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Case Report

Designing Construction 4.0 Activities for AEC Classrooms

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Abstract: This article describes the outcomes of the development of the project MATES to STEAM. The project is aimed at integrating Construction 4.0 content to a recently started new degree on Technologies on Civil Engineering. This integration is underpinned by the creation of STEAM-rich activities that can complement such degree. The philosophical design of these activities followed three requirements: (i) the activities should infuse Construction 4.0-related technologies, (ii) the activities should foster motivation among students with a STEAM vision by-design and (iii) the activities should be designed with a hardware-software independent perspective (open-source, accessible, affordable). Cornerstone and capstone projects as well as a set of workshops represent the demonstrators of these activities. All these demonstrators are knitted together in a single path in which an educational attempt to fill the identified Construction 4.0 gaps is proposed. The STEAM perspective provides completeness to the whole development. During the last two years, the project was developed and the design, the development and implementation of several demonstrators were completed. In the years to come, a systematic deployment and analysis of such demonstrators is expected when a full implementation of the new degree of Technologies in Civil Engineering will be addressed.

Keywords: construction 4.0; STEAM; education; digital twins; 3D printing; BIM; robotics; TLS

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1. Introduction

The Architecture, Engineering and Construction sector (AEC) includes a variety of professions shaped by evolving challenges and emergent opportunities. Professionals from the sector need a broad skillset to address global endeavors included in the SDG such as climate action, decent work and growth, clean water and sanitation, affordable and clean energy. These endeavors must shape altogether all technological advancements that are driving the industry. Inclusive and sustainable industrialization, together with innovation and infrastructure, are meant to unleash dynamic and competitive economic forces that generate employment and income.

All technological advances in the Architecture, Engineering and Construction sector (AEC) are presently shaping the framework Construction 4.0, a term coined some years ago which relates the Fourth Industrial Revolution (4IR) and its resulting network Industry 4.0, as an instantiation of the manufacturing industry to the built environment sector. The built environment sector is reaching maturity for leapfrogging to more efficient production, business models and overall, value chains. Such a transformation is possible through existing and emerging technologies and ubiquitous connectivity. According to Sawhney et al. [1], in AEC sector, the confluence of emerging technologies together with the needs of the sector, is generating a framework in which three themes can be identified: (i) industrial production (prefabrication, additive manufacturing, offsite manufacture and robotic assembly), (ii) cyber-physical systems (autonomous systems, digital twins, smart infrastructure) and digital technologies (BIM, extended realities, interoperability, cloud computing, blockchain, AI, computer vision, etc.).

Infusing technological advances in long-established curricula is an intricate task. In addition, the speed at which such technological advances occur outpaces the time in which curricula are generally updated. This has profound consequences for new generations of the sector and as a result, both teaching and research players at universities and industry require adaptation to those changes. Moreover, civil engineering curricula have seldom been infused with commonplace strategies related to automation, instrumentation, control, digital fabrication and the development of human-computer interfaces. Achieving Construction 4.0 for industrialization and technological development implies adopting several strategies [2]. These strategies should begin from the start of AEC studies.

With the aim of contributing to this gradual adaptation, an educational project has been developed at the School of Civil Engineering of the Technical University of Catalonia (UPC, BarcelonaTech). The name of the project is MATES to STEAM, which is a playful turnaround of the Spanish acronym MATES (an informal way of referring to Mathematics) to the STEAM acronym (Science, Technology, Engineering, Arts and Maths). This article describes the outcomes of the project, whose methodology is based on the creation of STEAM-rich activities for a new degree of Technologies in Civil Engineering with a particular focus on Construction 4.0.

The philosophical design of these activities was established following a threefold requirement: (i) the activities must infuse Construction 4.0-related technologies, (ii) the activities should foster motivation among students by STEAM by-design and (iii) the activities should be designed using a hardware-software independent perspective (open-source, accessible, affordable).

The article is organized as follows: Section 2 presents a discussion on published experiences related to different ways of infusing Construction 4.0 within curricula together with a succinct description of STEAM and Makerspaces (since these activities were conceived with a Maker perspective), Section 3 describes an overview of the proposed path. Subsequently, Section 4 provides a larger presentation of the designed activities in the form of demonstrators. Some of these demonstrators have already been implemented in the two-year duration of the project. Section 5 presents the conclusions and key takeaways.

2. Construction 4.0 and Formal Education in Civil Engineering

2.1. Research Design

In order to establish boundaries on the scope of the project and to gain insight on the *Weltanschauung* of Construction 4.0 and Education, a set of research methods were defined:

- Analysis of the available literature.
- Identification of research gaps and thus, of potential activities.
- Identification of spaces and facilities.
- Development and implementation of an exemplary set of activities for the Construction 4.0 classroom.

The first step consisted of the development of a systematic literature review. First attempts suggested that comprehensive reviews needed a refined search strategy. It is a quite intricate task to investigate exhaustively the state-of-the-art of educational activities related to Construction 4.0 in academia. While some attempts to contribute to Construction 4.0 in education may have been published in academic journals, many other disaggregate attempts may have not reached such forums. This represented a bias in the literature review that required establishing a narrower focus.

In order to tackle this review, a first educational question was asked: When/Why should an activity be linked considered as an educational form to Construction 4.0?

Let us start by defining the term. One broad definition of the term would conceptualize <<the use of ubiquitous connectivity for real-time decision making in Construction>>, which may correspond to an instantiation of the term Industry 4.0. The breadth of such definition is considerable and it proves difficult to trace in a systematic literature review. Another definition conceptualizes Construction 4.0 as <<a framework that encompasses different emerging technologies for the sake of tackling the current challenges within the industry>>. In this case, the definition becomes more specific yet disaggregate for developing a comprehensive state-of-the-art.

Whatever the definition given to it, the big change brought by Construction 4.0 seems to revolve around a decentralized connection between the physical space and the virtual space via ubiquitous connectivity.

Subsequently, a second educational question was asked: How are educational experiences enabling civil engineering students to travel seamlessly from physical-to-virtual and from virtual-to-physical realms? This question provided more focused spectacles and helped addressing a more systematic literature survey.

A literature review was performed by the author with the aim of answering the second question. Adopting the classification provided by [1], it is understood that the confluence of many emerging technologies coupled with the needs of the sector generate a framework with three identified branches:

- Industrial production (prefabrication, additive manufacturing, offsite manufacture and robotic assembly).
- Cyber-physical systems (autonomous systems, digital twins, smart infrastructure).
- Digital technologies (BIM, extended realities, interoperability, cloud computing, blockchain, AI, computer vision, etc.).

These branches represent a clearer definition of the physical-virtual-physical journey. Industrial Production presumes knowledge and skills on digital fabrication. Objects, assets, systems of the build environment are virtually designed and then fabricated automatically [3]. Cyber-physical systems in the built environment presume knowledge and skills on connectivity. Physical and virtual realms are synchronized in many ways [4,5]. Digital technologies presume knowledge of many of the trends that are shaping the industry needs such as BIM, computing and user interfaces [6].

In the following sub-sections, a concise literature review based on the aforementioned branches is presented. The selected papers revolve about the field of education in AEC.

