The long road to education for upcoming data-driven practices in architecture: gaps, difficulties and silos

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ABSTRACT: Today there are high expectations for the education of the next generation of digitally aware architects and engineers. While most of the existing publications on these educations focus on single innovative experiments, this research proposes an inclusive investigation of their larger trends, strengths and limitations. Based on a first bibliometric study a survey was defined and sent to a wide population of educators and trainers in both academia and practice. The results of this survey show numerous gaps and silos in what is taught today, and highlight as well the numerous difficulties met.

1 INTRODUCTION

Challenges are numerous for the next generation of architects and engineers, who will need to be trained to handle the ever-growing complexity of the built environment, including complex social contexts, pressured economic agendas and the need for highly sustainable building (UnitedNations, 2021). Digital toolsets and practices are being developed to support these demanding practices (Bernstein, 2018; Deutsch, 2016), but remain complex to fully integrate and implement (Bernstein, 2018; Charef et al., 2019; de Boissieu, 2020; Deutsch, 2019). Hence the AECO[1] industry is undergoing significant efforts to enable its digital transformations.

Digital practices in AECO includes especially Building Information Modelling (BIM) and Computational Design (CD). CD practices leverage the power of computation as well as computational thinking to empower architectural design (Carpo, 2017; Menges & Ahlquist, 2011). BIM, on the other hand, focuses on enabling better collaboration processes between the project stakeholders during the whole project life cycle through improved data management and data-oriented practices (Eastman et al., 2011; ISO, 2018). Previous researches have shown the importance of both these approaches (BIM and CD) in upcoming digital practices (Bernstein, 2018; de Boissieu, 2020, 2021; Deutsch, 2016, 2019).

Today there are high expectations for the education of the next generation of digitally aware architects and engineers. Through the multiplicity of digital practices and their requirements, what are the current trends of education and training? What are these educations and training strengths and limitations? How well represented are BIM and CD? How well connected are digital practices to other disciplines within education? Are some of the questions this paper is tackling.

2 CONTEXT

2.1 *Data driven practices in architecture and new skillsets*

Previous research identified the figure of the superuser as key in upcoming digital practices (de Boissieu, 2020, 2021; Deutsch, 2016, 2019) . The figure of the superuser (Deutsch, 2019) describes AECO professionals who leverage technology mindsets and skillsets to design, produce and manage. It describes and crystallizes a complex and not so well documented yet professional

[1] AECO : Architecture, Engineering, Construction and Operation

reality, in terms of skills, roles and career. It highlights the cultural and technical transformation underway and puts a name on a series of characteristics of new actors of the digital transformation, to finally recognize and make visible the complexity of their roles and skillsets. Superusers are experts in digital design technologies in general and are defined by their skills, mindsets and attitudes rather than by their roles. Also, while they have very strong technical knowledge, it's not what identifies them most. The competencies of a superuser comprise firstly the ability for computational thinking, but also inter-personal skills, such as the ability to communicate, connect and collaborate, and an ability to conceptualize and structure strategies for a project or for an office (Davies et al., 2015; de Boissieu, 2020; Deutsch, 2019). The figure of the superuser therefore goes beyond the distinctions between CD and its subsets (parametric, algorithmic and generative design), or between CD and other digital practices such as BIM.

2.2 *BIM and CD: the ever-growing silos*

While research on data-driven practices in architecture highlights the need of breaking the silos between BIM and CD (Bernstein, 2018; de Boissieu, 2021; Deutsch, 2016, 2019), the current practice seems to perpetuate the distinction between these practices, their actors and their works (Aish & Bredella, 2017; de Boissieu, 2020, 2021). These two silos seem to be perpetuated as well in education. A bibliometric analysis of the scientific research published on *scopus*[2] between 2010 and 2020 on architectural design education and digital practices shows a clear difference between BIM[3]-related and CD[4]-related papers (see figure 1). Bibliometric results as in Figure 1 show a real disparity between CD and BIM-related papers where BIM is over-represented, with as well a clear lack of publication interrogating both CD and BIM[5]. This silo trend seems to be increasing, as the publications about BIM in architectural design education have been growing signigificantly since 2010, while publications about both CD and BIM in education have not.

