The CDIO model in architectural education and research by design

Lucyna Nyka, Jan Cudzik & Katarzyna Urbanowicz

Gdańsk University of Technology
Gdańsk, Poland

ABSTRACT: Architectural education has always been related to experimentation: that is, defining concepts, drawing sketches, working on models, then testing and modifying them. This activity mirrors the CDIO learning methods and objectives. Despite this, research studies into the applicability of the CDIO model in architectural curricula are scarce. In the discipline of architecture, hands-on experiences are associated not only with one of the most effective methods of education, but also with a particular way of carrying out research, that is research by design. In this article, the authors present the integration of the CDIO framework into the architectural engineering curricula at Gdańsk University of Technology, Gdańsk, Poland, discuss the results, and indicate which components of architectural education have benefited most from this integration. Another objective was to initiate a discussion on the potential impacts of implementing CDIO into architectural curricula, and its relation to the research by design concept.

INTRODUCTION

Architectural education always has been related to experimentation: such as defining concepts, drawing sketches, working on models, then testing and modifying them to change the characteristics of the space, structure and light. This coincides closely with the main objectives of the CDIO (conceive, design, implement and operate) framework of project development. The CDIO framework leads students through the whole procedure, from concept, through design to implementation and, finally, operation and evaluation of engineering projects. However, it is equally important for students to acquire personal skills and to raise their awareness of societal and environmental issues [1].

For many years, CDIO has contributed to the quality of teaching in various fields of study. The question arises of what, if any, are the advantages of implementing the CDIO framework into architectural education? Analysis of the CDIO annual conference publications from the years 2005 to 2019 [2] reveal that with few exceptions [3], CDIO is little used in architectural education or, if it is used, it does not stimulate a discussion among education researchers. Moreover, according to the information issued on the CDIO official Web site, its use is limited to only several departments:

> *CDIO is currently in use in university aerospace, applied physics, electrical engineering, and mechanical engineering departments* [4].

It is becoming clear that CDIO may serve as a cross-disciplinary academic model applicable to other fields of engineering education and even to non-engineering disciplines [5]. It has been successfully implemented in chemical engineering curricula [6], geology [7], mass communication technologies, such as multimedia, digital media, cinematography and advertisement [8], and many other fields of studies, including medical technology and bioengineering design [9].

Conceive, design, implement and operate engenders hands-on experience and *learning by doing* concepts, which many consider central to education in general [10] and engineering education in particular [11]. In this approach, as Pusca et al note:

> *As part of hands-on activities in different engineering courses, students create and use models as purposeful representations, i.e. to analyse behaviours, processes or properties* [11].

In the discipline of architecture, hands-on experiences are associated not only with one of the most effective methods of education, but also with a particular way of carrying out research, within so-called research by design practice. Since many schools worldwide are obliged to integrate Master degree students into research tasks, the research by design concept is receiving growing attention in architectural curricula. According to the European Association for Architectural Education (EAAE) Charter on Architectural Research …*Any kind of inquiry in which design is the substantial constituent of the research process is referred to as research by design* [12].

Blurring the borders between learning and researching not only inspires students, but also fosters their creativity. First and foremost, numerous studies on research by design practice give valuable insights into the structure of the design process, deepening understanding of its analytical and exploratory phases [13], the role of experimentation in the production of knowledge [14], and how research by design works so effectively by converging theory and practice [15]. All these findings can be applied to education, and provide a significant impact on design-based and experimentation-based teaching methods.

Gdańsk University of Technology (GUT) is a research entity, and was the first higher education institution in Poland to become a CDIO member on joining in 2011. Almost immediately, preparatory work was undertaken towards an integration of the CDIO framework into several undergraduate and graduate engineering programmes. In 2012, the Faculty of Architecture (FA-GUT) Council decided to adopt the CDIO-based model of curricula into architectural studies, for both undergraduate and graduate programmes. The general objective was to contribute to the learning outcomes, to shape more distinctively the FA-GUT educational profile and to make it a more inspiring place to study.

