

STEAM activities for civil engineering curricula. From Calculus to Digital Twins

Rolando Chacón

School of Civil Engineering
Universitat Politècnica de Catalunya
Barcelona, Spain
ORCID 0000-0002-7259-5635

M. Rosa Estela

School of Civil Engineering
Universitat Politècnica de Catalunya
Barcelona, Spain
ORCID 0000-0002-4717-9111

Abstract—This full paper describes a set of pedagogical activities designed for students of all academic years in civil engineering programs. The pedagogical project has a twofold aim: i) exposing civil engineering students to Construction 4.0-related technologies and ii) fostering motivation and creativity among students by including STEAM by-design. In this paper, a set of STEAM activities designed for selected courses of this new degree in Civil Engineering Technologies is described. These activities are designed for the sake of promoting Construction 4.0-related skills to broad audiences in civil engineering by means of a learning pathway. This pathway is conceived using several branches of Construction 4.0. Namely, Industrial Production, Cyber-Physical Systems and Digital Technologies. All activities are designed using accessible and affordable Hardware and Software for scalability purposes. The selection includes a broad range of topics that are routinely taught in all academic years (1st to 4th) of the new degree.

Keywords—*STEAM, Civil Engineering, Construction 4.0*

I. INTRODUCTION

Engineering educators are continuously challenged for cultivating technical competencies in students that are faced to a continuously changing professional sector. The field of civil engineering faces grand challenges when it comes to digitalization of the sector. As a result, the present generation of civil engineering students encounter massive advances in sensing, information and computing technologies that continuously provide to the Architecture, Engineering and Construction sector (AEC) ways for dealing with the large variety of technical information at all project stages. The whole project life cycle, from conception, design, construction, to operation and maintenance is continuously infused with a rising amount of ubiquitously generated and distributed data. New sensors, new forms of visualization and new interoperable design tools are increasingly intertwined. The manifold forms of visualization, information modelling and simulation (VIMS) are called to be part of centralized information hubs in which all stakeholders establish data flow seamlessly [1].

Instrumentation, data-gathering, sensing, automation and construction robotics in civil engineering education has been pinpointed as a need for several years [2][3]. Nevertheless, civil engineering schools worldwide has not yet massively integrated instrumentation, sensing technologies, automation and data integration within formal curricula. Even though technologies have allowed proper implementation of

laboratory-based environments, their cost have been prohibitive for a massive application at undergraduate levels. As a result, academic experiences in which attempts to infusing such technologies in AEC education are scarce.

Education-wise, a laboratory-based pedagogy in science and engineering has been one of the greatest and most effective tools [4]. Physical experiences foster cognition and provide effective skill acquisition. Teaching labs are used in civil engineering to let the students discover and measure phenomena. Classical subjects are often provided with laboratory sessions in which students manipulate samples and develop reports on experiments in which magnitudes with practical applications are characterized. However, equipment is often expensive and limited. Consequently, students seldom develop their own measurement devices. In last years though, with the advent of low-cost electronics, the development of open-source labs has become plausible in several fields [5][6]. In recent years with the disruption of IoT, several AEC academic examples of implementation of low-cost systems in cities [7], buildings [8] water supply chain [9] or monitoring of historical constructions [10] have been published. When it comes to education, the development of IoT devices in civil engineering classrooms shows great potential due to the increasing affordability, both technical and economical [11]. AEC colleges and universities are increasingly infusing electronics, fabrication, sensors and coding. Examples in the fields of structural analysis [12-13], structural dynamics [14-15] and responsive architecture [16] show the great potential in many of the disciplines of the AEC sector.

The paper describes a set of pedagogical activities designed for students of civil engineering bachelor degrees at the School of Civil Engineering in Barcelona, Spain. The pedagogical project has a twofold aim: exposing civil engineering students to Construction 4.0-related technologies and ii) fostering motivation and creativity among students by including STEAM by-design. The activities are focused on the development of a set of workshops that erect a personal learning path for students of the School. Some of those workshops have already been systematically implemented in recent years. Some other are designed but not yet implemented. The paper shows the key takeaways of an educational project developed at the School of Civil Engineering aimed at infusing Science, Technology, Engineering, Arts and Mathematics throughout the development of a new degree in Civil Engineering Technologies.

II. FRAMEWORK OF THE DESIGNED LEARNING PATH

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, to the built environment. 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 within Industry 4.0. According to Sawney et al. [17], 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 (robots, digital twins, sensors-connectivity-actuators) and digital technologies (BIM, extended realities, interoperability, cloud computing, blockchain, AI, computer vision, etc.).

