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Biomedical Engineering Project Based Learning: Euro-African Design School Focused on Medical Devices*

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Biomedical engineering (BME) has the potential of transforming medical care towards universal healthcare by means of the democratization of medical technology. To this end, innovative holistic approaches and multidisciplinary teams, built upon the gathering of international talent, should be encouraged within the medical industry. However, these transformations can only be accomplished if BME education also continuously evolves and focuses on the internationalization of students, the promotion of collaborative design strategies and the orientation towards context relevant medical needs. In this study we describe an international teaching-learning experience, the "UBORA (Swahili for 'excellence') Design School". During an intensive week of training and collaboration 39 engineering students lived through the complete development process for creating innovative open-source medical devices following the CDIO ("conceive-design-implement-operate") approach and using the UBORA e-infrastructure as a co-design platform. Our post-school survey and analyses showed that this integral teaching-learning experience helped to promote professional skills and could nurture the future generation of biomedical engineers, who could transform healthcare technology through collaborative design oriented to open source medical devices.

Keywords: biomedical engineering; biomedical engineering education; open-source medical devices; biodevices; e-infrastructures; project-based learning; ABET professional skills; CDIO approach.

1. Introduction

Biomedical engineering (BME) has the potential of transforming medical care towards universal health care by means of the democratization of medical technology, which is one of the World Health Organization's 2030 objectives [1]. To this end, innovative holistic approaches and multidisciplinary teams, built upon the gathering of international talent, should be encouraged within the medical industry. However, this transformation can only be accomplished if BME education also evolves continuously, focusing on the internationalization of students, the promotion of collaborative design strategies, the orientation towards relevant medical needs and the relevance of biomedical standards and medical device regulations. Obviously in-depth theoretical knowledge on basic disciplines of science, medicine and technology typical of most BME programmes must continue to remain intact. In pioneering studies linked to the international accreditation (and related transformation) of BME degrees, the relevance of addressing design, prototyping and manufacturing aspects and the need of providing students with high ethical standards, have been put forward, as fundamental keys for empowering the biomedical engineers of the future to become natural leaders in biomedical device development projects [2, 3].

This type of comprehensive inter-sectorial training cannot be achieved without an intensive exposure to economic, ethical, health, safety and political issues, as necessary complements to the essential engineering design issues [4]. To this end, capstone design courses and project/problem-based teaching-learning methods seem to be among the more effective strategies [4, 5], especially if supplemented by industrial or international team-based collaborations [6, 7]. In addition, these student-centered teaching-learning strategies help to promote participant motivation (both students and teachers), which is a basic cue for successful formative experiences.

Among the more relevant international proposals promoting project-based learning (PBL) methodologies worldwide, is the CDIO™ Initiative (www.cdio.org). It is focused on the establishment of an innovative educational framework for producing the "engineers of the future", by providing students with an education which emphasizes engineering fundamentals through "Conceiving—Designing—Implementing—Operating" (CDIO) real-world systems, processes and products [8]. Throughout the world, a growing number of collaborators are adopting CDIO as the framework of their curricular planning and outcome-based assess-

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ment. CDIO also promotes collaboration and sharing of good practices among engineering educational institutions worldwide by means of well-established standards focusing not only on teaching methodologies, but also on the training of engineering educators and on the relevance of training environments, to cite just some relevant aspects of the improvement cycle [9].

Actually, complete CDIO experiences go beyond conventional PBL due to the fact that students end up with real working engineering systems, not just conceived and designed, but also constructed and working, which usually challenges and motivates them. As regards BME, CDIO experiences, in which students live through the complete development of medical devices during one or two semesters, have been recently developed with success by members of our team, both with under-graduate and graduate participants [10, 11].