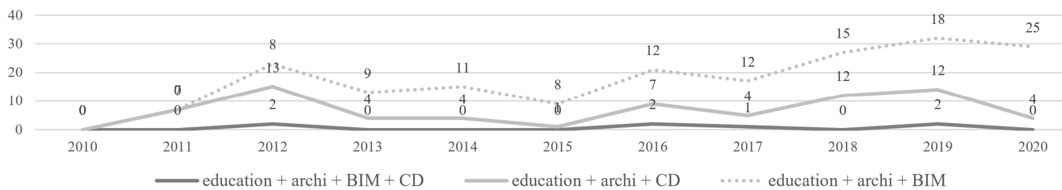

Figure 1. Evolution of BIM and CD related scientific publications for architectural design education between 2010 and 2020 through the *scopus* database

If these trends are significant for the scientific literature, they can be mitigated with a complementary bibliometric study of another publication database, this one dedicated to research on digital architecture.

2.3 *Bibliometric study of field expert scientific related publications*

CumInCAD[6] is a database for publications in computer aided architectural design (CumInCAD, 2021) supported by different specialized associations including ACADIA, CAADRIA, CAAD futures and eCAADe. As CumInCAD is specialized in digital architecture, all publications are

[2] *Scopus* is a publication database recognized as one of the most complete for peer-reviewed highly ranked journals.

[3] Research use on scopus.com : TITLE-ABS-KEY ("education" OR "Teaching" AND "architecture" AND "BIM" OR "building information modelling") PUBYEAR > 2009 PUBYEAR < 2021 AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ARTS"))

[4] Research use on scopus.com : TITLE-ABS-KEY ("education" AND "architecture" AND "computational design" OR "parametric" OR "generative design" OR "data driven") PUBYEAR > 2009 PUBYEAR < 2021 AND (LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"ARTS"))

[5] TITLE-ABS-KEY ("education" AND "architecture" AND "design" AND "computational design" OR "parametric" OR "generative design" OR "data driven design" AND "BIM" OR "building information model-ing") AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA , "ARTS"))

[6] http://papers.cumincad.org/

related to the AECO while it's not the case in scopus. A bibliometric data collection of CumInCAD shows that BIM and CD directly related papers are only a small share of the publications on education and digital architecture (Table 1): only 109 papers in total, out of a wider group of 525 papers which are dealing with education in general.

Table 1. Publication on education in CumInCAD

Key words	*Counts*	*Search formula*
education +BIM	25	{keywords} =~ m/education/i and {keywords} =~ m/BIM/i
education + CD	84	education {keywords} =~ m/Computational Design/i or {keywords} =~ m/parametric design/i or {keywords} =~ m/generative design/i or {keywords} =~ m/algorithmic design/i
education	525	{keywords} =~ m/education/i

The review of the 525 paper titles and abstracts found here allowed us to identify multiples recurring themes[7]. These recurring topics have been curated and leveraged in the following section of the research. This multiplicity of design technology topics related to education showcases its richness and complexity, which goes beyond the usual BIM and CD silos. But if in these papers education is interrogated through multiple fields and topics, it seems that very few of them have an interdisciplinary approach of education and very few are data-related as well (

Table1).

How are these multiple topics taught and connected in education? While most of the researches and publications present specific classes or studios, what are the current general trends of education to digital practices in architecture? This research proposes an exploratory inclusive study of education specificities and strategies for design technology, in both academia and practice.

3 METHODOLOGY

3.1 *A mixed quantitative and qualitative approach*

A mixed quantitative and qualitative approach is chosen in order to shed light on recent characteristics of architectural education, and especially to analyse the opportunities offered by education for next-generation digital transformation, beyond the usual disciplinary distinctions between the applications of BIM and CD. An approach of data collection through a survey is defined in order to reach an inclusive range of education and training descriptions.
A careful wording was chosen, in order to harvest more facts descriptions than opinions. Especially, the uses of the past tenses and specific timeframe is enabled in order to avoid obtaining biased answers about an average wished situation (Van Campenhoudt & Quivy, 2011).

3.2 *Structure of the survey*

The survey is structured in three sections to interrogate: 1- the socio-demographic contexts of the answers harvested, 2- the topics included or not in the education described by the respondents, 3- the difficulties and successes met. These sections include open and closed questions, allowing both quantitative and qualitative data to be collected, compared and to detail and complement each other's. Especially, open questions are included in order to gather more details about the education curriculum described by the respondents, but also to gather personal thoughts and opinions from them.