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. The world is changing and the need of skillful professionals who are able to provide innovative and creative solutions from a global perspective using the knowledge of the twenty-first century is a must. Civil engineering is an essential part of this development towards the societies of the future. It contributes to 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.

A 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 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 [18]. 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. Presently, the availability of educational online content, though sometimes disaggregated, is incredibly fertile for committed learners.

Figure 1 displays the framework of the designed learning path. The chosen degree is Technologies in Civil Engineering, which is a four-year long program recently implemented at our School. Students in this new degree are in their 2nd academic year by the 2020-2021 program. The framework encompasses cornerstone projects, capstone projects and a series of workshops. Over the past two years, a cornerstone project on interactive programming of mathematical functions have been successfully implemented. More than 150 students have already developed a coding activity in the context of Calculus, which is a 1st year compulsory topic. Another cornerstone project has already been prepared and implemented. This project is related to computational geometry and it is meant to introduce students to coding analytical geometry within virtual spaces. Both activities present an intertwined link between Maths (M) and Arts (A) throughout visual programming. It is worth pointing out that the former has already been infused within formal courses whereas the latter has only been developed as optional.

Then a series of activities for subsequent years have been identified, planned, developed. Some of them have been implemented for several years at Master levels whereas other are recently developed. These activities are initially designed as optional. The personal learning path is conceived for following the latest technological trends that are referred to as Construction 4.0. Smart infrastructure, Digital Fabrication, Automation and Robotics and Extended Realities are included. The Building Information Modelling layer is included in most of the workshops. By the end of the degree, capstones projects with advanced applications of cyber-physical systems in construction, namely, digital twins are planned as the final activity of this personal learning path. It is worth pointing out that the workshops are not necessarily meant to follow the structure of the 2nd and 3rd academic years.

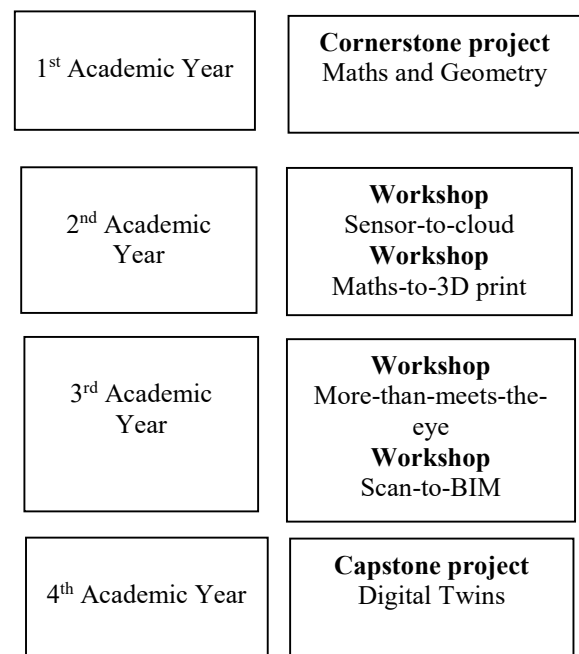


Fig. 1. Organization of the activities in a Construction 4.0 framework

III. CORNERSTONE PROJECTS. MATHS AND GEOMETRY

The cornerstone projects are established as activities related to Calculus and Computational Geometry. These activities are conceived for the sake of exposing our civil engineering students to the development of computational applications using basic concepts of mathematics and geometry.

The first project deals with an activity in which functions, derivatives and an introductory programming challenge are intertwined. Applied introductory programming are always useful for civil engineering students due to their uneven prior acquaintance with coding skills. The project is 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 course are given an optional yet graded task. The challenge of the activity is: For a given implicit function, an interactive visual application must be developed. This application requires 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 snippet. Students are entitled 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.

The activity has already been embedded in regular courses of Calculus. These students often have no prior knowledge in coding. The chosen tool is the platform Processing [19]. Processing is a programming language, development environment, and online community that promotes coding literacy within the visual arts as well as visual literacy within coding. The platform is considerably used by artists for the development of object-oriented, event-driven interactive applications in a diversity of realms such as mapping, music, animation, physics or installations. For the depicted activity, the full capability of the platform may seem overwhelming but its simplicity (and further potential in other workshops) gave to the facilitators strong reasons to use it. The language syntax is identical to Java but with a few modifications. Time and space are blended together intuitively. Lessons were conceived for students with no prior knowledge in coding visual applications and were structured in six sections as shown in Table 1.

