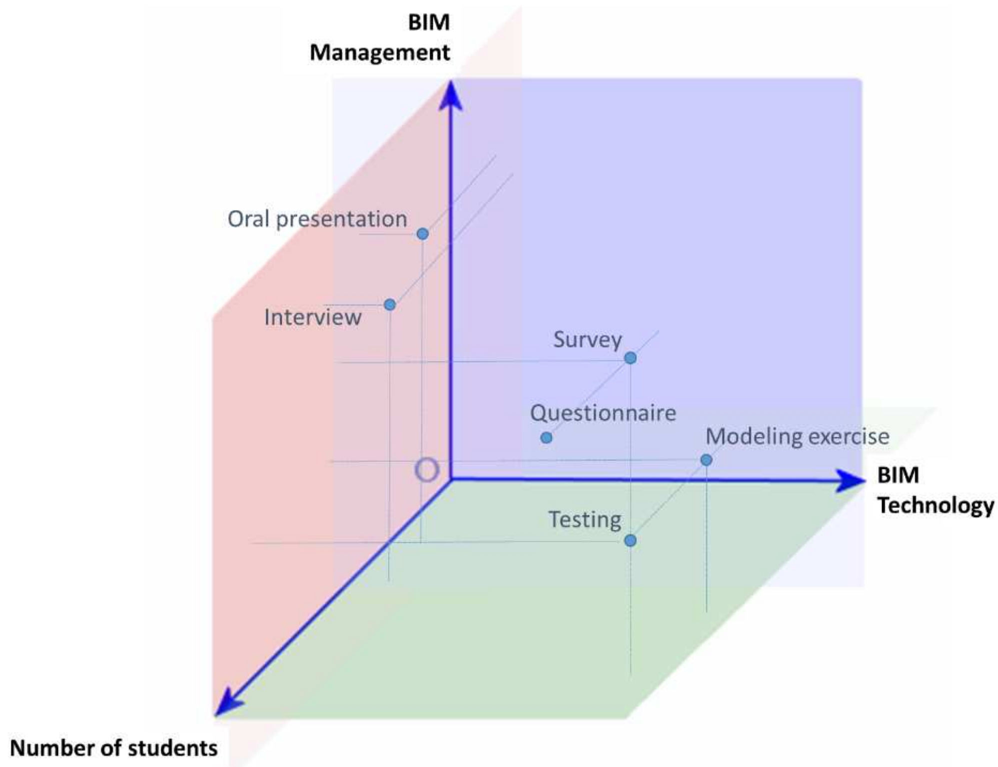

Figure 4: Evaluation methods according to the objective and the number of students

Because of the innovative nature of BIM courses, it is important to also use diagnostic assessment. The aim is to not only to evaluate the teaching, but to be able to continuously evaluate the teaching experience in order to improve it and to adapt it to current practices. Moreover, the results of such diagnostic assessment can give a good idea of the students' perception, which science teachers can use to inform their teaching (Treagust 1995).

3.3.3 The Technological Environment

While the technological environment is critical for the success of a BIM curriculum, it is not limited to mastering the current software. Indeed, as recently shown by Liu and Berumen, technology is rapidly evolving; throughout their careers as BIM professionals, students will have to adapt to new technologies (Liu & Berumen 2016), making “the ability to evaluate technologies, make wise decisions and choose the appropriate technology to use [is] more important than mastering the current software” (Liu & Berumen 2016). More emphasis should be placed on teaching the principles underlying the software, by comparing different solutions from different vendors and specialties, and by practicing the interoperability between them, based on real projects or realistic scenarios and examples.

A particular focus should be on open source technologies in order to contribute to the development of the OpenBIM initiative. It should be recalled that the BuidingSMART association and several CAD software vendors launched the OpenBIM initiative in 2012 as a way to increase the visibility of BIM and integrated process through more interoperability. Promoting OpenBIM and similar initiatives is important as it is a way for universities to maintain a neutral approach in the choice of the BIM software, and to encourage the use of neutral interoperability formats (such as IFC) in order to improve the collaboration practices in a sustainable way.