The description of the education provided is interrogated in the survey through a framework of topics for which the respondent has to set a status: from "not included in the curriculum" to "is

[7] Including the followings: immersion, VR, AR, video games, CAM, fab, robots, simulation and evaluation (structure, energy, environmental), coding, scripting, patterns, programming, open source, BIM, data driven, CD, generative design, representation, hand drawing, rendering, AI, ML, GIS, sustainability, simulation, energy, CFD, day light, geometry, math, structure, simulation, urban scale, city, architecture, landscape architecture, product design, responsive architecture, sensor, kinetic arch, shape grammar, collaboration, participatory design, coordination, project management, creativity, ideation, references, existing, heritage.

optional" and "is mandatory". An "I don't know" option is added to avoid inaccurate answers. The list of topics was defined based on literature review (see section 2.3 and table 5). This part of the survey is intended to provide quantitative data describing education trends, to interrogate especially 1-which topics are the most included in education, 2-which topics are the most included in combination, through interdisciplinary practices or not, 3- which topics are the least included in education.

4 DATA ANALYSIS

4.1 *Data collected*

The survey received 59 answers from August to October 2021. The answers received were relatively well balanced between academics and practioners, with a majority of academics: 35 of them (58%) versus 25 practionners (42%). A large number of countries is represented[8], with a majority from Europe (59%) and US (24%). Through a qualitative analysis of the declared professional expertise of the respondents, a relatively balanced representation of BIM and CD experience and skillsets is identified (see Table 2). Although BIM expertise is slightly more represented, CD expertise representation is significant compared to its general representation in the education literature. We can observe as well that 22% of the respondents have both CD and BIM expertise, which is much higher than what is usually represented in literature (see Figure 1).

Table 2: Respondents expertise analysis

CD expertise only	27%	11 academics, 5 professionals
BIM expertise only	34%	0 academics, 11 professionals
CD and BIM expertise	22%	6 academics, 7 professionals
Other expertise only (urban, project management, design, environmental analysis etc)	17%	9 academics, 1 professionals

The education described by the respondents are mainly aimed at architects (65%), several are at destination of a mixed audience from the construction industry (25%), 10% are for BIM specialists only while none are for CD specialists only.

4.2 *Recurring topics identified*

The results show a majority of topics included in education as "optional". While "mandatory" teaching inform us on the main focus of the class, the "optional" topics gives complementary insights. A majority of "mandatory" teaching focuses on 3D modeling, BIM modeling and BIM standard, which could be relatively expected, but also on Ability to collaborate and Ability to communicate (see table 3). Soft skills are very well represented in the trainings described: out of the 10 most included topics, 6 are soft skills (see in table 3 the category noted [SOFT]). With the important roles of soft skills in digital practices and digital transformation (Davies et al., 2015; Levan, 2016), this is a positive and interesting feedback. However, it would need to be interrogated further. For example, the Ability to collaborate which is largely declared as included in both academia and practice, is it really explicitly taught? Or is it an implicit expected competence? Is this topic explicitly evaluated? These questions would require further investigation.

Expertise related topics (the category noted [EXP] in table 3) such as Structural evaluation, Energy evaluation or Life Carbon Assessment, are very poorly implemented in the teaching of digital architecture. The most included expertise related topic is the Multidisciplinary coordination, which is strongly BIM related. The most advanced topics included (the category noted [ADV] in table 3) such as Form finding, AI or Data science, are some of the least included for both academia and professional training. BIM topics on the other hand are quite consistently taught in academia and in practice. Although we can notice that BIM advanced topics such as

[8] The detailed count of participants per country is as follow: Australia 2, Belgium 10, Canada 6, Denmark 2, France 12, Germany 2, India 2, Lebanon 1, Singapore 2, Spain 1, Suisse 1, United Kingdom 7, United States 8, Global 3.

BIM standards, BIM for multidisciplinary coordination or CDE[9], are significantly more taught in professional contexts than in academia. Visual programming is less taught in average than BIM modeling and BIM standard. It is also not more taught than Computational Thinking, while we would have expected for them to be taught in conjunction.

Table 3: Ranking of the topics according their mandatory presence in education: 1 is for the most included topic, 33 for the least included.