2.2. Literature Review: Industrial Production

In the case of Industrial Production, in the AEC sector, many forms of automation, robotics and digital fabrication (DF) are found in civil engineering educational programs based on workshops and various "hands-on" activities. Construction automation and robotics in civil engineering education programs have been a matter of academic debate since the nineties [7]. Long-term bibliometric analysis of educational research in construction for periods 1982–2017 show trends about how digitalization has permeated the sector gradually [8]. However, in recent years, due to vaster accessibility to technological advances, the sector has regained momentum. Technology-rich activities in AEC such as 3D printing, laser-cutting, 3D measuring machine, robots and drones have been documented in the literature. A considerable deployment of technologies is necessary when developing applications that infuse automation, robotics and digital fabrication in AEC classrooms. Adequate facilities such as laboratories, maker and fabrication spaces and medium- to large size hardware are needed for large sets of students simultaneously. Educational proposals are particularly developed in the realm of additive manufacturing and digital fabrication [9–12]. In the realm of construction robotics, References [13–15] have studied student's cognition and motivation when developing experiences in AEC classrooms. The greatest bottleneck to massive implementation of ART technologies in AEC classrooms is massive scalability due to the needs of bespoke facilities. Educational advantages are clear (engagement, motivation, meaningfulness and construction of real applications) but economic disadvantages are clear as well.

2.3. Literature Review: Cyber-Physical Systems

In the case of Cyber–Physical Systems (CPS), sensors, connectivity and user-interfaces are also found in educational literature (to a lesser extent though). Although the large academic discussion about the potential cognition enhancement that may be provided by CPS [16], less information is found in the case of AEC classrooms. However, as digitalization increases its effects in modern construction, more and more AEC-related schools will point towards integrating CPS experiences as cognitive enhancers [17]. In this particular case, planning and facilitating CPS educational activities require hardware and software in which facilitators require basic understanding for electronics and programming. As a result, educators requires knowledge on both technology and pedagogical use of these devices, which may be understood as a bottleneck. On the flip side, it is observed that meaningful applications can be developed in regular classrooms with open-source, low-cost accessible tools at a massive scale [18]. Although desirable, big laboratory facilities are not compulsory for the development of meaningful educational deployments. Massive implementation of CPS in AEC classrooms require knowledge-intensive preparation rather than heavy deployments and facilities, which represents a more plausible alternative in AEC-related faculties. Experiences for education and training are increasingly present in the AEC sector. For instance, Reference [19] presents CPS for training of workers, Reference [20] developed a platform for industrial internet and digital twins for the case study of an overhead crane. References [21,22] developed physical-to-digital application for structural engineering (statics and dynamics). In broader sense for civil engineering, Reference [23] presented a report with some applications of digital twins as cognitive enhancers for the classroom.

2.4. Literature Review: Digital Technologies

In the case of digital technologies, BIM and extended realities represent by far, the most mature fields educationally. Manifold educational projects have been presented in the last decade worldwide. When it comes to BIM, a myriad of case studies and educational experiences from which the student perspective, cognition, assessment and methodologies are summarized in several reviews [24–27]. It is clear that the training needs for the current and future construction industry with the main purpose to encourage (i) better employability, (ii) sustainable growth, (iii) motivation and (iv) increase digitalization skills are fostering BIM adoption at a very fast pace. Nevertheless, despite the increasingly widespread adoption of BIM worldwide, a steady flow of BIM-ready graduates required to meet the industry demand is not at the expected levels. Case studies are summarized by hundreds in the aforementioned reviews. Moreover, many immersive extended realities, augmented realities, virtual realities or to a larger extent, immersive experiences in AEC-related classrooms can be found in the literature. Reference [28] presented a critical review on the use of virtual reality for construction engineering education and training. Pedagogy and cognition represents one category followed by the use of Extended Realities for training in safety-related issues. Case studies in which several efforts on embedding immersive technologies for courses of sustainable building design, architectural pedagogy for building construction or immersive and non-immersive construction sites are found in the literature. For instance, Reference [29] explored AR in representation of steel architectural construction education. Reference [30] explored the use of immersive technologies for rethinking maritime education in the digital era. Reference [31] explored how AR enhance content delivery in a building design and assembly project. Reference [32] presented mobile augmented reality applications for teaching structural analysis. AR has also been used for pedagogical enhancement in descriptive geometry by [33].

2.5. Literature Review: The Role of Makerspaces

The makerspace of the School of Civil Engineering became the space for tinkering and the corresponding development of such activities. Makerspaces have become increasingly common venues of STEM and STEAM education and are rapidly being incorporated into undergraduate programs [33–37]. These spaces give students and instructors access to advanced design technology and facilitate the incorporation of a wide variety of projects into the curriculum. Manifold tools for industrial production (3D printers, robotic arms), cyber-physical systems (low-cost sensors, microcontrollers) and digital technologies (Open-BIM, VR, AR) are already utilized in makerspaces. The atmosphere provided by the makerspace can help to cross-pollinate ideas and to create a fertile substrate for tinkering. As the field of civil engineering evolves to address twenty-first century challenges, the demand for creative and innovative thinking rises. Construction 4.0 represents an interesting driving force for the development of applications by students in which creativity, computing and construction are blended together. Pedagogical methods such as active learning, team-based learning as well as problem-based learning support many of the goals of entrepreneurship [38]. As students think critically in teams to solve open-ended problems, they are given the opportunity to try new ideas. The classroom/laboratory can be an environment that allows students to take risk, possibly fail, and eventually succeed.

2.6. Literature Review: Discussion

Current state-of-the-art technologies for Construction 4.0 from an industry perspective were identified and analyzed. Specific educational applications of these technologies based on affordable, accessible and scalable tools were also identified. The categorization of the technologies is according to the definition of Sawhney et al. [1]: industrial production, cyber–physical systems and digital technologies. The literature review shows educational gaps as well as educational needs for the systematic use of tools in AEC classrooms. On the one hand, industrial production requires massive deployment of facilities, which is a drawback for implementation. On the other hand, digital technologies are quite established in the educational literature. In between, it is pinpointed how cyber-physical systems represent an accessible and affordable way of bridging the gap in AEC classrooms when it comes to implementing Construction 4.0 activities in which both Physical and Virtual realms are intertwined. In the following section, the design and development of Construction 4.0 is based on these key takeaways.

3. Construction 4.0 Path for the New Degree on Civil Engineering Technologies

3.1. Civil Engineering Technologies, a New Degree

The field of civil engineering is expanding beyond the traditional design and decision-making process. As global challenges continue, civil engineering requires innovation to maintain competitiveness. New social, environmental and economic models and scenarios pose significant challenges for the adaptation of current structures and systems, mobility management, transport and logistics, large infrastructure management, water supply, energy sources, waste reduction and environmental protection. Civil Engineering plays a key role on the improvement of people's quality of life, environmental protection and economic growth, which is nowadays and historically aligned with the SDG. In order to contribute to this adaptation, a new degree on Civil Engineering Technologies has been recently implemented at the UPC. Table 1 displays its new curriculum. The table is organized by academic years and fall/spring terms for each year. On a nutshell, the degree can be described as a journey from solid theoretical background in mathematics and sciences in first years to state-of-the-art technologies at the end of the degree. Fundamental civil engineering courses are also included as the core of these studies. Noticeably, the degree is nowadays unbalanced. Construction 4.0-related courses tend to be at the end of the studies in specific courses. It is identified that a complimentary path for students covering all academic years may fulfill this gap with Construction 4.0 related content.

Table 1. New degree on Civil Engineering Technologies.