In this article, the authors present the process of adaptation of the CDIO framework into the architectural engineering curricula, explain its characteristics, discuss the results, and indicate which components of architectural education have benefited most from the CDIO integration. Another objective of this article is to initiate a discussion on the potential impacts of the implementation of CDIO into architectural curricula, and its relation to the research by design concept.

INTEGRATION OF CDIO INTO ARCHITECTURAL CURRICULA

The process of integration of the CDIO educational framework into the architectural curricula at the FA-GUT started with a series of workshops with Faculty members, who offered to be CDIO initiators - early adopters of the programme. The second step was to identify a group of subjects where the introduction of new methods and approaches would be most beneficial to the learning outcomes and research by design objectives. The CDIO applicability study confirmed that architectural design projects, which are the central components of architectural curricula, would benefit most from the adoption of new methodologies.

However, it became clear that the impact of the implementation of CDIO into architectural engineering programmes would be greater if related to the better integration of computational design, which included advanced modelling, automation, simulations and digital fabrication [16]. The objective was to make students able to test CDIO-based model verification against both traditional physical architectural models, usually made of cardboard, wood or gypsum, as well as digital ones. According to Klahr et al, who have researched the effectiveness of physical versus virtual models in engineering design education, both physical and virtual ones should be considered as *hands-on* [17]. While tactile physical models have always been present in architecture, in some cases, as Klahr et al argue, virtual models may seem advantageous. Klahr et al note:

> *This is an important factor because computers may provide a unique opportunity for hands-on activities with virtual materials that avoid many disadvantages of physical hands-on materials* [17].

Consequently, one of the main goals related to the introduction of CDIO was to create a better learning environment to stimulate active learning and researching on different kinds of models, including virtual ones. Moreover, a need for new topics and subjects was identified, which should be introduced or strengthened in the curricula, mainly related to computational design and prototyping.

Another goal was to use the opportunity of the adoption of CDIO to introduce interdisciplinary courses that would facilitate integration of architectural forms with different kinds of kinematic systems [18], including responsive and interactive ones. Another idea was to encourage students to experiment on merging architecture with floating structures, and on implementing light architecture and media architecture solutions into the process of designing, modelling and evaluating architectural ambient surfaces and environments [19].

This group of new issues initially seemed problematic for integration into precisely structured architectural curricula, since they were located in-between disciplines, such as architecture and electronics, architecture and mechanical engineering, architecture and environmental engineering [20], and even architecture and marine engineering. This triggered an invigorating discussion on the changing profession of architecture and subsequent new challenges related to technological advancements, cultural shifts, and environmental threats, with the conclusion that architectural curricula should reflect agile adaption to these changes and offer much room for critical investigations.

The next step in adoption of the CDIO educational framework was to map discipline-specific learning outcomes to CDIO objectives. Since architecture is one of the regulated professions, there are many curriculum requirements issued at both the European and national levels with which study programmes must comply. Therefore, study programmes are often verified against professional chambers' recommendations [21], UNESCO competency framework objectives, and the requirements of national and international accreditation boards.

However, the most important document is Directive 2013/55/EU of the European Parliament and of the Council of 20 November 2013 on the recognition of professional qualifications [22]. According to this document, architectural training, while maintaining a balance between theoretical and practical subjects, shall guarantee, at a minimum, the acquisition of the precisely defined knowledge, skills and competencies set out in 11 points. Revealed in the study was that eight of 11 learning outputs indicated in the Directive would substantially benefit from the integration of the CDIO model into existing curricula. This positive evaluation of the relevance of the CDIO educational framework opened up the process of integration of it into architectural engineering studies.