3.4 The Implementation Strategy

The implementation strategy is related to the implementation approach, the timing and the necessary industrial partnerships.

3.4.1 The Implementation Approach

In 2006, Horne identified three main approaches to introduce IT into the construction academic curriculum: modular, progression and integration.

In a modular approach, a stand-alone module is incorporated into the program (Horne 2006). This strategy provides a good entry point for universities, who can provide a better awareness of a promising technology without taking much risk, while assessing the real potential, stability and potential it has for the industry. A typical example of this strategy is the seminal example of Stanford in 1993 with the course Computer Integrated Architecture, Engineering and Construction (Fruchter 1999). Another example is reported by Kubicki and Boton (2011) on the use of 4D simulation to teach the structural principles of high-rise buildings at the University of Liège.

The progression strategy selects and introduces appropriate new software into the different years of the curriculum. The advantage of this strategy is to gradually integrate IT with a curriculum while ensuring that the students assimilate the underlying and related concepts so as to easily associate the theory with IT practice. To illustrate this approach, Horne (2006) gave the example of the School of the Built Environment at Northumbria University, where 2D CAD, a BIM tool (Revit) and its uses (design, energy analysis, costing, etc.) are gradually incorporated from year 1 to year 4. Note that year 3 is spent in industry in order to experience industry practices and challenges.

The integration strategy usually comes after the two previous ones and inserts complementary elements of IT throughout the university modules. In this approach, elements of the BIM approach are introduced into a large proportion of modules throughout the curriculum. Such an approach should be the ultimate goal of incorporating BIM in the curriculum. BIM can then be used as an axis with which to integrate the academic curriculum. It provides an interesting way to facilitate academic integration (Horne 2006), as suggested by the AIA's report on integrative education (Cheng 2006). It is also a good way to make the link between current practices and innovative uses. The BIM education approach used by Pennsylvania State University illustrates this integration approach (Messner n.d.).

3.4.2 Timing

Timing is a crucial aspect in the integration of BIM in education. An ideal integration should be gradual and make a progressive and complementary use of the various implementation strategies outlined above. We propose to start with standalone modules, so as to develop awareness, and then continue with a progression approach, before reaching a full integration. This progressive strategy allows the possible feedback that may come from students or other stakeholders from the education system to be acquired and incorporated. Among other benefits, it is important to progressively obtain and maintain the support of third parties responsible for the management of education systems.

A phased integration also helps to gradually develop common responses to important issues raised recently by Faust (2016), namely:

- Is BIM really sustainable or just a "fashion effect"?
- Is there a need for BIM in the local market?
- What are the specific needs of the local industry?
- Where an undergraduate program can encompass a BIM curriculum?

Providing answers to these questions makes it possible to establish a good policy of continuous improvement, as well as an effective and long-term collaboration with industry to better meet their needs.

3.4.3 The Industrial Partnership

As stated by Kocaturk and Kiviniemi (2013), there is an increasingly high demand for new specialisations related to BIM in the construction industry. Because "one size does not fit all" (Kocaturk & Kiviniemi 2013), it is important to work closely with industry in order to understand its particular needs. It is then possible to ensure that the BIM program is really adapted to these needs. In general, partnerships between universities and architecture, and engineering and construction (AEC) firms can benefit both parties. Indeed, the firms can provide universities with a good understanding of their needs as well as identifying research issues, funding opportunities, case studies, job opportunities and even some experienced lecturers. In return, the industry can take advantage of the high-qualified staff resulting from the education programs, the trainees, the technological watch, the research and development (R&D) resources from the universities (Figure 5). An example of industry/academia partnership is described by Succar and Sher (Succar & Sher 2013). Moreover, based on the study of the Irish BIM education context, Hore et al. (2016) have recently demonstrated the benefits of a good collaboration between education institutions.