Term/Academic Year	1st	2nd	3rd	4th
Fall	Economics, business and legislation Metric geometry and representation systems Chemistry Mathematics Physics	Differential geometry and differential equations Mobility and transport networks Probability and Statistics Strength of materials and structures Urbanism	Numerical modeling Soil Mechanics Structural Analysis Structural Technology (I) Surface and underwater hydrology	5 optional courses among the following: Risk assessment for natural hazards Instrumentation and Remote Sensing Machine Learning and data science Programming for Science and Engineering Sustainability, social and environmental impact
Spring	Algebra and Geometry Calculus Construction Materials Geology Rational Mechanics	Environmental Engineering Geomatics and Geographic Information Hydraulics and Hidrology Mathematical models in physics Roads and Railways	Communication Techniques Construction procedures and electrotechnics Geotechnical and geological engineering Maritime and Port Engineering Structural technology (II)	Final Bachelor's project Business and Administration 2 more optional subjects among the following: Software tools for civil engineering Urban mobility and decision support Digital Twins and Augmented Reality Entrepreneurship and Innovation

3.2. Individual Learning Paths

Degrees are usually complemented with personal learning paths. A complementary personal learning path is a learner-centered approach that emphasizes learner-specific goals and objectives, as well as preferences that a learner elects on their own. Students comprehend their personal learning pathways through several ways such as: (i) the identification of elective courses through preference of topics that are the most relevant to student's current or future professional activity, (ii) use of accountable side-courses, workshops, capstones, hackathons or (iii) development of internships and academic exchanges. Many other ways may also shape a unique path, personalized, which is outside of the regulated formal learning process [39]. On the other hand, the unexpected disruption that generated the global pandemics has changed profoundly the perception of learners towards content acquisition. The potential of online learning embeddedness in formal education leapfrogged. The post-pandemics educational scene will inevitably blend in-campus and online learning which may also contribute to the personal choices that will shape all individual learning paths.

3.3. Proposal of Construction 4.0-Rich Complementary Learning Path for the New Degree

In order to contribute to the new degree curriculum, a comprehensive Construction 4.0-related complementary learning path is proposed. Content, activities, workshops, cornerstone and capstone projects erect the frame of this learner-centered pathway. These activities are referred to as demonstrators. The objective of the proposal is to aggregate Construction 4.0 content coherently and subsequently, to propose this content to students at the School of Civil Engineering. Figure 1 displays the overall proposal. Details on each of the developed demonstrators are given in subsequent sections.

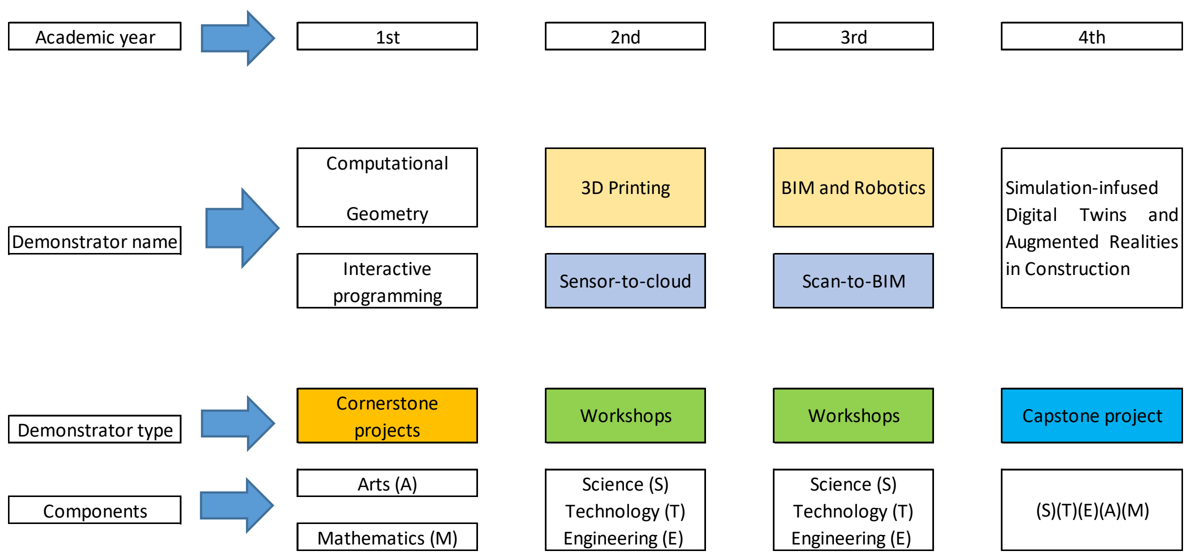

Figure 1. Construction 4.0-related complementary learning path.

In the 1st academic year, demonstrators consist of cornerstone projects related to coding. These projects are aligned with the actual curriculum and the particular goal of such projects is to infuse coding and programming topics that are simultaneously taught in courses of Calculus, Algebra and Geometry. Pilot implementations within formal courses have already been taken place at the School. The principal STEAM components of such projects are Maths (M) and Arts (A).

In 2nd and 3rd year, demonstrators consist of a set of workshops. Different themes of Construction 4.0 such as Automation and Robotics, Digital Fabrication, BIM or IoT represent fertile topics for the generation of workshops that can be updated year by year. The principal STEAM components of such projects are Science (S), Technology (T) and Engineering (E). Moreover, these demonstrators are conceived as specific journeys "from virtual to physical" or "from physical to virtual". These demonstrators are self-contained but require coding skills, which are provided in the cornerstone projects.

In 4th year, a capstone project allows closing the loop by integrating all (S)(T)(E)(A)(M) components in a single demonstrator. The demonstrator is related but not limited to the course "Digital Twins and Augmented Realities in Construction", included in the new degree. Notwithstanding, this demonstrator may also represent a Construction 4.0 basis for projects developed in many of the other courses taught at 4th year.

4. Current Developments and Implementations of the Learning Path

The main outcome of MATES-to-STEAM is the definition of meaningful activities and their corresponding infusion within the degree. Throughout the development of the educational project, some of the STEAM activities have already been implemented in the classroom, others have been displayed to students while others are at the proof-of-concept level. The evolutionary nature of the sector suggests that these activities will progress accordingly with new advances that are undertaken on a year basis.

4.1. Cornerstone Projects. Maths and Arts

The first set of projects is defined as cornerstone due to the need of basic understanding of coding. The demonstrators have been already implemented twice. In the first two editions, the demonstrators have been conceived as a challenge proposed to students which deals with mathematics. Applied introductory programming are always useful for civil engineering students due to their uneven prior acquaintance with coding skills. The first (2020) and second edition (2021) of the demonstrator were aimed at reinforcing concepts of differentiation throughout a hands-on coding activity. The formal Calculus syllabus (M) including derivatives is illustrated by students by designing a beautiful visual application (A). Students enrolled in the Calculus course were given an optional yet graded task. The challenge of the activity was: For a given implicit function, an interactive visual application ought to be developed. This application requirements were: (i) drawing the curve and (ii) drawing a tangent line to the curve as the mouse pointer is placed on any of its points (x,y). The first requirement is a straightforward static code in which points of coordinates (x,y) are plotted in a Canvas. The second requirement is more advanced dynamic interactive code that presumes an adequate use of time and space within the application. Students were open to use creativity and beauty in the development of such applications by plotting moving primitives (points, lines, rectangles, circles, triangles) in a 2D space with a creative formatting.

Didactic material in the form of video tutorials and a pdf was distributed among participants. Lessons were conceived for students with no prior knowledge in coding visual applications and were structured in six sections as shown in Table 2. The 2020 and 2021 editions of the cornerstone project have been developed with 1st year students of Calculus. Face-to-face tutorships have not been allowed during these editions due to the health regulations in the country. As a result, only web meetings were held during the experience, which has been satisfactorily implemented via online collective meetings. The aggregate time (lecture and autonomous work) is approximately 3 h.