Table 1. Structure of the lessons for the cornerstone project. Interactive programming

The Canvas The unit: Pixels The coordinates	Frames per second Milliseconds Delay	Points, Lines, Vectors Rectangles, Squares, Circles, Triangles
Space	Time	Primitives
Data types If/then/Else, For, While Functions	Background, RGB, Color, Fill, Stroke	Translation Rotation
Basic instructions	Format	Movement

A basic structure of a visual program in Processing follows two functions: i) `setup()`, in which aspects such as size of the Canvas (in pixels), definition of path to files or to

serial communication and other fixed parameters are established. This function executes once and must contain not invariable parameters. Subsequently, ii) the function `draw()` which runs indefinitely. It runs according to the order of written commands from top to bottom and repeats in a loop. The speed of execution between each loop can be regulated by using the delay command.

The first edition of the activity was set during the 2019-2020 academic year for 1st year students of Calculus at Bachelor levels. As documentation, a set of pdf files as well as an online video tutorial are given to the students. Other online resources available are recommended. Unfortunately, face-to-face tutorships were not allowed during this edition due to Health Regulations in the country. As a result, only web meetings were held during the experience. The second edition of the activity has been held during the 2020-2021 academic year for 1st year students of Calculus at bachelor levels as well. Online meetings have also been the way to answering questions in a session devoted to it.

When it comes to numbers, for the first edition, a total amount of 158 students were enrolled. 50 curves of implicit functions were identified (cardioid, nephroid, lemniscata, cissoids, etc). The activity was developed by groups of up to 3 students, which represented nearly 99% of participation. 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. 20 groups (58 students) submitted adequate projects, which represents 50% of participation. 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 6 European Credit Transfer System (ECTS) with an approximate amount of 4 hours of lectures per week during the whole academic year.

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 to the coordinates generated by the mouse pointer $(x,y)=(mouseX, mouseY)$. Maths and interactive programming were successfully blended together as a learning activity.

Fig. 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.

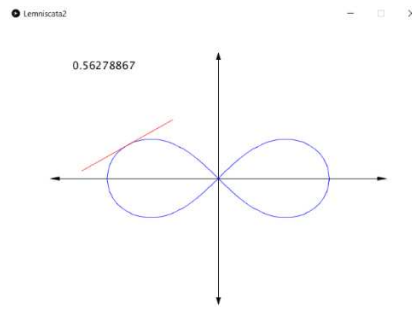


Fig. 2. Typical results obtained with a curve and its tangent line in Processing

The second part of the cornerstone projects is related to computational geometry. In order to explore adequate scope and limitations of the activity in a regular course, the workshop has been under development and preparation with more advanced students. These students had no prior knowledge in algorithmic programming but are acquainted to Calculus and coding.

The main idea is to expose students to computational geometry in a virtual space that is eventually compatible with BIM. Points are there treated in (x,y,z) text form and transformed to points instances of the “Rhino.Geometry” set of classes available in Grasshopper [19]. 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 2 displays the present structure of the lessons.

Table 2. Structure of the lessons for the cornerstone project. Computational Geometry

Points, lines, planes, surfaces, volumes	Draw functions Draw derivatives Draw tangent planes using gradient vectors	GH and Python. List, tuples, dictionaries
Grasshopper	Functions in GH	Coding

Fig. 3 shows a typical window of an algorithmic programming snippet. One can see boxes and links between those boxes, which are conceived for treating certain types of input and for generating certain types of output. These boxes can be also tailor-made using Python, Visual Basic or C# languages, which opens a vast array of possibilities for manifold applications in engineering.

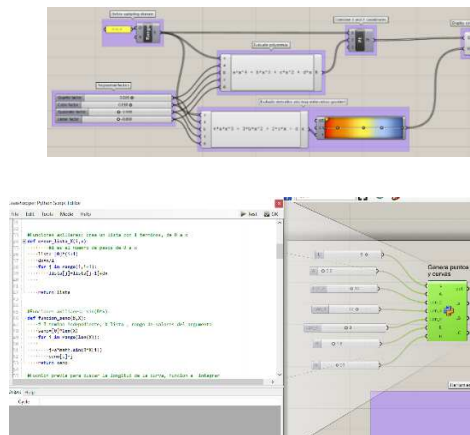


Fig. 3. Schematics of visual algorithmic programming including connections and codes.

The result of these codes is visualized in Rhino as shown in Fig.4. Students can develop geometries (from simple to complex) using mathematics, visual programming and beautiful visualizations.