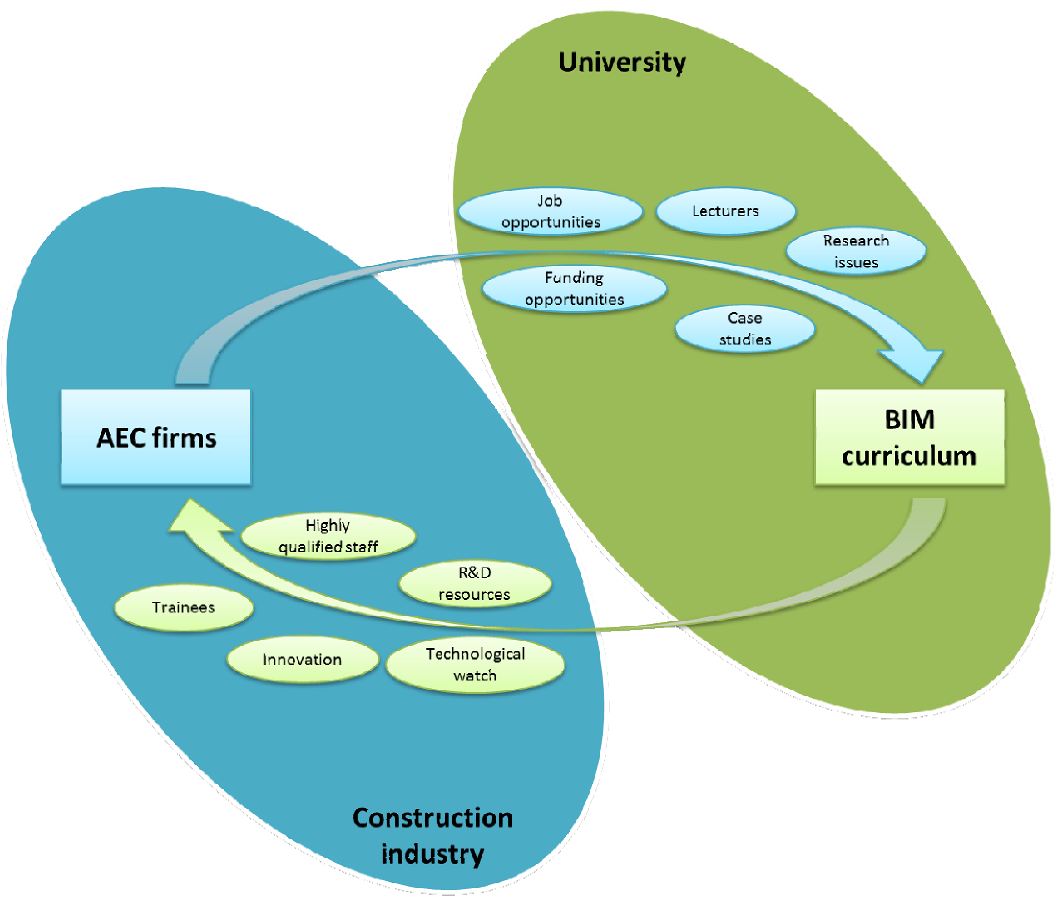

Figure 5: Bi-directional interaction between industry and university

4. Evaluation and validation of the proposed framework

The method used for the development of the proposed framework is inspired by Design Science approach (March & Smith 1995; Hevner et al. 2004) of which evaluation is a fundamental aspect (Pries-Heje et al. 2008). It is important to evaluate how the proposed framework is what it needs to be, and to improve it in order to adapt it to the real needs of the users. Two evaluation perspectives are generally used in Design Science Research to evaluate proposals: *ex ante* evaluation and *ex post* evaluation. While *ex ante* perspective "provides theoretical models to evaluate a proposal without actually implementing the system" (Boton et al. 2013), in ex post perspective, the proposals are evaluated after implementation.

In the research presented in this paper, an *ex post* perspective has been used to evaluate the proposed framework. It took the form of a case study on a Canadian engineering university, presented below. According to Gerring (2004), a case study is "an intensive study of a single unit for the purpose of understanding a larger class of (similar) units". This approach is distinguished from other methods by its reliance "on co-variation demonstrated by a single unit and its attempt, at the same time, to illuminate features of a broader set of units" (Gerring 2004). One of the most practical results of case studies is their use in forming descriptive inferences (Gerring 2004). The case study might be descriptive, explanatory or exploratory (Yin 2013). The case study method can use both quantitative and qualitative evidence. This information can come from observations, verbal records, andieldwork, with multiple data collection methods including ethnographies, participant-observation, etc. (Yin 1981).