Table 2. Structure of the lessons for the introductory project of interactive programming.

Concept	Tools
Space	The Canvas, The unit: Pixels, The coordinates
Time	Frames per second, The Unit: Milliseconds, Frame Rate
Geometrical Entities	Points, Lines, Vectors, Rectangles, Squares, Circles, Triangles
Instructions	Data types, If/then/Else, For, While, Functions
Format	Background, RGB, Color, Fill, Stroke
Movement	Translation, Rotation

When it comes to numbers, for the first edition, a total amount of 158 students were enrolled. Fifty curves of implicit functions were identified (cardioid, nephroid, lemniscata, cissoids, etc.). Each group was given a curve from the pool randomly. Students were provided with a bonus point (1 out of 10) as a reward in case of adequate submission. The activity was set when the course had reached 75% of its regular path and represents an optional marking grade of 10% of the total. For the second edition, the reward system changed. The submission allowed substituting the lower grade obtained during the course. Twenty groups (58 students) submitted adequate projects. The activity was set when the course had reached 75% of its regular path and represents a maximum yet optional marking grade of 10% of the total as well. It is interesting to point out that in the second edition, students were not locked down and lectures were held in Campus whereas for the former, students were locked down and lectures were fully remote. Moreover, it is important to pinpoint that the Calculus course of first year has six European Credit Transfer System (ECTS) with an approximate amount of 4 h of lectures per week during the whole academic year.

Results of the activity in 2020 and 2021 editions are available [40,41]. Participation in the first Edition in the optional online version (during lockdown) reached 98% whereas participation in the 2nd Edition reached 50% (face-to-face, after the lockdown). During the development of the activity the students (i) plotted the curve in the canvas, (ii) found the differentiation of an implicit curve (using chain rule and other concepts) and (iii) used the derivative function for drawing a tangent line whose angle of rotation must be in accordance with the coordinates generated by the mouse pointer (x,y) = (mouseX, mouseY). Figure 2 shows an example of a Lemniscata and its tangent developed by one of the participants. A simple plot of the function in a 2D space is presented. Axes are drawn using lines and triangles and the function is plotted using points. The tangent line appears only when the mouse pointer is set on the curve at any point. A text indicating the slope is added for verification purposes.

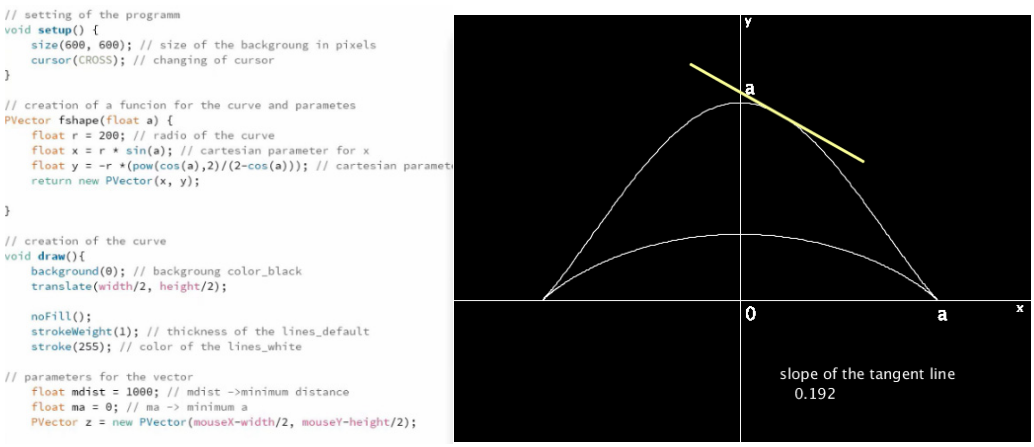

Figure 2. Typical results obtained with a curve (bicorn) and its tangent line.

Moreover, at the AEC sector, many designers are exploring the use of algorithmic programming platforms that encompass computer-aided parametric design, mathematics, structural analysis and ultimately, Building Information Modeling (BIM). Namely, currently available popular Software for parametric representation of geometry, such as Grasshopper in the Rhino environment, or Dynamo in the Autodesk environment provide "parametric representation" of a geometrically- and semantically-rich instance in which the user can define a complex geometric model by incorporation a sequence of algorithmic calculations. That is to say, changing parameters on such models can trigger a cascading recalculation of the output, similar to the recalculation of a spreadsheet but on a CAD environment.

Consequently, another version of the cornerstone project provides an introductory programming course using Maths and Arts in these parametric design tools. The chosen platform is Grasshopper as a versatile algorithmic programming environment. The professional sector is increasingly demanding competences in the use of algorithmic modeling but their use in academia is still in its infancy (in civil engineering schools at least). The main idea is to establish a link between a virtual 3D space in which points (x,y,z) can be mathematically used as points instances of the "Rhino.Geometry" set of classes. Rhino.Geometry wraps a set of methods that are applicable to several geometrical instances such as 3D points, lines, planes, surfaces and volumes using Python scripting. The result is a geometric language in which the designer develops complex geometries mathematically. Table 3 displays the present structure of the lessons. The aggregate time (lecture and autonomous work) is approximately 3 h.

Table 3. Structure of the lessons for the introductory project of computational geometry.

Concept	Tools
Space	The virtual 3D space. Grasshopper
Geometrical Entities	Points, Lines, Vectors, Surfaces, Volumes, Meshes
The namespace	Rhino.Geometry
Entities	Functions, Derivatives, Tangent planes, Gradient Vector

The cornerstone project has been prepared but not yet implemented in formal courses. It has been tested and analyzed in the form of a workshop with 15 students of 3rd academic year or higher. In 2022, the algorithmic modeling is mature enough to be formally offered for 1st year students. Figure 3 displays some of the potential outcomes on the generation of 3D geometries using Python and Grasshopper.

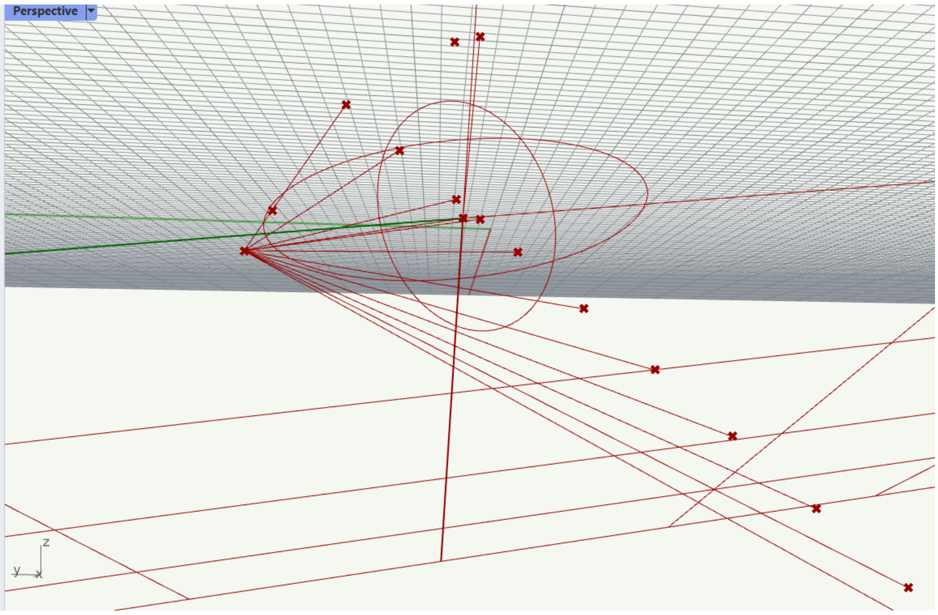

Figure 3. Typical results obtained with the computational geometry tools.