BENEFITS OF INTEGRATING CDIO INTO ARCHITECTURAL CURRICULA

Each building is a complex value-added engineering system, where structural design and spatial concepts are mutually interwoven, contributing to the tectonics of a building. Many different factors must be taken into account, such as statics, light quality, circulation of users, air circulation, environmental impacts and cost. The focus of architectural education always has been on critical thinking, modelling and verifying the model, but with the emergence of innovative manufacturing tools, new opportunities arise. Apart from traditional handmade scale models of architectural objects or systems, students now work on 1:1 models, physical models and digital virtual models, never translated to physical haptic forms. Digital virtual models have become more important considering the widely discussed performative attributes of architecture and the rapid development of performance simulation tools [23].

To make students able to enter these new fields of experimentation, several courses supporting the architectural design studio were modified, including structural design, CAD classes and descriptive geometry courses, where the analogue approach towards the problem was expanded to the parametric one. The students were given the opportunity to conduct the entire process of design, from conceiving the geometric form, through designing it in parametric design software, to implementing it with 3D printers, and then formulating conclusions and guidelines for future use. To make the students fluent in digital modelling the advanced CAD classes were updated, where students were able to practise parametric design by working on an algorithm-based project with the use of the Grasshopper visual programming language of the Rhinoceros 3D CAD application. The course was aimed at expanding students' skills, and gave them a new digitally driven approach towards the early-stage design process. Within a few years of the introduction of the programme, there was a noticeable change in students' skills, from operating on basic modelling software to experiments on advanced computation models.

Short Projects Implemented with CDIO

Another feature of the curricula modifications were short elective architectural projects to let students personalise their study programmes and to stimulate their creativity. Short projects provide opportunities, so important in the CDIO approach, to pursue iterative designs. Another example of the newly introduced subjects was the elective Parametric Architecture in an Historical Context studio, aimed at problem identification and solving using adaptive parametric algorithms created, applied and verified by the students, which involved experimentation on virtual models. The students had freedom in the selection of topics and proposed diverse solutions. The students had to deal with historical urban quarters, buildings and surfaces, hence demonstrating that parametric systems may support heritage site preservation [24].

The reviews stimulated discussion and led to changes in project proposals, thanks to the application of the easy-to-use algorithm-based tools (Figure 1). Students, in an anonymous survey, evaluated the results very highly, with an overall score of more than 4.6 on a scale of 1.0 to 5.0.

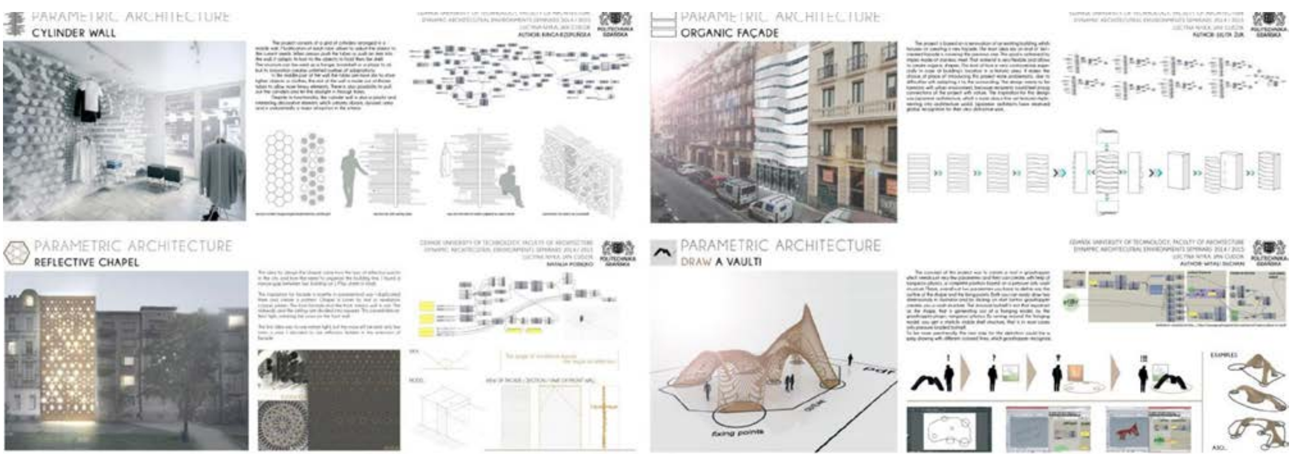

Figure 1: Adaptive spatial problem solutions created with parametric design by students taking the elective: Parametric Architecture in an Historical Context (Supervisor: J. Cudzik, FA-GUT).