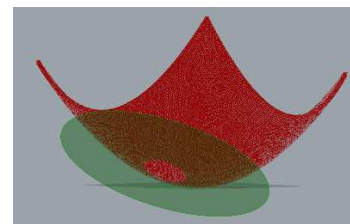
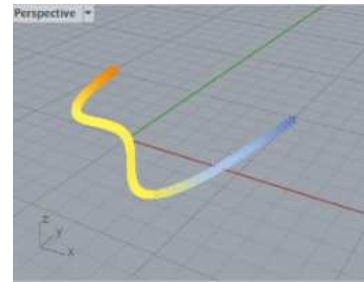


Fig. 4. Simple geometries developed in virtual spaces using computational geometry. Curves and surfaces.

IV. (S)(T)(E)(A)(M) WORKSHOPS

The core of the project is a set of workshops aimed at providing Construction 4.0 concepts using a (S)(T)(E) approach. Smart Infrastructure, Digital Fabrication, BIM and Extended Realities represent Construction 4.0 branches that are covered with the set of activities. Some of the workshops have been systematically developed in the context of Master courses while others are prepared for future deployment.

A. Sensor-to-cloud

Knowledge on basic electronics and circuitries is a must in all engineering branches. Low-cost prototyping platforms are ideal tools for massive educational deployments in which hands-on activities are developed. In the last years, workshops on the use of sensors, data acquisition systems and user interfaces have been developed at the School in the form of lessons for introductory electronics using the platform Arduino [20]. 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). A vast amount of online content and resources for students is nowadays available. The platform is considerably used by DIYers and STEAM-based educational programs. Object-oriented, event-driven interactive applications in a diversity of realms can be developed. The language syntax is identical to Processing, one of the platforms used for the cornerstone projects. On the other hand, an IoT platform developed at our School for connecting sensors to the cloud is used for the corresponding cloud services. Table 3 displays the structure of the required lessons.

Table 3. Structure of the lessons for Sensor-to-cloud

LEDs Knobs	Analog (LDR, Accel) Digital (Laser, Ultrasound)	Servomotor
Basic circuitry	Sensors	Actuators
Data types Functions	Measurement accuracy Rotation	Concepts on things, keys, tokens, payload
Coding	Calibration	Cloud services

A basic structure of an Arduino code follows two functions: i) setup(), in which aspects such as initialization of functions, serial communication or other fixed parameters are established. This function executes once and must contain not invariable parameters. Subsequently, ii) loop() which runs indefinitely. It runs according to the order of written commands from top to bottom and repeats in a loop. The speed of execution between each loop can be regulated by using the delay command. We can see then than students acquainted with the cornerstone project follow a sort of continuation of tasks using same syntaxes.

In previous editions of the workshop the students i) connect basic circuitry of sensors and servomotors, understand the basics of microcontrollers and ii) send the measured magnitudes to the cloud via the provided IoT platform. Fig. 5 shows images of some of the already developed workshops and Maker experiences.



Fig. 5. Sensor-to-cloud developed in recent years in which sensors, microcontrollers and interfaces are ut together.

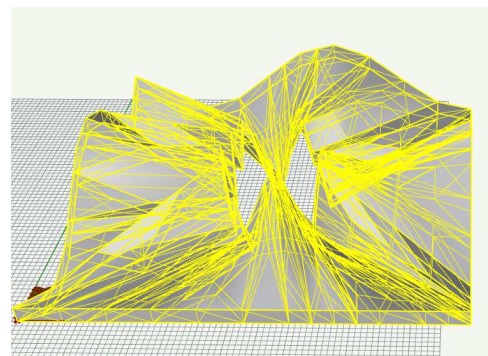
B. Maths-to-3D print

Knowledge on basic concepts of 3D printing is a must in all engineering branches. Students are increasingly acquainted with 3D modelling, which is a major requirement for

generating physical objects using 3D printing. However, not all students have been adequately exposed to the generation of physical objects. The main aim of this workshop is to link concepts of computational geometry treated in the cornerstone project to the materialization of mathematically defined surfaces and volumes. Students are guided in the generation of a complex shape with specific requirements for 3D printing (reduced volume, reduced thickness, need of support material, etc). The workshop is straightforward for students acquainted with the Rhino.Geometry namespace depicted in the cornerstone project. At the end of the workshop, students 3D print out a complex shape (like the one displayed in Figure 6 whose mathematical definition is entirely known and defined by the students. 3D printers as well as base material are provided by the School in limited amounts. Students are also briefed with economy and sustainability conditions for avoiding unnecessary generation of pieces. Figure 6 displays the virtual shape, the Python snippet within the Grasshopper environment and the physical shape.