4.2. Core Workshops. Science, Technology, Engineering

Several demonstrators in the form of workshops have been developed and implemented in recent years at the Makerspace of the School of Civil Engineering. In the context of this project, the demonstrators have been selected and adapted for the sake of designing a consistent set of activities related MATES-to-STEAM and Construction 4.0. The evolving nature of the Construction 4.0 field makes that these workshops should also have an evolving nature. In today's form, the set of activities is presented as comprehensive covering several topics of industrial production, cyber-physical systems and digital technologies. These demonstrators are also conceived as "virtual-to-physical" or "physical-to-virtual" journeys using connectivity, which represents a consistent definition of Construction 4.0 presently.

4.2.1. Sensor-to-Cloud

Understanding basics in electronics is today a need for all engineering students. In addition, the rapid development of IoT enables the connection between the physical- (nature, people, cities, industries, etc.) and the virtual-worlds (internet, computers, and mobile devices), which relentlessly brings new ecosystems at all levels of engineering. Nevertheless, civil engineering students are less exposed to measuring and electronics when compared to other engineering degrees. The sensor-to-cloud workshop aims at bridging the physical–to-virtual gap of students when it comes to measuring physical or chemical magnitudes. In the last decade, an explosion of low-cost, open-source microcontrollers and microcomputers have enabled a massive use of electronics by many collectives including students of all disciplines. Makerspaces have often benefited from this accessibility. A vast amount of online content and resources for students is nowadays available. Platforms are considerably used by DIYers and STEAM-based educational programs.

Introductory electronics are generally taught in the Makerspace using microcontrollers. Electronic prototyping platforms include a range of electronics such as programmable boards, sensors, mechanical parts, simple open-source software that can be afforded by the laboratory facilities (both technically and economically). The programming level and circuitry complexity enable facilitators to design workshops with varying duration. Depending on the level of detail to be tackled, basic workshops may range from a couple of hours to a couple of days. For the cloud services, students are provided with accounts to Smartlab, a sensor-to-cloud platform for Windows, Linux (incl. Raspbian) and MacOS developed at the School of Civil Engineering. The aim of the platform is to enable students to send sensor data from their own experiences to a server. The platform was initially conceived at the Makerspace for enabling cloud services to students doing research within the laboratories of the School. Table 4 displays the present structure of the lessons. The aggregate time (lecture and hands-on work) is approximately 4 h.

Table 4. Structure of the lessons for the workshop: Sensor-to-cloud.

Concept	Tools
Basic circuitry	LED, Knob
Sensors	Analog (LDR, Accel) Digital (Laser, Ultraound)
Actuators	Servomotors, Motors
Time	The Unit: Milliseconds, Frame
Calibration	Displacement and rotation
Cloud Services	IoT concepts, Smartlab, JSON

The workshop has been implemented in recent years fairly systematically. New generations of AEC students present a quite open attitude towards electronics. Quite surprisingly, sensors and microcontrollers are increasingly introduced at K-12 levels, which on the one hand facilitates the development of such experiences but also on the other hand, it raises the expectations of students when it comes to the use of technology in AEC classrooms.

The extended version of the workshop (12 h) is yearly deployed at the School of Civil Engineering since 2017 in the frame of the Master Course "Experimental Techniques in Construction". Sensors, Data-Acquisition Systems, Cloud Services and User Interfaces represent the core of the lessons. The vast majority of students have no prior knowledge in electronics and by the end of the lessons, AEC-related applications are successfully developed. For instance, Figure 4 shows the information flow from experiment to the cloud. Encompassing sensors, signals and physical phenomena intertwines Science, Technology and Engineering in a single real problem.

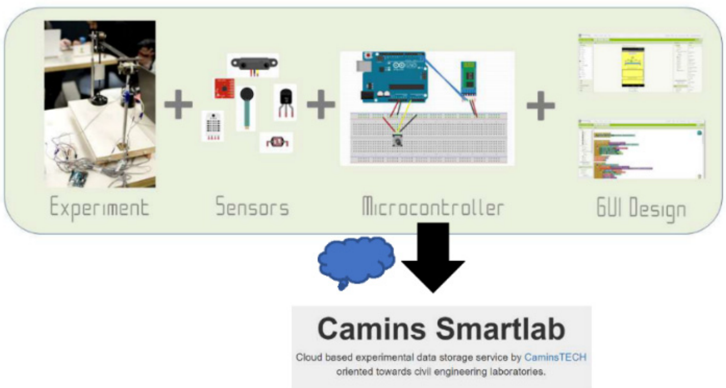

Figure 4. Sensors, microcontrollers, transmission, cloud services.

4.2.2. D Printing

Digital fabrication and the vast amount of possibilities offered by additive and subtractive technologies have also permeate the AEC sector to a considerable extent. Additive manufacturing techniques have gained popularity in recent years after the expiration of several long-term patents. Until recent years, these technologies were out of reach of most educational institutions due to their cost. Presently, 3D printing has reached maturity and mainstream accessibility. On the other hand, educational environments are great recipients of the open-source movement of digital fabrication.

Three-dimensional (3D) printing allows the materialization of a wide range of geometries from 3D model data using several materials ranging from polymers of various kinds to more sophisticated automated printing using concrete deposition or metal wire-and-arc technologies. The construction industry is at research levels when it comes to possibilities of 3D printing of concrete and steel elements. Material anisotropy, automation of processes and bespoke applications are only few of the many active research lines. Meanwhile, proof-of-concepts in 3D printing are already at the grasp of AEC-related schools and faculties. The journey from digital-to-physical using 3D printing can be fully accomplished by students nowadays. Integrating 3D printing within topics in which such technologies are- or will be relevant in the near future represents an interesting way of infusing such technologies meaningfully.

Under this premise, the design of a basic workshop related to 3D printing have been undertaken at the School of Civil Engineering. The aim is to bridge the virtual-to-physical gap. Educational possibilities that involve the use of 3D printing within courses of computational geometry have been explored. This workshop presumes that the cornerstone project related to computational geometry is completed previously. 3D printing of complex mathematical geometries provides skills and insight related to additive manufacturing. Realism and an interesting exercise of mathematical creativity using programming can be intertwined. Figure 5 displays results of the final exercise developed by students in the latest edition of the workshop. This edition included both bachelor and master students. Table 5 displays a basic structure of workshop. The aggregate time (lecture and 3D printing) is approximately 2 h.