All these advances in student-centered methodologies have taken place in parallel to other international coordinated transformations in higher education, including the implementation of the European Area of Higher Education [12], which has stressed the preeminent role of students in the teaching-learning process and caused a shift from the traditional teacher-centered magisterial lessons towards a prevalence of student-focused activities. PBL approaches and student internships in foreign institutions and external organizations (i.e., companies and research institutes) are now common in higher education, especially in engineering, and contribute to the acquisition of wide sets of professional skills, even before reaching professional practice, which should be highlighted. In fact, even if PBL has been sometimes described as too expensive or resource-intensive and as too complex to implement with large groups of students, there are several strategies and techniques that help to improve their effectiveness and efficacy, without dramatic increases of costs and teacher dedication [13]. Recent technological advances, including the combination of computer-aided design & engineering resources with rapid prototyping techniques (e.g., 3D printing, electronic rapid prototyping, software rapid prototyping tools) and software for design also help to promote the teaching-learning impacts, while contributing the overall sustainability of these highly-formative options [14].

Nevertheless, as it happens with equitable access to healthcare, holistic and student-centered teaching-learning strategies and programmes are far from being the norm worldwide, especially in modern engineering disciplines, such as BME. This is particularly true of Africa, which is the focal point of our intervention. Even though PBL can be implemented without great investment at a university level just by focusing on the training of focus groups of devoted professors, the lack of political insight and long-term vision, the rigidity of educational systems and the reluctance to change of old-school professors are some of the reasons that limit the potential of these educational paradigms and their more global projection. PBL has already been introduced in some universities in Africa, although its impacts have yet to be measured [15]. Its effects are potentially socially transformative and could help to promote an inclusive approach towards knowledge production and dissemination, emphasizing collective learning [16].

However, taking again the example of BME, excluding South Africa and apart from a few singular initiatives (i.e., in Nigeria and Ghana), no university in sub-Saharan Africa offers a complete BME graduate & post-graduate programme [17], apart from the MSc programs offered by Addis Ababa University and Jimma University (both in Ethiopia), and only two universities on the African continent (Pretoria and Johannesburg) have joined the International CDIO Initiative for promoting PBL-related experiences. Besides, many countries in Asia and Africa are facing barriers to achieving health-related Sustainable Development Goals, SDGs due to the shortages of qualified health staff, their often inequitable distribution, and gaps in their capacity, and lack of affordable and reliable medical devices.

Consequently, international capacity building and innovative global collaborative approaches are needed, both for transforming BME towards universal healthcare and for expanding the educational strategies that will support such a transformation. Fortunately, inspiring pioneers such as the e-NABLE community and with the Patient Innovation network [18, 19] have demonstrated the potential of collaborative design methods. Others have established international networks including the African Biomedical Engineering Consortium (ABEC), implementing teaching-learning initiatives in the form of innovator summer schools, focused on specific biomedical engineering topics, with the support of the United Nations Economic Commission for Africa (UNECA) [20, 21].

Following their steps, in this study we describe an international (initially Euro-African) one-week intensive teaching learning experience, the "UBORA Design School" (first edition, 2017), in which 39 engineering students experienced the complete development process of innovative open-source medical devices, following the CDIO approach. This integral teaching-learning experience has helped to promote their professional skills, according to students' own reflections, and to plant the seed towards a future generation of biomedical engineers, who will collaborate as members of the "UBORA Community" by using the UBORA e-infrastructure, which is also presented. Our intervention stands out for: (i) being inclusive and international, (ii) oriented to global health problems solved collaboratively and (iii) deployed following an integral CDIO cycle in just five days, in which students apply engineering design principles towards safe medical devices.

2. The UBORA project and its objectives: linking research and education for transforming biomedical engineering

This section describes the context of the "UBORA Design School", which has been developed with the support and within the framework of the "UBORA: Euro-African Open Biomedical Engineering e-Platform for Innovation through Education" project (funded by the European Commission through the "Horizon 2020 Research and Innovation Programme" with grant agreement number 731053 within the "INFRASUPP: Support to policy and international cooperation" call) [22]. The UBORA project is trying to encourage a shift towards open-source biomedical devices (OSMD) and the democratization of medical technology by implementing an e-infrastructure, UBORA, for the open source co-design of new solutions to face the current and future healthcare challenges of Europe and Africa. UBORA brings together very representative European and African universities and their technological hubs (supporting biomedical design and prototyping laboratories and incubators) to develop and establish a new engineering-design methodology for the straightforward development of biomedical devices in a collaborative and open source way. At the same time, new methodologies for training the biomedical engineers of the future are being performed with the support of the UBORA e-infrastructure, which constitutes both a platform for co-design in biomedical engineering and for open biomedical engineering education, linked to "engineering for all" principles [23] and aimed at fostering open-source medical devices and supporting related trends.