Table 4. Structure of the lessons for maths-to-3D print

Surfaces, BRep, Volume	Thickness, density, need of support, total volume, printing time	STL, IGES
Computational geometry	3D printing requirements	File formats



```

Grasshopper Python Script Editor
File Edit Tools Mode Help
17 def de(x):
18     for j in range(1,i+1):
19         lista[j]=lista[j-1]+dx
20     return lista
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220
2221
2222
2223
2224
2225
2226
2227
2228
2229
2230
2231
2232
2233
2234
2235
2236
2237
2238
2239
2240
2241
2242
2243
2244
2245
2246
2247
2248
2249
2250
2251
2252
2253
2254
2255
2256
2257
2258
2259
2260
2261
2262
2263
2264
2265
2266
2267
2268
2269
2270
2271
2272
2273
2274
2275
2276
2277
2278
2279
2280
2281
2282
2283
2284
2285
2286
2287
2288
2289
2290
2291
2292
2293
2294
2295
2296
2297
2298
2299
2300
2301
2302
2303
2304
2305
2306
2307
2308
2309
2310
2311
2312
2313
2314
2315
2316
2317
2318
2319
2320
2321
2322
2323
2324
2325
2326
2327
2328
2329
2330
2331
2332
2333
2334
2335
2336
2337
2338
2339
2340
2341
2342
2343
2344
2345
2346
2347
2348
2349
2350
2351
2352
2353
2354
2355
2356
2357
2358
2359
2360
2361
2362
2363
2364
2365
2366
2367
2368
2369
2370
2371
2372
2373
2374
2375
2376
2377
2378
2379
2380
2381
2382
2383
2384
2385
2386
2387
2388
2389
2390
2391
2392
2393
2394
2395
2396
2397
2398
2399
2400
2401
2402
2403
2404
2405
2406
2407
2408
2409
2410
2411
2412
2413
2414
2415
2416
2417
2418
2419
2420
2421
2422
2423
2424
2425
2426
2427
2428
2429
2430
2431
2432
2433
2434
2435
2436
2437
24
```


C. Scan-to-BIM

Knowledge on basic concepts of BIM is also a must in AEC. Students are, however, unevenly acquainted with 3D modelling using specialized Software that is increasingly interoperable and user-friendly such as Revit [22], which also includes computational geometry tools such as Dynamo [23]. Basic BIM tutorials and courses have been available in the AEC educational sector for several years. Reviews on educational practices, needs and challenges of BIM in AEC classrooms are available [24]. Building Information Modelling (BIM) changed paradigms one decade ago. The level of implementation of BIM in the market is presently high enough. Education-wise, BIM has hitherto been adopted by many AEC-related schools and universities. BIM-friendly environments are crucial for interoperability and as result, they represent an ideal standard in education at various levels. All sorts of 3D branches such as modelling, measurement, simulation, monitoring, construction tracking, and computational geometry can seamlessly communicate one to another. Proper ontologies and protocols need to be established for such purposes.

This particular workshop is not related to basic tutorial of a given BIM platform. Instead, it is conceived as a continuation of the computational and mathematical geometry set developed in previous workshops. Scan-to-BIM is a workshop in which students use a Terrestrial Laser Scanner developed at the School for the generation of point clouds in simple geometries such as planes, surfaces or volumes. Point clouds are measured and sent to algorithmic programming tools in BIM-enabled platforms such as Grasshopper or Dynamo. The analysis of the measurement requires mathematical understanding and identification of methods for the definition of these geometries in a virtual space in which these geometries can be embedded (S)(E)(M). This workshop is aimed at introducing students to the “as-built” concept. The build environment is increasingly virtualized at design levels using BIM but also, increasingly virtualized at construction stages using several technologies, in which Terrestrial Laser Scanners are often used.

TLS technologies implemented for educational purposes is still scarce in the AEC academic educational research. Most probably, this is due to the high-cost professional TLS have had in last years. However, it is emerging as a new teaching tool, capable of generating a new environment several sources of information are concentrated in a 3D virtual model. Students can be physically present during the generation of the point cloud and be subsequently provided with the corresponding results in plain text formats. 3D model learning environments are potential paradigm shifters in teaching and learning process. TLS emerges as one of the natural devices to bring real 3D information from the site to civil engineering classrooms. As an alternative, a DIY laser scanner was developed at the School (Fig. 7) and facilitates its use in AEC classrooms.