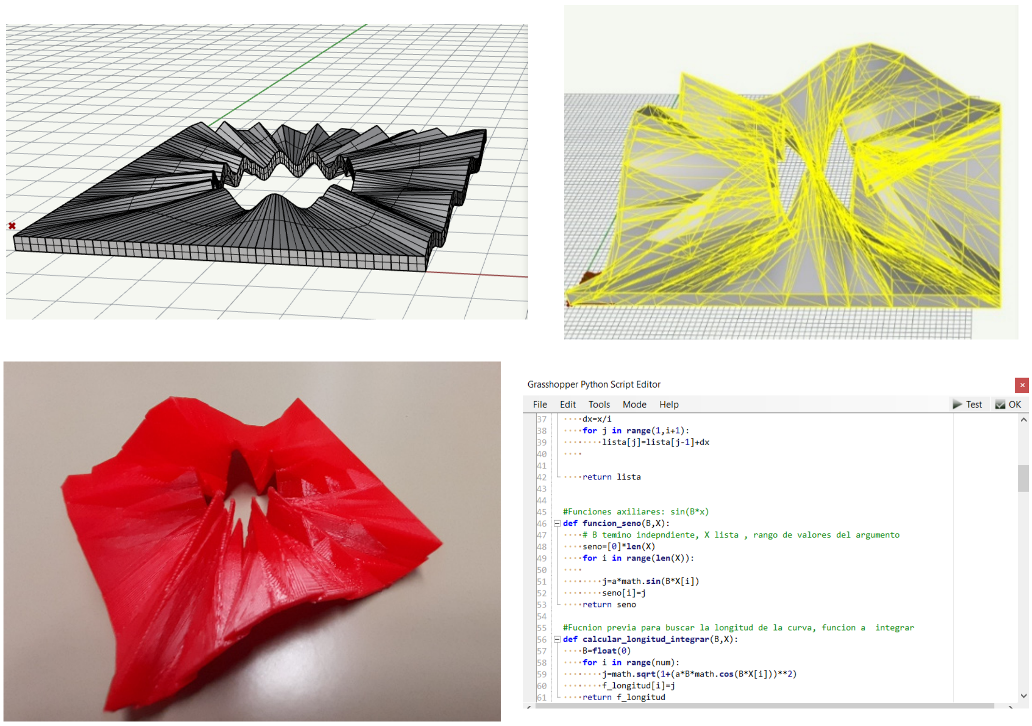

Figure 5. Three-dimensional (3D) printing of a mathematical surface developed using computational geometry tools.

Table 5. Structure of the lessons for the workshop: 3D printing of constructional steel joints.

Concept	Tools
Space	The virtual 3D space. Grasshopper
3D Materials	Types, density, support material
Maths	Parametric geometry

4.2.3. Scan-to-BIM

Terrestrial Laser Scanner (TLS) are devices of a great usefulness in Construction 4.0. They allow virtualizing with great accuracy 3D geometries. The ground, the structure or more broadly, the built environment can be virtualized with the aid of TLS. Virtualization requires understanding of point clouds that may be taken by the device by the millions. Commercial or research-oriented laser scanning technologies often offer mathematical algorithms dedicated to feature extraction from point clouds. Most of them are dedicated to identifying more complex geometrical elements (edges, planes, meshes, objects), to be subsequently used in a huge variety of analyses. In educational contexts, TLS are of great interest in AEC classrooms as data generators for computational geometry case studies. An initiation to geometry analysis in virtual spaces represents an interesting workshop aimed at filling the gap between laser scanning, virtual spaces and subsequently, BIM.

In this respect, the workshop is aimed at developing mathematical algorithms for the identification of simple geometries that are measured using a laser scan. Objects whose shape can be mathematically described are chosen as straightforward examples. The identification of a plane as well as the identification of a sphere are performed using interpolation algorithms embedded within Rhino and Grasshopper, tools that can be linked to BIM platforms seamlessly.

As an example, two wooden plates forming a corner with an unknown angle are used for demonstration. A terrestrial laser scan developed at the School of Civil Engineering [42] generates a point cloud for each wooden plate from which a sequential feature extraction is performed: first, planes containing both plates are interpolated from point clouds. Then, the intersection of these planes define a line which features an edge. If this edge is intersected with a horizontal plane passing by the TLS base, the relative coordinate of the corner is obtained. As a result, planes are obtained by interpolation, intersection of two planes or intersection of a plane and an edge are performed using intersection methods. Figure 6 shows the results obtained after the whole procedure.

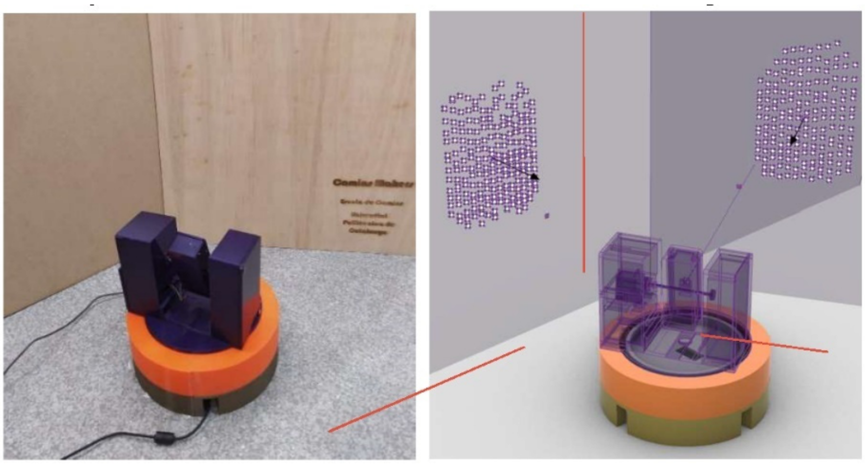

Figure 6. Identified corner using TLS measurements and computational geometry tools.

Moreover, Figure 7 displays similar identification procedure but in this case, with a physical sphere and its corresponding identification in the virtual space. Table 6 shows a basic structure of the workshop. The aggregate time (lecture and autonomous work) is approximately 3 h.

Table 6. Structure of the lessons for the workshop: TLS-to-BIM.

Concept	Tools
Entities	Planes, spheres, corners
Scanner	Description and use
Identification	Fit-to-Geometry

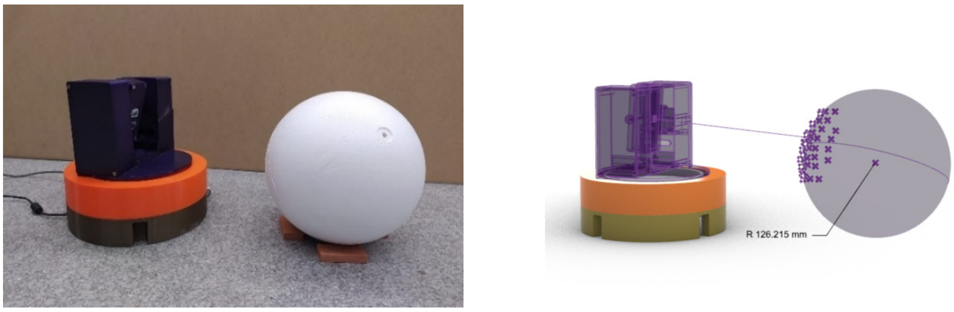

Figure 7. Identified sphere using measurements and computational geometry tools.

4.2.4. BIM-to-Robotics

Both BIM and Robotics are vast fields. Introducing Robotics within the frame of BIM-enabled applications is a great challenge that requires considerable research and development. However, a basic data transmission between physical objects (such as a basic robotic arm) and BIM-enabled platforms can be meaningfully performed by students. Cost-effectiveness, time-efficiency and accessibility can be achieved using 3D printed parts, open-source electronics and computational geometry. With the aid of servomotors and microcontrollers, a robotic arm with several degrees of freedom is used for demonstration and development of the workshop. Small commercial robotic arms are available in the market but it is also possible to design one using 3D printing, servo-motors and microcontrollers from scratch. In either case, the key challenge is to couple the movement of these degrees of freedom with the corresponding geometrical entities in a BIM-enabled platform. Figure 8 shows the assembly of a robotic arm with up to six degrees of freedom. With the use of microcontrollers, students can control de angular position of all servomotors in the physical realm. This device is available at the lab. The workshop is aimed at using the device rather than at building it from scratch (which is feasible but it would take longer time and more resources).