The UBORA e-infrastructure is aimed at taking engineers and engineering students through a process of (i) needs identification and specification, (ii) device classification, (iii) regulation, (iv) computer-aided design and simulation, (v) rapid prototyping, (vi) testing and (vii) final preparation of production. Each stage is vetted and monitored by experts to ensure that safety criteria are met during the design process. The UBORA project is supported by policymakers and stakeholders covering the whole life cycle of biomedical product development and propelled by a series of design schools and design competitions. The first of these high-level teaching-learning events is the "UBORA Design School" of Nairobi, presented in this study, which constitutes one of the most relevant cornerstones of the UBORA project. A first version of the UBORA e-infrastructure was presented at the school and validated as a reliable, effective and efficient tool for supporting the co-design of innovative medical devices and as a valuable teaching-learning resource. This international and integral teaching-learning experience took place from 11–15 December 2017 at Kenyatta University (Nairobi, Kenya) and its objectives, organizational issues and results are presented and discussed in the following sections.

3. The "UBORA Design School 2017": teaching-learning objectives and organizational issues

3.1 Teaching-learning objectives and expected outcomes

When planning the "UBORA Design School 2017" the aim was to instill an appreciation of the multidisciplinarity of biomedical engineering and to let students live through the complete development process of innovative biomedical devices in an international team-based environment. Consequently, we focused on providing systematic methodologies and techniques to specify, conceive, design, classify, prototype and produce biomedical devices [24]. To promote ethical issues and to highlight the relevance of applying open-source design methods and focusing on global health concerns, the innovative biomedical devices to be developed were focused on "child and maternal health". The same topic had been already employed during the international design competition for selecting the participants of the design school (see next section). At the end of the design school, students were expected to have improved their engineering skills and have adapted them for working in international design teams, applying collaborative design and systematic engineering-based development methodologies, oriented to the biomedical field, for the straight-forward, safe and regulation-compliant development of biomedical devices. Improved computer-aided design and simulation skills, capacity for materials selection and understanding of how to classify and prototype medical devices were also among the expected outcomes for participants.

Before starting the design school we selected 8 biomedical devices to be conceived, designed, implemented and operated during the intense one-week CDIO experience. The devices were chosen on the basis of the outcomes of a "needs assessment campaign" conducted by the Uganda Industrial Research Institute (UIRI), together with an analysis of the ideas presented to the international design competition (see next subsection). The devices identified, whose feasibility to be developed in just one week—for educational purposes—was also analyzed, were:

1. Continuous airway pressure for neonate (CPAP).
2. Instrumented pacifier to reduce sudden infant death syndrome.
3. Warmer for infants with hypothermia.
4. Universal splint for articular immobilization.
5. Face protecting splint for children with broken nose.
6. Phototherapy device for treating infant jaundice.
7. Portable cooler for vaccines.
8. Resuscitation device for newborns.

Section 3.4 describes how a group-based PBL approach was used to realize the 8 devices during the school letting students live through a complete conceive-design-implement-operate cycle.

3.2 Selection of participants by means of an international competition

In order to select the 39 participants, a medical device design competition was launched 9 months before the school. The design competition was implemented in two stages: the first involved submission of a 1-page concept, while the second was a more detailed execution plan for an innovative medical device. A total of 113 projects were submitted at the first stage, from which 60 were selected for a second round. After the second round, 24 particularly relevant projects and their teams were awarded a travel fellowship for one team member to attend the "UBORA Design School 2017".

Among the projects and solutions presented, all of which were centered on infant and child mortality and health we can cite: medical devices for detecting or preventing malaria, portable vaccine coolers, systems for the sterilization of medical and instruments, incubators for newborns, devices for monitoring pregnancy, breast pumps with milk cooling systems, 4D printed ergonomic supports, polymeric devices for articular pathologies and CPAP devices for babies, to mention just a few examples.