Fig. 7. Terrestrial Laser Scanner developed at the School (Virtual and Physical)

The workshop begins with measurement in live sessions. The TLS measurement process is presented as well as the workflow to obtain 3D point clouds in real time using a BIM-enabled Terrestrial Laser Scanner. This device sends to Grasshopper (the computational geometry platform) filtered points in real time already in the Rhino.Geometry namespace format, which facilitates the workshop to the students who get directly the point cloud. This previous step is also aimed at triggering cognition by means of an immersive visualization of 3D point collection and thus, understanding of the active principles behind professional TLS can be illustrated. A scientific critical debate of the accuracy of the results can be triggered in the classroom together with factors that affect the measurement such as the environmental light, the reflectivity of the material, the angle of incidence of the laser beam on the object surface, positioning errors or range limitations. Figure 8 displays the measurement set deployed in the last edition in which a surface, a sphere and a wall were used as examples.

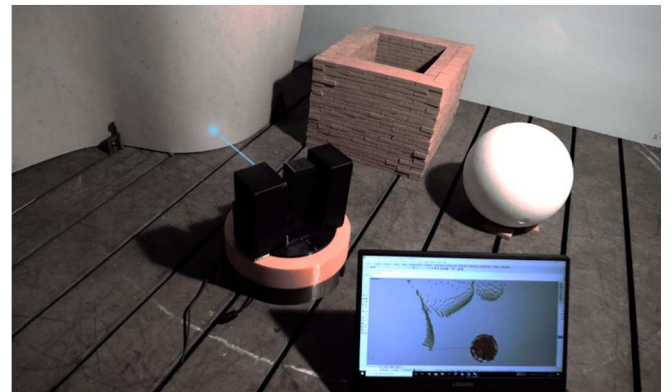


Fig. 8. Measurement set, Scan-to-BIM of a sphere, wall and surface.

Results are then embedded in Grasshopper and the workshop consists of identification of simple geometries such as planes, surfaces and volumes. Figure 9 shows examples of the results obtained with the TLS already visualized using the Rhino.Geometry namespace. Further explanations about the development and functionalities of the TLS have been submitted for publication in a journal paper.

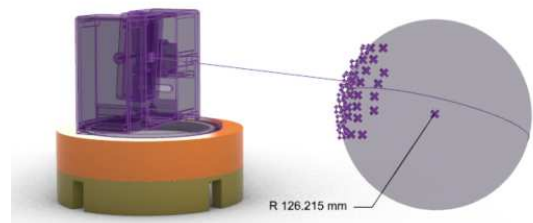
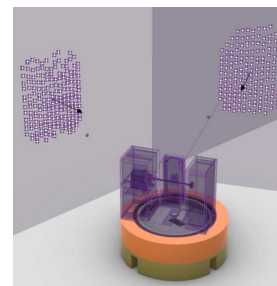


Fig. 9. Physical measurement of the set within Grasshopper.

D. More than meets the eye. Extended realities

This workshop is nowadays under development. VR and AR technologies are relatively well-established tools with a diversity of applications spanning many fields. VR is an interactive simulated environment generated with computers which replaces the user's physical world with a fully synthetic environment. The interaction between such an environment and the user is typically generated with special screens, soundsystems, and joysticks embedded in customized helmets or glasses. AR is a real-world environment enriched with layers of information that are perceived by the user by means of multiple modalities. Screen-infused glasses with embedded hardware are one typical application of AR systems. However, mobile phones, light projectors or other reality-enhancers are also considered as such. In such scenarios, the user's awareness of the real environment is preserved by compositing physical/ virtual worlds in a blended space. The user sees the real environment and layers of graphical information (or text) that is added and updated in real time. One of the uncontested contributions of VR/AR is their potential to enhance sensorial perception as well as to trigger advanced learning to users by means of immersive experience because realistic immersive creations represent tools for visual communication of massive data. So far, the workshop has been related to the development of VR and AR applications that enhance the perception of the structural behavior of real tests [25] using sensors, microcontrollers, the cloud and a VR user interface. The results obtained are very promising for limited users in research facilities but it is less affordable and accessible for larger groups. A thorough understanding of the technologies available nowadays is needed for the sake of deploying meaningful activities related to extended realities to larger groups in AEC classrooms.



Fig. 10. Virtual reality reproduction of a test using real time measurements.

V. CAPSTONE PROJECTS. DIGITAL TWINS AND ROBOTICS

The development of digital twins from scratch by students represents an ideal capstone project in which all technologies are summarized [26]. Physical systems that may or not included automation and robotics are virtualized using sensors. Computational geometry and/or visual programming tools allow developing graphical user interfaces for twinning the assets. Applications with minimum ingredients for basic examples can be developed in due time by civil engineering students that have followed the personal learning path. The systematic use of DT proves useful and affordable for the development of encompassing capstone projects. Interestingly, the development of digital twins provides a basic understanding of cyber-physical systems, which is one of the main branches that can be found in Construction 4.0. Digital Twins have already been explored by many students at

our laboratory facilities and guidance for cornerstone projects has already been provided. Figure 11 to 13 show several examples already developed in structural analysis, steel structures or geotechnics.