Another elective short project workshop required students to fabricate an architectural model of a design at a 1:1 scale, testing the algorithm, virtual model and physical model relationships. This was a unique opportunity for students to take part in an entire complex architectural design process. This showed them how intense and unexpected architectural design is, where algorithms are involved in a production of forms and how they can manage the risks. This workshop, conducted as a summer school, was held with a group of 14 students from several faculties of architecture in Europe, who carried out the entire design process for a piece of furniture, a bench, within one week using computational tools.

The students had to learn the basics of parametric design, develop the final form from a possible mix of putative solutions, and then develop the entire fabrication process. The outcome of this short design studio was a bench with an additional bike rack that was inspired by the shape of a wave. After creating the first prototype, the students evaluated the proposed form, discussed what could have been done differently, and then incorporated conclusive remarks into the software script with which the final form was created (Figure 2).

Figure 2: The digitally fabricated model of urban furniture created with parametric design at a 1:1 scale (Supervisor: J. Cudzik, FA-GUT).

From the two projects discussed above new insights were revealed into the conceive-design-implement-operate stages of product development. In the first project, the verification was based only on the evaluation of 3D virtual models. Since optimisation programmes allow for very fast adaptation based on various factors, the structure efficiency, light conditions and other environmental or user-oriented characteristics could be easily modified, leading to an improvement of the primary model. The verification loop was very simple in this case, as it involved a software application and a virtual model, and it could be referred to as *software in the loop* (SiL).

In the second project, which was a 1:1 design exercise, the process of evaluation was more complex, since the implementation (construction of the model) could be applied to both the virtual model and physical object. However, the final outcome of the design process was the physical object. The initial evaluation was SiL since the verification loop goes from the properties of the virtual object visible on a computer screen to the modification of the chosen algorithms. During the workshop studio, despite the fact that this stage of verification went well, when the prototype was built, the ergonomic disadvantages of the bench were revealed. This returned the process once again to the algorithm phase. This process could be called *hardware in the loop* (HiL), since it involved evaluation of a physical model (Figure 3). Structural form verification gave a sharp edge to the course, which activated the students and motivated them towards creative investigations and vivid discussions.

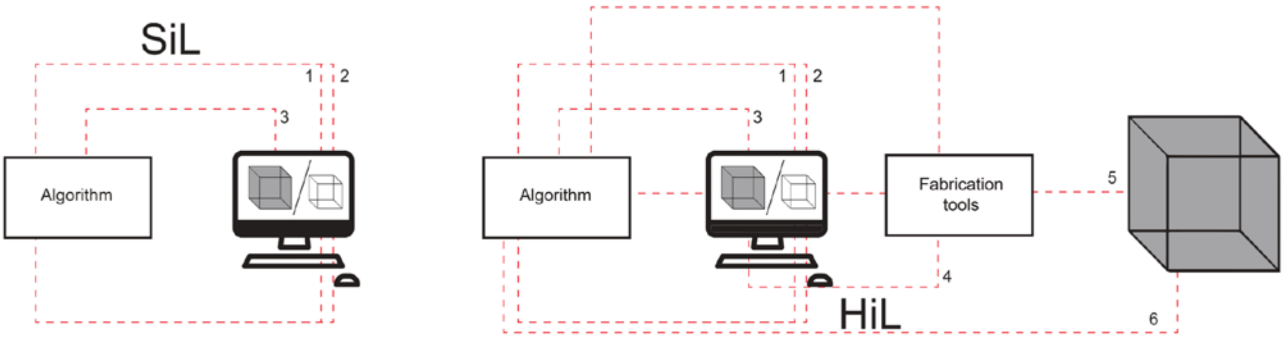

Figure 3: *Software in the loop (SiL)* and *hardware in the loop (HiL)* (Authors: L. Nyka and J. Cudzik).