The objective of the case study presented in the next section is to evaluate the proposed framework by 1) illustrating the main challenges raised with a concrete case, and 2) providing validation elements to iteratively improve, consolidate and validate the proposed framework. The framework presented above is the final version, improved after multiple iterations based on the progressive of the case study.

5. Case Study based on a Canadian Engineering University: the ETS-Montreal Experience

In this section, we present the three steps followed for incorporating BIM in the curriculum at ETS-Montréal. The context and the approach steps are introduced and discussed according to the proposed framework.

5.1 The Context

ETS-Montreal is a Canadian academic institution with an applied engineering-centred mission. To this end, it maintains a close relationship with companies and engineering organisations to ensure that the given education corresponds to the real needs. ETS-Montreal trains engineers in five major business sectors: environment and construction, aerospace and land transportation, energy, health technology, information and communication technologies.

The construction engineering department is dedicated to the training of highly qualified personnel according to the needs of the Quebec (and more generally, Canadian) local market. Thus, an important link with the various components of the Canadian construction industry is established and regularly maintained. This link includes defining and conducting research and development projects related to the issues encountered by the industry. Regarding the scientific research, the integration and teaching of information technology is one of the activities of a research lab and an industrial chair.

In the following section, the 3-step approach used for BIM teaching at ETS Montreal is discussed according to the proposed framework.

5.2 The Skills to be Acquired

The skills to be acquired are the main important starting point for BIM curriculum development. In the light of the framework presented above, the level of education, the core competencies and the BIM-specific knowledge related to the ETS-Montreal experience are discussed.

5.2.1 Level of Education

From the Canadian perspective, there are three levels of BIM education: at college (or CEGEP in Quebec) for the training of technicians or technologists, where BIM tools are learned for 3D design; in a University bachelor degree program where students are trained on working with multidisciplinary design-build collaborative BIM; and in University's master degree programs where students are trained to be change agents, highly qualified staff able to implement BIM technologies, and to manage BIM projects.

At ETS-Montreal, the first BIM lessons were not dedicated to any specific level. In order to ensure both the end user and the client participation, practitioners from the construction industry as well as ETS-Montreal's administrative and student sectors were invited to attend the presentations and to provide their feedback. The course consisted of a 'Design lab' experiment, reported by Forgues et al. (2011). It was the entry point of BIM education at ETS-Montreal and was conducted jointly by ETS-Montreal and McGill University through two multidisciplinary courses offered in 2009 and 2011.

The second step, consisting of a standalone regular BIM course, was introduced at the master degree level. This intensive course is the first regular one on this topic in

Quebec at the university level. It aims at introducing students to the BIM processes, the use of leading software associated with BIM, and the planning and monitoring of virtual models production. The course focuses on practical modeling work, and thus it is mainly given in an IT laboratory.

Based on the success of the standalone regular BIM module and in response to increasing requests from the industry, a dedicated graduate short program has been developed. This program was designed as an additional training which should enable engineers or professionals to quickly acquire a good knowledge of BIM, thereby training the professionals required for BIM implementation in construction firms and projects.

5.2.2 Core Competencies and BIM-specific Knowledge

As explained above, the introduction of BIM education at ETS-Montreal followed three gradual steps. Due to its objective, the first step (the 'design lab' experiment) was not clearly or explicitly linked to the core competencies, as it was not dedicated to any specific level of education. However, a particular emphasis was put on demonstrating the "new skills and technological competencies […] required to address the upcoming challenges" (Forgues et al. 2011). The main aim was to show how BIM could efficiently support problem-solving and to provide "knowledge on how and when" to use these new skills efficiently (Forgues et al. 2011).