Most of the finalist teams reached a basic prototyping and testing stage, following the recommendations provided by the organizers of the competition and by the participating mentors, in order to better answer the questions from the two-stage evaluation sheets, which served as a sort of "lean canvas" or creativity promotion templates to guide the development process. Besides the 24 finalists, 15 teams who had been admitted to the second stage were selected to choose a representative to participate in the "UBORA Design School 2017". They were either supported by their universities or self-sponsored. Additional details can be found at: http://ubora-biomedical.org/design-competition. As the first of its kind, in this pilot trail, the competition was reserved to students enrolled at universities of the ABEC consortium (http://abec-africa.org/universities/) or UBORA (http://ubora-biomedical.org/team/) accounting for a total of 20 institutions from 12 countries.

The medical device design competition can be considered as the first part of the "UBORA Design School" [25]. Indeed, it is also quite formative as the participants engaged in the first steps of a CDIO cycle during the preparatory stage, conceiving novel ideas in a collaborative fashion. Following the scheme of this first implementation, forthcoming editions of the UBORA Design Schools will be accessible through worldwide medical design competitions, which will be considered as an integral part of the training process.

3.3 Organizational issues and temporal planning

Organizing a complete CDIO project-based learning experience over just one week, while also providing students with contents and supporting workshops, is challenging and required intensive planning and scheduling. A summary of contents according to the teaching-learning objectives described in Section 3.1 (with lessons, workshops and keynote presentations) is illustrated in Table 1, which includes also a schematic timetable. Summarizing, we planned one basic lesson linked to the fundamental aspects (engineering-design methodologies, prototyping of medical devices, standards & regulations and usability of medical devices) for each of the first four days (Monday to Thursday). In addition, 15 workshops and keynote talks were distributed over the first four days, giving students the opportunity to appreciate the extensive applications of BME. At least 3 time slots were set aside each day for hands-on group activities, in which the groups (guided by their mentors) could develop their projects applying the concepts acquired. The first morning was devoted to the opening ceremony and formation of groups, while the last morning was completely dedicated to fine-tuning the projects. The last afternoon (Friday) was reserved for the final presentations, overall assessment and a short closing ceremony in which the best 3 projects were nominated. Hands-on activities continued after dinner and, given the intensive nature of the school, the Thursday afternoon tour and a closing dinner were the only social events organized, which had also a cultural purpose.

Table 1. Summary of contents: Lessons on biomedical project development, workshops or seminars and keynote presentations of the "UBORA Design School 2017"

Teaching event	Topic	Date
Lesson	CDIO Methodology for Medical Devices	Day 1
Lesson	Standards and Regulations on Medical Devices	Day 2
Lesson	Technologies for Prototyping and Manufacturing Biodevices	Day 3
Lesson	Usability of Medical Devices	Day 4
Workshop	Creativity Promotion in Biomedical Projects	Day 1
Workshop	Programming in Matlab®	Day 1
Workshop	Tracking Movements	Day 2 (M)
Workshop	Electronic Rapid Prototyping	Day 2 (M)
Workshop	Electronic Measurements	Day 2 (A)
Workshop	Mass Production by Injection Molding	Day 2 (A)
Workshop	Medical Imaging Processing and Matlab®	Day 3
Workshop	Arduino and Matlab® for Prototyping Medical Devices	Day 3
Keynote talk	Economic Development and Healthcare Technology	Day 1
Keynote talk	Clinical Needs and Medical Equipment	Day 1
Keynote talk	In Vitro Models for Reducing Animal Testing	Day 2
Keynote talk	Textile Technology in Robotics and Biomedical Engineering	Day 3
Keynote talk	Affordable Healthcare	Day 3
Keynote talk	From Mind to Market	Day 4
Keynote talk	Soft and Smart Robotics in Bioengineering	Day 4

3.4 Device development groups

Group forming and mentor and project assignment to the different groups was performed some weeks before the starting of the design school. We sought to form the groups such that they had an adequate balance of gender, cultural background and skills in an effort to promote multidisciplinary approaches and multiculturalism of the EU-African experience. None of the groups had more than one student from the same university or country, again enhancing diversity and internationalization. Moreover, mentors were allocated to the 8 selected projects on the basis of their specific technical or medical expertise. Given that groups had only 5 days to design and prototype innovative devices, mentors prepared supporting resources in advance, so as to facilitate the students. The students did not know the group they were assigned to or the devices they would develop until the presentation pitches on the first morning of the school.