Figure 8. Braccio. Arduino-based robotic arm.

In the virtual realm, the angular position of physical servomotors is coupled using computational geometry tools. This control of physical objects is performed using Rhino and Grasshopper, tools that can be linked to other BIM platforms seamlessly. The workshop is thus intended to help students familiarizing with the control of rotation of objects using vectors, trigonometry, angular position, virtual entities such as solids or meshes. Figure 9 shows an exemplary representation of the same robotic arm shown previously, but in this case, students are taught to control physically and virtually the rotation of all degrees of freedom by means of servomotors and knobs. Basic orders are also programmed as robotic routines (to follow specific movements or sequences). Table 7 shows a basic structure of the workshop. The aggregate time (lecture and autonomous work) is approximately 2 h.

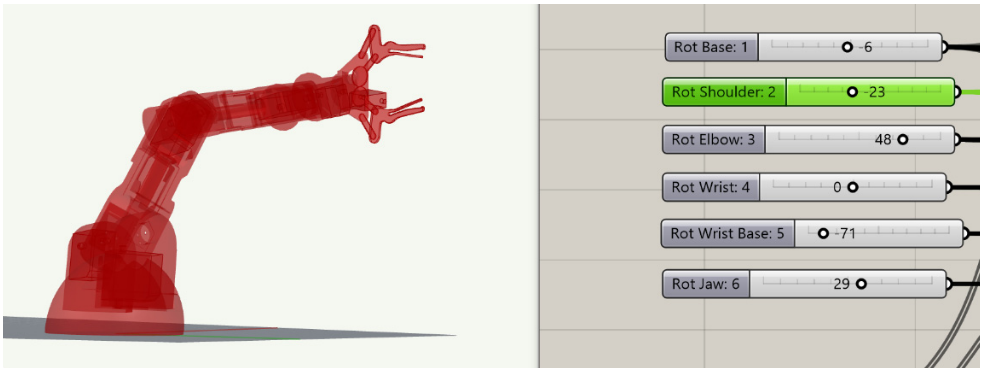

Figure 9. Coupling servomotors with computational geometry tools.

Table 7. Structure of the lessons for the workshop: BIM and Robotics.

Concept	Tools
Space	The virtual 3D space. Grasshopper
Virtual geometry	Rotation of objects using vectors and planes
Physical Geometry	Understanding of coupled servomotors.
Virtual-to-Physical Identification	Synchronized movement of the asset

4.3. Capstone Projects. Science, Technology, Engineering, Arts, Maths

The last set of demonstrators correspond to Capstone projects. If one adapts the Sawhney et al. [1] definition of Construction 4.0 to the AEC educational environment, the result is the following: "the confluence of educational emerging technologies together with the needs of the adaptation of the educational sector, are generating manifold possibilities for hands-on educational activities".

One of the key takeaways of the educational activities of the Laboratory in recent years is the integrative power of digital twins. The development of basic yet complete digital twins presumes knitting together many of the construction technologies in a single project. Moreover, it presumes to acquire a basic yet comprehensive level of understanding of how information flows from the physical to the virtual realms or vice versa. The development of digital twins in construction has been one of the driving forces of the laboratory activities. It has already been included as an optional course in the 4th Year of the new degree on civil engineering technologies (Table 1). With the name of "Digital Twins and Augmented Realities in Construction", the course will start from 2022–2023 academic year onwards. It will represent a fertile territory for exploration on the field in which measurements, coding, visualization, simulation, physics, statistics, design and many other disciplines are encompassed. Lectures and hands-on activities knitted together in the form of a capstone project represent the core of the new course. One points out immediately that the development of digital twins represents a clear example of a (S)(T)(E)(A)(M) activity in the framework depicted in Figure 1.

Hitherto, the environment that has been provided to students for the development of hands-on experiences proves effective. Several capstone projects have been developed by students at the lab in recent years, some of them represent incipient design concepts while others integrate comprehensively many technologies. Students are provided with a brief, with the necessary tools and with a collaborative working space. Educators and technicians are available for help at particular pre-scheduled hours for any enquiry students may have. The organization of the pre-scheduled laboratory hours require two separate levels:

- The fabrication level, in which participants create and develop DT following a tutored path, a set of lectures and a briefed project. This part may take up to 20 h of guided and autonomous work. At this level, the problems are mathematically simple and the focus is on the development of the three-dimensional DT (physical, virtual and connection). In this part, lectures and guidance correspond to 50% of the total time (10 h).

- The twinning level, in which students develop applications with added mathematical and physical complexity as well as a higher level of realism. These applications may include other layers such as VR/AR, BIM-enriched interactions or predictive capabilities. This part may take more than 20 h of autonomous work. Concepts of Interactive Object-Oriented Programming (OOP) and three dimensional computational geometry tools are needed. Thus, advanced lectures on such topics are also given. In the ideal scenario of students that have already performed cornerstone projects and workshops, the total required time for the development of digital twins reduces substantially.

Examples of developments on digital twins are presented in Figures 10–12. In particular, these examples show the potential of digital twins in the specific field of structural engineering. However, its implementation is not limited to this field [23]. For instance, Figure 10 displays a basic digital twin of a beam (built using foam for visualization purposes). The beam is subjected to a controlled rotation at the end. The value is sent to the computer using an Arduino via a serial port. A graphical user interface that displays both shear and direct stresses in real time was developed in processing [43]. Figure 11 displays a basic digital twin of a simply supported beam (in this case, made of stainless steel). The beam is subjected to a controlled load and its corresponding response is measured using a laser (deflection). The value is sent to the computer using an Arduino via a serial port. A graphical user interface that displays the phenomenon visually and quantitatively was developed in Processing [44]. Figure 12 shows a digital twin of a cable net structure. In this case, more variables are monitored and linked to the computational model. The effect of temperature (measured at key points of the net) is coupled in real time via IoT and computational geometry to a structural model [45]. There is a huge margin for sophistication in this field. Not only on the level of sophistication of the mathematics in which the project may be underpinned but also, on the level of sophistication of the incoming technologies. In this paper, only the developed works that fit to the scope of the educational proposal of Figure 1 are presented. Other twins that involve more advanced VR/AR technologies and computer vision have been also developed by the group at master levels [46,47].

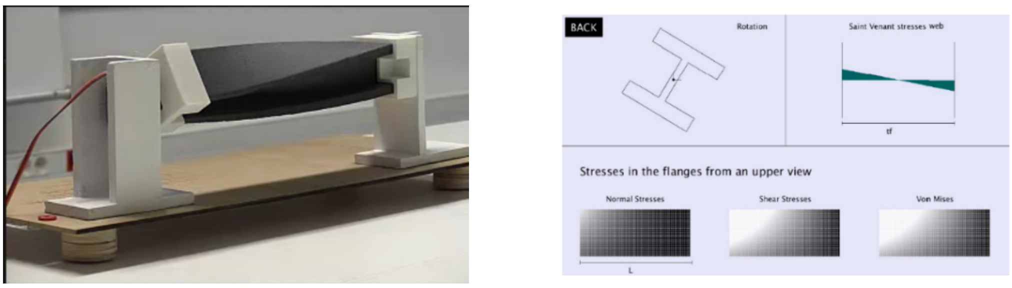

Figure 10. Beam subjected to torsion loads. Physical and virtual representations.