Categories	*Topics*	*Ranking for practioners*	*Ranking for academia*	*Average ranking*
[SOFT]	Ability to collaborate	5	3	1
[TECH]	3D modelling	6	1	2
[SOFT]	Ability to communicate	4	2	3
[TECH]	BIM modelling	1	5	4
[SOFT]	Critical thinking	11	4	5
[SOFT]	Ability to learn	7	6	6
[BIM]	BIM standard	2	11	7
[SOFT]	Change management	3	10	8
[SOFT]	Problem solving	12	7	9
[TECH]	Visual programming	17	8	10
[BIM]	CDE	8	17	11
[EXP] [a]	Coordination process	9	18	12
[TECH]	CAD	18	9	13
[ADV]	Computational thinking	13	14	14
[SOFT]	Philo or history tech	15	16	15
[BIM]	Interoperability	10	25	16
[TECH]	Rendering & VR	16	19	17
[SOFT]	Ability to lead	14	23	18
[EXP] [a]	Project management	19	22	19
[EXP] [b]	Daylight evaluation	26	12	20
[ADV]	Opt / form finding	27	15	21
[TECH]	Small fab (laser cut etc.)	30	13	22
[EXP] [b]	Energy evaluation	22	20	23
[EXP]	Math & geometry	23	21	24
[TECH]	GIS	21	29	25
[TECH]	Textual programming	24	26	26
[EXP] [c]	Heritage BIM	20	30	27
[ADV]	Data science fundamentals	31	24	28
[EXP] [b]	LCA evaluation	25	31	29
[TECH]	Big Fab (robotic etc.)	28	27	30
[EXP] [d]	Structural evaluation	32	28	31
[TECH]	Augmented Reality	29	32	32
[ADV]	AI, Machine Learning	33	33	33

4.3 *Recurring patterns emerging: trainings types*

While 3D modeling, BIM modeling, collaboration and communication are over represented (Tables 3 and 4) and are combined with any other topics, some other topics are significantly more

[9] CDE : Common Data Environments (ISO 19650)

discriminating. From those "niche" topics and some recurring combinations, some education patterns are emerging (Table 4).

Table 4: Heat map of recurring topics organized by observed patterns (from A to F). The score is the percentage of "mandatory" occurrences, the underlined scores highlight the initial definition of the patterns

Topics	A	B	C	D	E	F
Collaboration	30%	75%	75%	75%	75%	100%
Computational thinking	25%	>25%	25%	100%	75%	100%
Visual programming	25%	25%	25%	75%	100%	75%
At least 1field related topic [EXP] [a]	25%	50%	60%	30%	30%	100%
At least 1field related topic [EXP] [b]	50%	25%	25%	75%	60%	30%
Form-Finding	25%	>25%	>25%	50%	50%	>25%
BIM standard	30%	75%	100%	30%	30%	100%
BIM modeling	30%	100%	100%	30%	50%	100%
CDE	30%	60%	75%	30%	30%	100%
Interop	>25%	40%	60%	>25%	30%	60%
AI or Data Science	>10%	>10%	>10%	>20%	20%	>20%
3D modeling	100%	75%	75%	75%	75%	75%
Trainings count	*35*	*29*	*21*	*17*	*15*	*5*

The table 4 shows six types of training (from A to F), proposed from the identification of key topics and key topics combinations (the underlined scores in the table). The training types are displayed from the most used (column A in the left) to the less used (column F in the right). Respondents' answers are sometimes presented several times (a training can be A and C for example). From these initial characterizations, meaningful patterns and insights emerge.

The A training type includes 3D modelling as its only discriminating topic. It's the most used training type, but includes a wide range of miscellaneous topics, from soft skills to advanced BIM skills, all which are all represented in a fairly low and homogeneous way. This mainly shows that 3D modeling is still very present in Digital training today, for beginners as well as for advanced training, and seems to be a very present basic knowledge, much more than CAD is nowadays for example (see table 3).

The B training type is BIM modeling focused, while the C type is BIM modeling and BIM standard focused. The difference between both is relatively small, showing that BIM modeling is mainly taught in conjunction with BIM standards, and often with inputs on relatively advanced BIM topics such as CDE and Interoperability.

The D type training is focused on Computational thinking, which is surprisingly not as clearly linked to visual programming training as one would have thought. Type E shows a visual programming training type, which is close to D type, but shows as a difference an extra proximity to BIM modeling. This shows that type D includes visual programming trainings practices more oriented on data management processes, which could be considered close as well to Computational thinking (Bernstein, 2018; Carpo, 2017; Deutsch, 2016) even though it wasn't highlighted as such by the respondents. It could show that in these cases visual programming is used more as a utilitarian tool to support potentially traditional data management processes, without including Computational thinking.

Both the types D and E are showing a connection with environmental expertise related training (noted [EXP] [b]) significantly more important than other types. While types B and C show a stronger connection to Coordination and project management topics (noted [EXP] [a]). This would suggest that BIM related teaching are often focusing on Multidisciplinary coordination, and more poorly related to other fields of expertise.

The F type is focused on both computational thinking and BIM standard. This type is poorly represented (7 times less than the type A for example) and seems to be more expert topics training, with significantly more mandatory topics than the other types.