3.5 Supporting resources

Apart from counting with the previously described teaching materials, with internet connection and with the support of the UBORA e-infrastructure, students counted with several additional tools and resources for developing their design, prototyping and testing tasks during the design school: Common computer-aided design and simulation software, with licenses provided by the members of UBORA or from companies offering student licenses, such as NX-10 (Siemens Lifecycle Management Solutions), Catia v.5 (Dassault Systemes), Autodesk Moldflow and Matlab (The Mathworks), enabled the teams to perform designs and mechanical, thermal, fluidic and manufacturing simulations. Two fused-deposition modelling 3D printers (Flashforge Creator Pro) with the related free supporting slicing software helped students to materialize their designs. One Arduino starter kit for each team, including common pressure, temperature, light and vibration sensors, LEDs, micro-motors and actuators promoted the development of "smart" systems capable of monitoring some relevant human signals and responding to them, after adequate signal processing with the Arduino micro-controller, according to specifications of the different biodevices. Finally, some supporting oscilloscopes, kits for paper rapid prototyping, low-cost 3D scanner and common materials from mechanical and electronic workshops helped students along the week. We would also like to highlight some materials used in the electronic rapid prototyping workshop, which served to demonstrate and encourage the students to develop smart, affordable, battery operated, user-friendly and reliable medical devices that the rural health work forces can use for improving the quality of diagnosis, and thus improving patient care and safety. In this workshop, low cost opto-sensors, for recording blood pressure from the capillaries, and low cost piezoelectric sensors, for recording the arterial pulse pressure, using simple and smart interface with instrumentation amplifiers INA128 were used.

4. The "UBORA Design School 2017": successful implementation and main results

4.1 Overview of the implementation process

Overall the design school was implemented according to the initial planning, with all 39 students and with the 25 professors and mentors arriving in Nairobi without major delays. Minor adjustments, consisting of a couple of lessons performed via Skype and two additional modifications to the topics of keynote speeches did not affect the overall teaching-learning programme and the 8 groups of students were able to complete the desired complete CDIO cycles with their biomedical projects (see examples shown in Figs. 3 and 4) using the UBORA e-infrastructure as a support and working tool.

Taking into consideration the relationship between students and mentors during the design school, we would like to stress the great ambience of collaboration achieved, especially taking into account the international and multi-cultural audience, which was a source of inspiration for all. Gender balance was very appropriate with a 42% of female students and mean student age was 23 years, with most students (around a 75%) in the range of 21–25. Regarding nationalities, students from the following countries (numbers in brackets) were involved: Kenya (9), Uganda (7), Spain (6), Italy (5), Ethiopia (4), Egypt (2), Tanzania (3), Malawi (2) and Sweden (1), which to our knowledge constitutes one of the most international complete CDIO experiences ever.

On the last afternoon, just after the final presentations, students were surveyed for obtaining their impressions regarding the topics and contents for the planned teaching-learning sessions, seminars and workshops, their opinions about organizational issues, their perceptions about the biodevices developed and their feedback in connection with the promotion of professional skills during the intensive study and design week. The survey was performed using an online formulary (Google surveys) and 34 out of 39 participants provided their responses, mainly using Likert scale type questions (with values from 1 to 5), which are presented in Figs. 1, 2, 5 and 6 and analyzed and discussed further on.

Apart from that, some additional personal impressions about the design school and about the usability of the UBORA e-infrastructure were gathered by using blank questions. Finally, informal conversations and discussions among colleagues and participants helped us to additionally analyze the performed actuations. These more personal feedbacks are presented in the discussion section, together with main lessons learned, remaining challenges and future proposals.