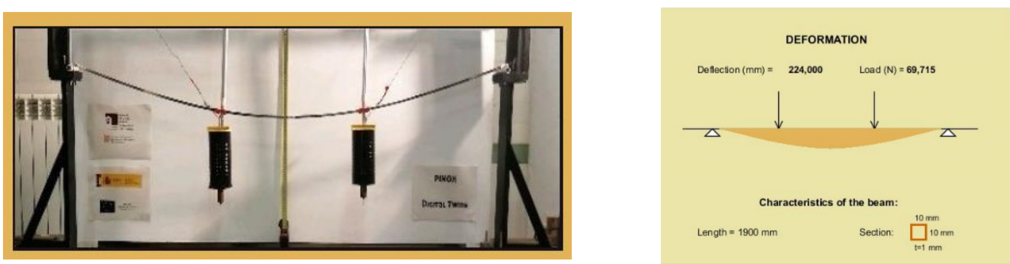

Figure 11. Beam subjected to transverse loads. Physical and virtual representations.

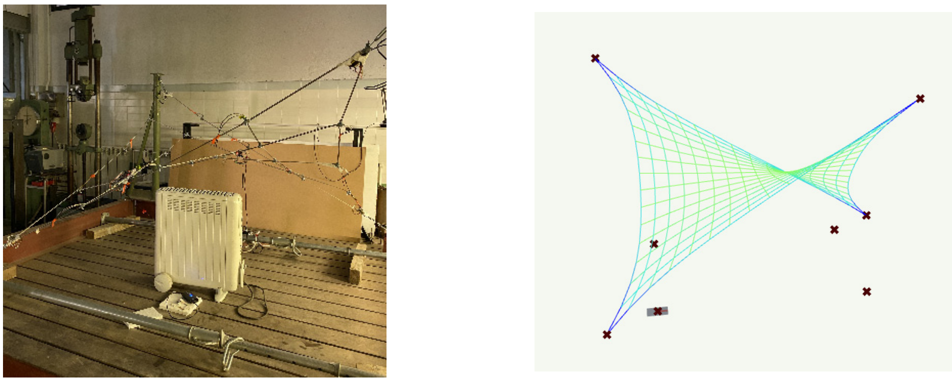

Figure 12. Cable net. Identified corner using low-cost TLS.

4.4. Relevance of the Activities from the Construction 4.0 Perspective

The relevance of the material needs to be depicted to AEC students. Generally speaking, it is well understood that disaggregated material may become irrelevant and counterproductive. In the following, a brief explanation of the benefits of each demonstrator is summarized and presented succinctly.

Cornerstone projects: Coding represents a paramount skill in Engineering. Acquiring coding skills is relevant to all engineering students. In particular, even though AEC students may follow formal courses on programming, the proposed workshops focus on two specific aspects that are seldom present in AEC classrooms: (i) the development of interactive event-driven applications with a focus on the variable *time* and (ii) the development of computational geometry applications with a focus on programming on a 3D *space*. Both *time* and *space* are fundamental in the development of practical applications suggested in further workshops.

- Workshops:
    - Sensor-to-cloud represents a journey from physical-to-digital. AEC classrooms are filled with countless attempts of understanding both natural and built environment. Practically every single magnitude studied in AEC is prone to be measured with sensors. Acquiring basic skills on measurement is thus, very relevant.
    - Three-dimensional (3D) printing represents a journey from a virtual space to the materialization of an object. The workshop provides not only a better understanding of the virtual space but also, it sets some realisms to the boundaries provided by 3D printers. In AEC, physical boundaries are always present, the built environment is limited by the capacities of the means.
    - Scan-to-BIM represents a journey from physical magnitudes to a BIM-compatible space. The workshop shows one of the most promising technologies for the built environment, which is laser scanning. The workshop provided a real time illustration of how points are measured with sensors (lasers, accelerometers in this case) and virtualized with computational geometry tools. In AEC, the use of "as-built" entities in BIM software presumes an understanding of these principles.
    - BIM-to-Robotics represents a journey from virtual to physical within a BIM-compatible space. The workshop introduces the potential of automation in construction with accessible and affordable equipment. It illustrates to AEC students what has been more traditionally present in other engineering branches, instrumentation and control of machines.
- Capstone projects: Digital twins as pedagogical vehicles represents a comprehensive activity. Both the development as the usage are didactic. The flow of information goes from physical-to-digital and vice versa. Sensors are needed, Virtual spaces are needed and a seamless communication between both realms is required. For this purpose, programming interactively using *time* and *space* is a requirement. Digital

twins also represent one of the most promising conception in the built environment for a better understanding and management of the assets at design, construction and maintenance stages.

5. Conclusive Remarks and Outlook

Developments and findings of the recently finished educational project MATES-to-STEAM are presented in this article. The findings are classified in the following key takeaways:

- Current state-of-the-art technologies for Construction 4.0 from an industry perspective were identified and analyzed. Specific educational applications of these technologies based on affordable, accessible and scalable tools were also identified. The categorization of the technologies is according to the definition of Sawhney et al. [1]: industrial production, cyber–physical systems and digital technologies. The literature review shows educational gaps as well as educational needs for the systematic use of tools in AEC classrooms. On the one hand, industrial production requires massive deployment of facilities, which is a drawback for implementation. On the other hand, digital technologies are quite established in the educational literature. In between, it is pinpointed how cyber-physical systems represent an accessible and affordable way of bridging the gap in AEC classrooms when it comes to implementing Construction 4.0 activities in which both Physical and Virtual realms are intertwined.
- One of the key takeaways of the educational activities of the Laboratory in recent years is the integrative power of digital twins. The development of basic yet complete digital twins presumes knitting together many of the Construction technologies in a single project. Moreover, it presumes to acquire a basic yet comprehensive level of understanding of how information flows from the physical to the virtual realms or vice versa.
- It is observed that Civil Engineering students are lacking specific knowledge for their proper inclusion in the Construction 4.0-related job market. This aspect is being addressed by educators and schools at a rather slow pace. Civil engineering schools are unevenly integrating Construction 4.0 activities in existing curricula. Coding and computational geometry tools are cornerstone skills that are required throughout the development of other technology-rich workshops.

Following the depicted classification, a framework for defining an affordable, accessible and scalable implementation of Construction 4.0 in a new degree on Civil Engineering Technologies was proposed. Cornerstone projects, workshops and Capstone projects were conceived with the intention of filling the identified gaps. All activities were knitted together using a (S)(T)(E)(A)(M) educational approach. Cornerstone projects are intended to foster motivation at early stages of the degree. Maths (M) and Arts (A) are blended together in hands-on activities. Subsequently, the set of workshops are intended to provide necessary knowledge on different engineering (E) technologies (T) with a critical scientific approach (S). Thus, the capstone projects result on integrators of all aspects dealt with along the degree. A (S)(T)(E)(A)(M) development of digital twins for civil engineering represents an accessible, affordable and scalable vehicle for infusing Construction 4.0 in civil engineering classrooms.

In the years to come, a systematic implementation of all demonstrators depicted in the report will be deployed as the new degree of Civil Engineering Technologies develops. Further research will be needed in more quantitative aspects of the longitudinal research such as assessment on the learning processes, effectiveness of the designed path and ultimately, adequacy of these workshops with the job market.

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