Another type of engineering education experiment with CDIO involved working on dynamic process-oriented models. Using parametric design, the students were asked to create their visions of basic kinematic objects that could improve the quality of daily life. Students developed various kinematic systems with algorithms they created and adjusted. One of the students' proposals was a façade with a noise-absorbing dynamic system that could decrease sound pollution in a dense urban environment. This technology inspired another group of students to create a system of multi-angled rotatable panels that would create a complex form of light reflecting surfaces integrated into the façades of buildings.

The projects were reviewed by critics who had diverse experience and backgrounds, which gave the students additional valuable feedback. After the review, the students had an opportunity to apply some of the recommendations to their algorithms and to redesign the proposed structures. A survey conducted after the classes revealed that more than 90% of the students taking the class highly appreciated the tools they had learned. The majority of students (75%) confirmed that the model verification processes were both learning- and research-oriented, and contributed to the quality of the project. More than 80% of the students agreed that they would recommend the classes to other architecture students.

Another elective seminar introduced into the Faculty curriculum, called interactive art installation (Figure 4), is an experimental design studio carried out in an interdisciplinary, team-based environment. The students are encouraged to find innovative solutions for media art interventions on the GUT campus. They were challenged to specify the strengths of the location, the deficiencies, as well as potential and opportunities, and propose solutions based on an implementation of interactive technologies in art-architecture projects. This elective seminar was an experimental co-operation between the Faculty of Architecture (FA-GUT) and the Faculty of Electronics, Telecommunications and Informatics (FETI-GUT), with the goal of achieving a constructive dialogue in interdisciplinary student groups.

Through the process of investigation and acquisition of knowledge, the students worked on improving the quality of the space, changing the perception of it, and even on stimulating social activities [25]. Besides strengthening the students' interpersonal skills in teamwork and communication, an additional aim of the seminar was to experiment, adapt the solutions and iterate them into a tested prototype, until the final product was ready for implementation in real space. Although both the interdisciplinary co-operation, as well as prototyping aspect, are still in an experimental phase, they constitute input to the study programme in the use of CDIO.

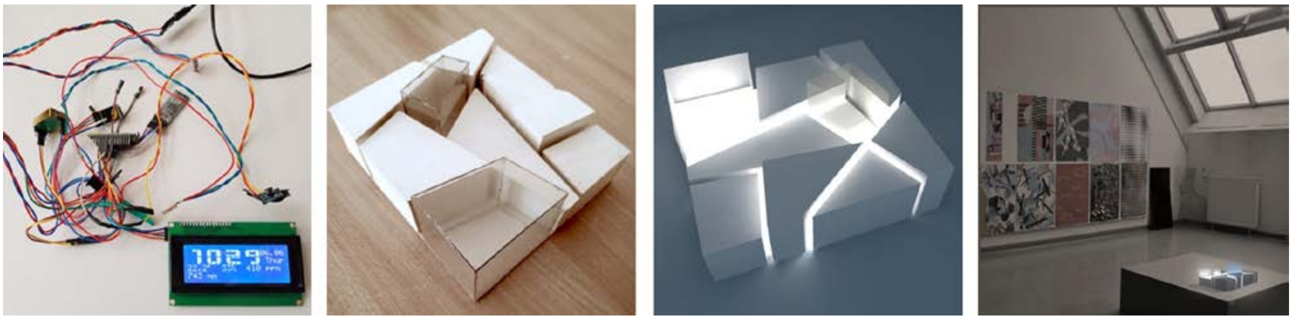

Figure 4: Prototype of a student project for a CO_2 and temperature measuring device (Authors: FA-GUT students A. Kuchta, A. Kłosiński; and FETI-GUT students H. Yancheuskaya, D. Stuba, M. Bajorowicz; Supervisors: K. Urbanowicz, FA-GUT and S. Gajewski, FETI-GUT).