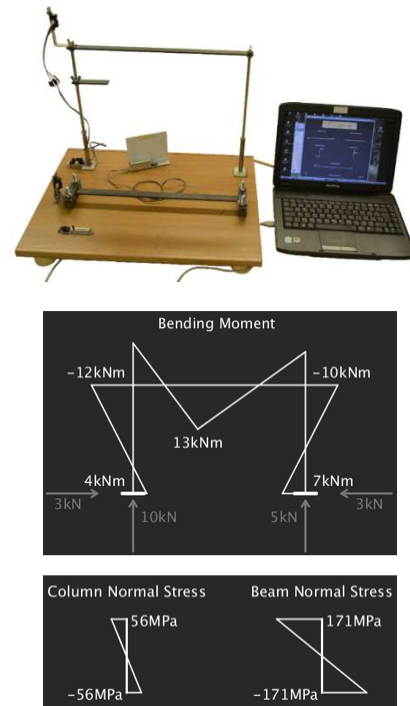


Fig. 11. Digital twin of a miniature one-bay frame

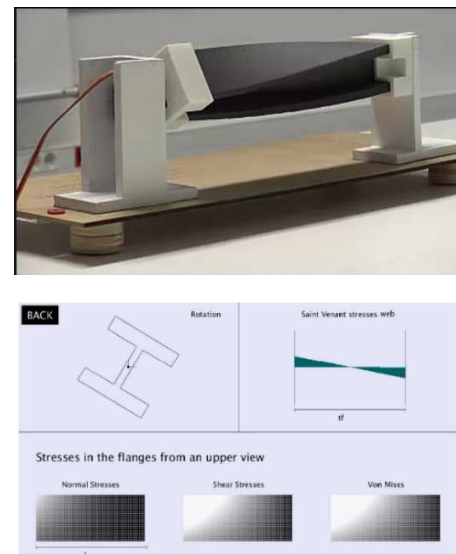


Fig. 12. Digital twin of a miniature beam subjected to torsion loads

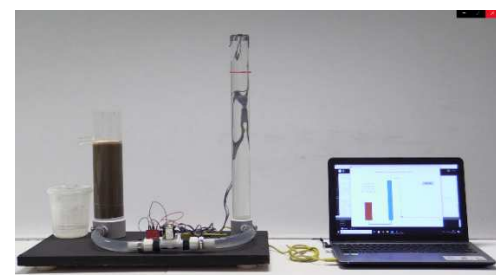


Fig. 13. Digital twin of a miniature reproduction of a permeability test in geotechnics

VI. CONCLUSIVE REMARKS

In this paper, a set of cornerstone, capstone and intermediate workshops encompassing fabrication, coding and instrumentation in civil engineering courses are presented. The set is aimed at facilitating a personal learning path on Construction 4.0 to AEC students. The workshops are conceived in a way added technical competences are added to motivation and creativity among students by merging (S)(T)(E)(A)(M) concepts. Blending together these concepts is becoming paramount in civil engineering schools since the present generation of civil engineering students encounter massive advances in sensing, information and computing technologies that continuously provide to the Architecture, Engineering and Construction sector (AEC) ways for dealing with the large variety of technical information at all project stages.

The implementation of these developments in the classroom in the context of Construction 4.0 is under development. The effectiveness of these tools has been assessed in some workshops (Cornerstone projects in Calculus, with positive results) but have not yet fully deployed in others (i.e., more than meets the eye).

Since new and emerging technologies in the AEC sector are transforming and creating new opportunities, the need of infusing AEC curricula according to current technological progress becomes a crucial debate. In Construction 4.0, advances in Industrial Construction (Robotics and Digital Fabrication), Cyber-Physical Systems (Digital Twins or Smart Infrastructure) and Digital Technologies (BIM, and Extended Realities) represent the advent of a new era in the field. The paper shows an example of a cyber-physical system that can be infused within AEC classrooms with scientific (S), technological (T), engineering (E), artistic (A) and mathematical (M) perspectives.