The second step (the standalone regular BIM course at the master degree level) aimed to teach students the main concepts and principles for the implementation of BIM. Upon their completion of this course, students should be able to: understand and manage the different uses of BIM and associated technologies; create BIM models for various construction disciplines (architectural, structural, MEP) and integrate them into a federated model; understand interoperability issues and how to transfer data from

BIM software to another one; understand the existing formalisms and tools for the representation of the workflow and the data flow required in a BIM project; define a consistent and efficient strategy to implement BIM; and understand the impact of BIM on the construction industry throughout the life cycle of a building or a facility. The BIM-specific knowledge is thus clearly developed, but not directly related to the core competencies. The main reason for this generalisation is that it is a standalone course which was not really integrated into a complete engineering curriculum.

In the third step (the dedicated short program), the BIM knowledge is more anchored in the core competencies. This more integrated program aims to improve knowledge regarding the planning, execution, monitoring and management of BIM projects, relying on advanced techniques in project delivery information flow management. More specifically, this program allows students to understand the impact of information technologies and integrated approaches on industry practices and the concepts of BIM organizational maturity; to define the BIM uses applicable to a project, to define workflows and information flows related to these uses, to develop, implement and manage a BIM management plan and to control the production and the coordination of digital models; to become familiar with the different types of BIM platforms and the related issues of interoperability and different exchange protocols for design and manufacture; as well as to choose the procurement strategies and organization of work and establish metrics to measure performance for the purpose of continuous improvement.

The short graduate program consists of 6 modules including a seminar on construction management; a module on information technology in construction, an introduction to Building Information Modeling; a module dedicated to BIM project management and monitoring; a module on construction phase planning using 4D simulation and cost estimating using 5D modeling; and a module on BIM-based energy simulation and analysis.

5.3 The Teaching Approach

5.3.1 Teaching Methods and the Technological Environment

In the first step, undergraduate students were organised into five teams with independent workspaces that included electronic devices, a personal computer, a discussion board, a printer, a projector, and an Internet connection. Each student also had their own laptop. Over three two-day intensive sessions, the students' design and modeling skills were complemented with BIM information and dedicated software capsules, including *Design Builder, Ecotect Analysis and Revit Architecture*.

The standalone regular BIM course at the master degree level (step 2) was divided into three sections: introduction of the basics of BIM and architectural design, structural design and construction, and collaboration and specific applications for coordination and analysis. It includes required readings that students must have done before each intensive session, making it possible to focus on the practical aspects of the teaching for an effective Project-Based Learning approach. A number of software packages are learned, including *Autodesk Revit, Design Review, Tekla Structure, Tekla BIMsight,* and *Autodesk Navisworks*. Classes are taught in an IT laboratory by BIM-specialized industry professionals. The maximum number of students accepted into the course is limited to 30 students.

In the third step, the dedicated short program was designed as a as supplemental training to allow engineers or professionals to quickly acquire a good knowledge of BIM and to provide the efficient professionals necessary for BIM implementation in construction firms and projects. The structure and the methods used in each module are specific to the peculiarities of the module but are inspired by those used in the standalone course which became a part of the program.

5.3.2 Evaluation Methods

In the first step, students are invited to work in four groups. Each group chooses a common project that the members will work on. They then have to design and develop their proposal during the integrated sessions of design *charrettes*. The teams are invited at the end of each 2-day session to present the result of their iterations and to discuss them in terms of financial, sustainability and technical feasibility criteria. Each presentation is followed by constructive feedback from the other professionals.

In the standalone regular BIM course master degree program, students are invited to complete a session work that integrates the knowledge they have acquired. This work takes the form of a construction project for which students, working in pairs, must gradually develop architectural, structural and coordination models. Quizzes are designed to assess students' individual understanding of the required readings. An individual final exam is also proposed in order to assess the students' overall understanding and to evaluate their perception of BIM uses according to their initial expectations.

Similar evaluation methods are planned to be used in the different modules of the dedicated short program.

5.4 The Implementation Strategy

5.4.1 Approach and Timing

As seen above, the introduction of BIM at ETS-Montreal followed a gradual 3-step approach: a first 'design lab' experiment at the undergraduate level from 2009 to 2011, a standalone regular module at the master degree level to raise awareness from 2014 to

2016, and finally a dedicated short program starting in 2017 to achieve comprehensive integration.