EVALUATION AND CONCLUSIONS

The introduction of new learning methods always should be carried out as a participatory process. To evaluate the CDIO-based methodologies, a survey of a group of second-degree students was undertaken by J. Cudzik during lectures on *contemporary architecture issues*. The group consisted of 85 international students, of which 68 took the survey. The survey showed that the majority of students (over 95%) understand and expect the project development process to be a fluid transition, from conceiving an idea to testing the model and, in their opinion, such a design methodology should be practised during studies. At the same time, the students admitted that working with the use of innovative modelling technologies with access to digital fabrication tools contributes to the quality of the CDIO process.

More than 85% of the students thought it important or very important to work on innovative software and fabricate physical models. More than 85% of the students thought that the experiences of form fabricating and testing will or will definitely influence their future design decisions. About 75% of the students opined that the experimentation-based process of model verification merged learning with researching, and not only increased their skills, but also stimulated interest in architecture as a research discipline.

Another survey took place among the students of the elective subject, Interactive Art Installation, led by K. Urbanowicz and L. Nyka in the summer semesters of 2018 and 2019 at the FA-GUT; 85% of the students found the topic very interesting or interesting. Almost 70% considered the subject as interdisciplinary and going beyond the standard architectural curricula. A majority of the respondents (87%) considered the topic of interactive and multimedia technologies to be useful if not necessary for future architects. Only 25% of the respondents had a chance to collaborate between disciplines during their earlier studies, and 75% stated that access to such courses was insufficient.

The majority of the students (81%) were pleased and satisfied with taking part in this elective subject. Most of the students (75%) admitted that working within this studio not only enriched their knowledge of interactive technologies and modes and of their application in architecture, but also stimulated research on space perception. A majority, 68.8% of the respondents, esteemed that taking part in the subject sensitised them to this issue.

From the teachers' perspective, CDIO-based methodologies effectively structured the process of project development. It engaged students with model verification loops, systemised studio work and encouraged critical thinking on proposed solutions. Referring to such a clear methodology is particularly important in the discipline of architecture, where the process of design, whether learning- or research-oriented, is highly individualised, and choices are never fully objective but often highly personal [15]. This often makes students very attached to their initial concepts. During the majority of the short projects and interdisciplinary studio activities, both strategies, researching by design and learning by doing, smoothly complemented each other, which gave the students an invigorating impulse towards experimentation and fostered their creativity.