4.4 *Difficulties and success experimented by the interviewees*

Through the qualitative analysis of the survey answers recurring difficulties and successes are analyzed using the training types groups identified in section 4.3. The difficulties identified are quite recurring across the different training types and both academia and practice, with especially: 1-the lack of time available, 2-the heterogeneity of the students' background knowledge and 3-the lack of digital "preparedness" of the students. These difficulties might especially explain the lack of advanced topics and even field topics observed in education (table 3 and 4).
Despite these difficulties, the respondents are in average satisfied[10] with their education and training work. The successful strategies met by the respondents are mainly oriented through 1-the use of industry case study, 2- project focused work, 3-the use of eLearning and blended learning. Follow-up interviews would be needed to interrogate these strategies further.

5 DISCUSSIONS

5.1 *Gaps: An education focused only on a reduced number of key topics*

The first hypothesis of the research was that digital education in the AECO industry was mostly focused on both BIM and CD, with a silo effect between both. But while a first bibliometric study of scientific publications validates this hypothesis (2.2), a second bibliometric study showed that Digital in education had a much wider focus in expert communities (2.3). Based on this later results, a survey was defined. Results show that the wide topics highlighted by the expert community publications are only very rarely taught, leaving 3D modeling and BIM as the mains topics tackled in education (4.1). The gaps are major between the multiplicity of advanced topics developed by the research and the industry and their poor implementation in education, even though educators and teachers from the survey are in average more knowledgeable in computational topics than the industry standard (4.1). The identification of these gaps corroborate one of the observations about the superusers: they are mainly self-taught (Deutsch 2016).

5.2 *Silos: A limited number of topics combinations*

While the hypothesis of the research was that the silos between BIM and CD observed in practice would be found in education, the survey shows that silos in digital education are actually going well beyond that. While indeed Computational thinking and BIM related topics are rarely taught in conjunction (table 4), fields expertise such as structural evaluation or energy evaluation are rarely taught with neither of them as well (Table 4). As one of the respondent wrote to describe the situation he/she was in: "*Digital education is still not integrated into the global curriculum. Computers on one side, structure on another, energy, on another and even studio is in its own bubble.*".

5.3 *Difficulties: Recurring difficulties whatever the topic is*

A surprising result from the survey is the relative homogeneity and recurrence in the difficulties raised by the respondents, either they were in academia or in practice, or either their teaching is 3D modeling oriented (Type A in section 4.3), BIM oriented (types B and C) or CD oriented (D and E). The lack of time, the heterogeneous knowledge background of students as well as their lack of digital preparedness are a general difficulty to advance education further.

5.4 *Further investigations needed*

All the results of this paper show the need to interrogate Digital education for architects and engineers in an inclusive, holistic way. While the focus is often put on interesting innovative teaching experiments, most of the everyday teaching still meets major difficulties to keep up with the

[10] To the question "Would you describe this training/education as satisfactory in general?" with the scale going from "1" as not satisfactory at all, to "5" as very satisfactory, the average answer received is 3.7.

industry, while it should prepare students to be ahead of it. And while during the last years the focus of the industry was mainly on exceptional and experimental buildings, it seems that digital practices could now have the maturity to reach everyday architectural design (Davis 2021). This research shows that education keeps struggling with filling the gaps and breaking the silos needed for such a shift. While this survey allowed to reach a large number of diverse teachers and educators, it opens a new set of questions that could be answered by further surveys or interviews.

6 CONCLUSIONS

This paper proposes an exploratory research to identify trends of current pedagogical practices in the formation of architects and engineers with Digital technologies, in order to interrogate the future education of data-driven design practitioners. The originality of the research is the focus on the presumably inter-disciplinary aspect of such practices, as well as the inclusive survey on didactic strategies. This research sheds light on recent characteristics of architectural education, bringing valuable feedback to the discourse on tools and methods.

A large bibliometric study (2.2 and 2.3) enables a preliminary mapping of current educational practices, which is leveraged in the survey to reflect the actual diversity of context currently found in architectural and engineering education. A large inclusive survey enables the collection of both quantitative and qualitative data, highlighting the numerous gaps currently existing in education as well as its difficulties and silos.

Survey results raise the question: Are we training the next generation of superusers? If so, how? Or are we instead – in both academic and practice – merely responding to 'the bottom line' i.e. deadlines, the lowest common denominator, whatever is required to 'get the job done'? The survey results lead one to conclude the latter: business demands in practice and job-related skills in academia, seem to currently drive what is taught and learned in architecture and engineering.

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