The 'design lab' experiment was necessary to explore the question and to show how BIM could be useful to support core competencies. It was not a regular course or part of any regular program, limiting the risks or complications for a university. It was very helpful, however, since it was a good opportunity to show BIM to the community (academic and industrial) and to gather feedback about how the different actors position themselves regarding BIM education and to assess their needs and expectations.

The standalone regular master degree level module was a first response to these expectations. It was an opportunity for the university to cover the most urgent needs without going too far in terms of investment or conflicts with existing programs and courses. This intermediary milestone was also necessary for identifying the main challenges and issues in the development of a more integrated BIM program. The evaluations from the students were an important aspect and they were carefully analysed. The module benefited from a continuous improvement approach and progressively found its best balance between theory and practice. The success of this standalone course was a good indicator of the increasingly positive reputation acquired by the university in BIM education.

After three years, ETS-Montreal was ready to develop a more integrated BIM program. A dedicated short program has then been initiated, a program that benefits from all the achievements of the previous BIM education experiences: the technological environment, the institutional context, the notoriety, the teaching methods and experience, etc. The content of this program was discussed with ETS-Montreal's industrial partners in order to consolidate the partnership with the local industry and to ensure it meets the expectations the industry actors.

5.4.2 The Industrial Partnership

The partnership of ETS-Montreal with the industry in the framework of BIM education was crucial for its success. ETS-Montreal provides the local industry with highly qualified staff, research and development resources, trainees, etc. In response, the support of the industrial partners includes funding opportunities, case studies, job and internship opportunities, etc. Experienced lecturers also come from industry, improving the content and applicability of the lessons delivered. For example, the standalone course was given by two practitioners from industry who also have solid academic backgrounds. The first one is the BIM/VDC (Virtual Design and Construction) director in one of the biggest contractor firms in Canada, holding a Ph.D. degree in architecture and with postdoctoral experience at ETS-Montreal. His profile is especially appropriate for making the bridge between the academic and the industrial worlds. His presence has the double advantage of reassuring the students about the industry's needs and expectations, and the ability to motivate them regarding the importance of research and development for the future of the construction industry. He is complemented with an engineer who is the BIM director in another large engineering group. His position, combined with his previous experience as CEO of a consulting firm specialized in construction and metallic engineering, ensures that he is very well prepared to handle some particular aspects of BIM-related issues.

The dedicated short program content has been defined and validated with representatives from the local construction industry in order to ensure it meets the industry's needs and expectations. This approach is not specific to the BIM short program; it is common to all the programs developed at ETS-Montreal. Indeed, due to its nature, ETS-Montreal has had strong links with industry for more than thirty years. One of the main indicators of these links is the high proportion of research funds coming from industrial partnerships, considered as one of the highest among Canadian universities.

6. Lessons learned and discussions

The ETS-Montreal BIM education experience presented above is very useful for illustrating and discussing the different aspects of the proposed framework. It also shows the need for a critical analysis of what is currently being done in engineering universities BIM introduction experiences.

The main positive aspect of the ETS-Montreal experience is the gradual approach taken, which shows how a continuous improvement process is necessary in order to adapt the content to the challenges encountered and to incorporate the feedback from both students and industry. This aspect is particularly important in order to ensure a coherent change management and to best integrate the different stakeholders involved in the curriculum development.

Another positive aspect at the ETS-Montreal is the interdisciplinary nature of the BIM education content. Indeed, to be fully efficient, a BIM curriculum needs to transversally cover multiple disciplines in order to illustrate the full potential of the BIM approach over a project's lifecycle. The approach taken by ETS-Montreal illustrated the importance of finding a good balance between technical and managerial skills in terms of BIM knowledge. Indeed, while the first BIM curricula focused on software and related competencies, the recent trends are (and should be) oriented towards a more balanced approach in order to better cover the market needs, as identified in recent studies (Abdirad & Dossick 2016; Boton & Forgues 2015).