ACKNOWLEDGMENT

The authors acknowledge the financial support provided by the Institut de Ciències de l'Educació de l'Universitat Politècnica de Catalunya in the frame of the annual grants for innovative practices for the project "de las MATES al STEAM". Likewise, the authors acknowledge the commitment of the students working in the project

REFERENCES

- [1] F. Leite, Y. Cho, A. Behzadan, S. Lee, S. Choe, Y. Fang, Y. R. Akhavan, and S. Hwang. "Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry". *Journal of Computing in Civil Engineering*, vol. 30(6), 2016.
- [2] W. Boles, J. Wang. "Construction Automation and Robotics in Civil Engineering Education Programs". *Journal of Professional Issues in Engineering Education and Practice*, vol. 122(1), pp. 12-16. 1996
- [3] S. Christodoulou. "Educating Civil Engineering Professionals of Tomorrow." *Journal of Professional Issues in Engineering Education and Practice*, vol. 130(2), pp. 90-94. 2004
- [4] L. Feisel and A. Rosa. "The Role of the Laboratory in Undergraduate Engineering Education." *Journal of Engineering Education*, vol. 94(1), pp. 121-130. 2005
- [5] J. Pearce. "Building research equipment with free, open-source hardware." *Science*, vol. 337(6100), pp. 1303-1304, 2012.
- [6] F. Bouquet, J. Bobroff, M. Fuchs-Gallezot, and L. Maurines. "Project-based physics labs using low-cost open-source hardware". *American Journal of Physics*, vol. 85, pp. 216-222, 2017.
- [7] A. Alavi, P. Jiao, W. Buttler and N. Lajnef. "Internet of Things-enabled smart cities: State-of-the-art and future trends". *Measurement*, vol. 129, pp- 598-606. 2018
- [8] M. Karami, G. McMorro and L. Wang. "Continuous monitoring of indoor environmental quality using an Arduino-based data acquisition system". *Journal of Building Engineering*, vol. 16, pp. 412-419. 2018
- [9] J. Paul and W. Buytaert. "Chapter One: Citizen Science and Low-Cost Sensors for Integrated Water Resources Management". *Advances in Chemical Pollution, Environmental Management and Protection*, vol. 3, pp. 1-33. 2018
- [10] C. Basto, L. Pelá and R. Chacón. "Open-source digital technologies for low-cost monitoring of historical constructions". *Journal of Cultural Heritage*, vol. 25, pp. 31-40. 2017.
- [11] R. Chacón, D. Codony, and A. Toledo, "From physical to digital in structural engineering classrooms using digital fabrication". *Computer Applications in Engineering Education*, vol. 25, pp. 927-937, 2017.
- [12] J. Huang, S.K. Ong and A. Nee. "An approach for augmented learning on finite element analysis". *Computer Applications in Engineering Education*, vol. 27 (4). 2019
- [13] R. Chacón and S. Oller. "Designing experiments using digital fabrication in structural dynamics". *Journal of Professional Issues in Engineering Education and Practice*, vol. 143, pp. 1-9, 2016.
- [14] R. Slocum, R. Adams, K. Buker, D. Hurwitz, H. Mason, C. Parrish and M. Scott. "Response spectrum devices for active learning in earthquake engineering education." *HardwareX*, 4, e00032. 2018
- [15] K. Kensek. "Integration of Environmental Sensors with BIM: case studies using Arduino, Dynamo, and the Revit API." *Informes de la Construcción*, vol. 66(536), e044, 2014.
- [16] R. Chacón, H. Posada, A. Toledo and M. Gouveia. "Development of IoT applications in civil engineering classrooms using mobile devices". *Computer Applications in Engineering Education*, vol. 25, pp. 927-937, 2017.
- [17] A. Sawney, M. Riley, J. Irizarri. "Construction 4.0 An Innovation Platform for the Built Environment". London: Routledge. 2020
- [18] Pogosyan, M. (2020). "Development of individual learning paths system in engineering education". *Frontiers in Education* 2020.
- [19] <http://processing.org>
- [20] Grasshopper. Algorithmic modelling for Rhino. <https://www.grasshopper3d.com/>
- [21] <http://arduino.cc>
- [22] Revit. Multidisciplinary BIM Software. Autodesk. <https://www.autodesk.com/>
- [23] Dynamo. Open source graphical programming for design. <https://dynamobim.org/>
- [24] Wang, L., Huang, M., Zhang, X., Jin, R., Yang, T. 2020a. "Review of BIM Adoption in the Higher Education of AEC Disciplines". *Journal of Civil Engineering Education*, 146(3). [https://doi.org/10.1061/\(ASCE\)EI.2643-9115.0000018](https://doi.org/10.1061/(ASCE)EI.2643-9115.0000018).
- [25] Gürdür Broo, D., Boman, U., Törngren, M., 2021. "Cyber-physical systems research and education in 2030: Scenarios and strategies". *Journal of Industrial Information Integration*, 21. <https://doi.org/10.1016/j.jii.2020.100192>.