REFERENCES

1. Crawley, E.F., Malmqvist, J., Östlund, S., Brodeur, D.R. and Edström, K., *Rethinking Engineering Education: The CDIO Approach*. (2nd Edn), Berlin: Springer-Verlag (2014).
2. Proceedings of the International CDIO Conference, 19 December 2019, http://www.cdio.org/node/6306
3. Fischl, G., Granath, K. and Bremner, C., Mapping architectural engineering students' learning in group design exercises. *Proc. 14th Inter. CDIO Conf.*, Kanazawa, Japan, 849-859 (2018).
4. The CDIO™ Initiative is an Innovative Educational Framework for Producing The Next Generation of Engineers, 19 December 2019, http://cdio.org/about
5. Martin, J. and Wackerlin, D., CDIO as a cross-discipline academic model. *Proc. 12th Inter. CDIO Conf.*, Turku University of Applied Sciences (2016).
6. Cheah, S.M. and Yang, K., CDIO framework and skillsfuture: redesign of chemical engineering curriculum after 10 years of implementing CDIO. *Proc. 14th Inter, CDIO Conf.*, Kanazawa, Japan, 99-114 (2018).
7. De León, A.T., Project-based learning and use of the CDIO syllabus for geology course assessment. *Global J. of Engng Educ.*, 16, **3**, 116-122 (2014).
8. Tangkijviwat, U., Sunthorn, W., Meeusah, N. and Kuptasthien, N., CDIO-based curriculum development for non-engineering programs at mass communication technology faculty. *Proc, 14th Inter. CDIO Conf.*, Kanazawa, Japan, 129-138 (2018).
9. Lantada, A.D., Ballesteros Sanchez, L.I., Chacon Tanarro, E., Moreno Romero, A., Borge Garcia, R., Pelaez Garcia, M.A., Ramos Diaz, R., Ruiz, J.J., Coordinated design and implementation of *Bioengineering Design* and *MedTech* courses by means of CDIO projects linked to medical devices. *Proc.14th Inter. CDIO Conf.*, Kanazawa, Japan, 170-179 (2018).
10. Winthrop, R., Williams, T.P. and McGivney, E., Accelerating Progress in Education with Hands-on, Minds-on Learning. 15 February 2020, https://www.brookings.edu/blog/education-plus-development/2016/07/14/accelerating-progress-in-education-with-hands-on-minds-on-learning/
11. Pusca, D., Bower, R.J. and Northwood, D.O., Hands-on experiences in engineering classes: the need, the implementation and the results. *World Trans. on Engng. and Technol. Educ.*, 15, **1**, 12-18 (2017).
12. The EAAE Charter on Architectural Research (2012). 22.03.2020 http://www.eaae.be/about/statutes-and-charter/eaae-charter-architectural-research/
13. Pais, M.R., Research by design in architecture: an approach into the exploratory research phase. *Architecture and Educ. J.*, Lusofona University, N11/2014, 487-502 (2014).
14. Nourrigat, E., Experimentation as a method, the project as a production of knowledge: theory and practice according to Buckminster Fuller. *Architecture and Educ. J.*, Lusofona University, N11/2014, 95-103 (2014).
15. Schurk, H., *Design or Research by Doing*. In: Ellefsen, K.O., van Cleempoel, K. and Harder E. (Eds), Research by Design. Diepenbeek: EAAE (2014)
16. Cudzik, J. and Radziszewski, K., Parametric design in architecture education. *World Trans. on Engng. and Technol. Educ.*, 17, **4**, 448-453 (2019).
17. Klahr, D., Triona, L.M. and Williams, C., Hand on what? The relative effectiveness of physical versus virtual; metrials in an engineering design project by middle school children. *J. of Research in Science Teaching*, 44, **1**, 183-203 (2007).
18. Radziszewski, K. and Cudzik, J., Robotics in architecture. *World Trans. on Engng. and Technol. Educ.*, 17, **4**, 459-464 (2019).
19. Życzkowska, K. and Urbanowicz, K., Architectural education and digital tools: the challenges and opportunities. *World Trans. on Engng. and Technol. Educ.*, 17, **3**, 326-331 (2019).
20. Nyka, L., Bridging the gap between architectural and environmental engineering education in the context of climate change. *World Trans. on Engng. and Technol. Educ.*, 17, **2**, 204-209 (2019).
21. Borucka, J. and Macikowski, B., Teaching architecture - contemporary challenges and threats in the complexity of built environment. *IOP Conf. Series: Materials Science and Engineering*, 245, 082058 (2017).
22. Directive 2013/55/EU of the European Parliament and of the Council of 20 November 2013.
23. Kolarevic, B. and Maklavi, A.M., *Performative Architecture - Beyond Instrumentality*. New York: Routledge (2005).
24. Lynn, G. and Gage, M.F., *Composites, Surfaces, and Software: High Performance Architecture*. New Haven: Yale School of Architecture, 104 (2010).
25. Urbanowicz, K. and Nyka, L., Media architecture and interactive art installations stimulating human involvement and activities in public spaces. *CBU Inter. Conf. Proc.*, **4**, 591-596 (2016).