The ETS-Montreal experience also highlighted the importance of a good partnership with the local construction industry. The involvement of industry representatives is critical to ensure a solid commonality with with business practices and an effective bidirectional exchange between training and practice. In the case of the ETS-Montreal, the involvement of the industry is reflected not only in the choice of skilled professionals as teachers, but also in the definition of the training content. Feedback from practitioners is the key to help position the training offer according to the needs of the local market. In addition, integrating students' research subjects and internships closely with Montreal firms brings a clear added value to the training.

However, the case study does show a certain number of limitations in the ETS-Montreal experience, the first being the lack of complete integration between BIM-specific knowledge and the core competencies. This lack is well-illustrated by the fact that BIM has not been introduced at the bachelor degree level. Note that the bachelor degree level is where engineering core competencies are expected to be acquired, including both foundational and industry-specific competencies. The underlying issue here has been identified and was explained by Sacks and Barak (2010): "A common debate in many civil engineering degree programs concerns the tension between the need to provide comprehensive education and training and the pressure to limit the number of credits in the bachelor degree".

It is also more and more necessary to mention the question of the agility necessary in todays' curriculum in relation to a changing industrial environment. The industry is changing rapidly; knowledge is no longer generated by academic research but by advances in the industry. Thus, the tight relationship with industry depicted in Figure 5 deserves special attention, as the links between teaching and research keep the programs' content up to date.

Another important limitation in ETS-Montreal's case lies in the lack of involvement of the university's administration and management. BIM is a disruptive technology; it difficult for many university staff to be aware of what competencies the industry will be demanding in the future and how to integrate them with today's needs. A major difficulty is the rigidity and fragmentation of the research, academic and pedagogical structures, which tends to create a strong resistance to change. Obtaining support from management and administration is thus key to overcoming this resistance to change. However, with the lack of market pressure, these administrators are barely or not at all aware of the issues and the importance of BIM, and tend to oppose the integration of BIM instead of encouraging it. We must add that in Canada, engineering curricula are subject to approval by accreditation by third parties who are usually disconnected from innovative business practices. The use of the proposed framework can be a good opportunity to make the connection. For example, it can help in the definition of how the progressive introduction of new technologies and practices like BIM can improve the existing graduate attributes' assessment system (required by CEAB) and to implement a continuous improvement mechanism.

7. Conclusion

The engineering universities are facing major dilemmas for a successful BIM introduction in their curricula. Many frameworks have been proposed for different aspects of BIM implementation in education. However, no comprehensive framework has been presented to support BIM introduction in engineering universities, nor to assist researchers in the comparison of BIM programs. This paper proposed a comprehensive framework, encompassing the skills to acquire, the teaching approach, the evaluation methods, the technological environment, the industrial partnerships, the implementation approach and the timing.

The ETS-Montreal case study is a unique opportunity to illustrate the use of the proposed framework. Future work will focus on how such a framework can be used and evaluated in other academic contexts. Similar programs around the world will be studied in the light of the framework in order to consolidate it as well as to identify and formalize the common best practices. Further evaluations and validations will also be conducted in order to the generalizability of this work to other emerging technologies and practices. The new dedicated short program at ETS-Montreal will be closely monitored to assess how it works and how it is perceived by the students, as well as by local industry. Future work will also study in more details the link between disciplines and roles in order to better address the varied requirements of different professionals and students. Due to the high level of complexity in these requirements, we have made the choice, in this paper, of a good level of abstraction in order to provide a consistent and understandable proposal.

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List of abbreviations

ABET:	Accreditation Board for Engineering and Technology
AC:	Academic Competencies
AEC:	Architecture, Engineering and Construction
AIA:	American Society of Architects
BIM :	Building Information Modeling
BTK:	BIM Teaching Knowledge
CAD:	Computer-Aided Design
ETS:	École de Technologie Supérieure
IMAC:	Illustration, Manipulation, Application, Collaboration stages
ISTC:	Industry-Sector Technical Competencies
IWTC:	Industry-Wide Technical Competencies
PBL:	Project-Based Learning
PEC:	Personal Effectiveness Competencies
Ph.D.:	Philosophiæ Doctor
R&D:	Research and Development
VDC:	Virtual Design and Construction
WPC:	Workplace Competencies