Concerning lesson contents and planned topics of

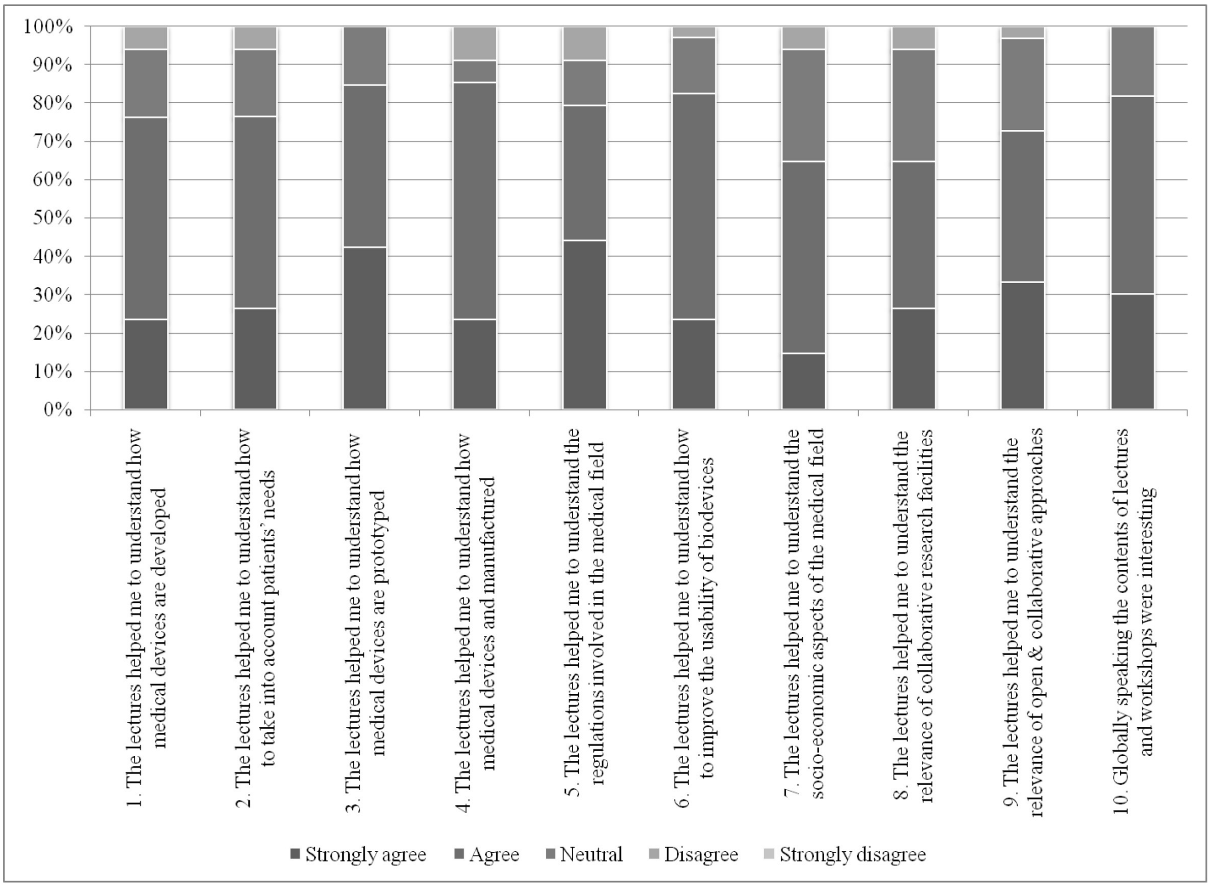

Fig. 1. Summary of results regarding students' opinions about the interest of topics and contents for the planned teaching-learning sessions, seminars and workshops.

workshops and seminars, the assessments presented in Fig. 1 show an extraordinarily positive perception from students, with typical sums of responses valued with 4 and 5, in the 5-point Likert scale used, reaching percentages from 70% to 80%. More than an 80% of students agreed or strongly agreed that globally speaking the contents of lectures and workshops were interesting. The overall engineering-design process and the approach to prototyping, manufacturing and regulatory environment were clearly understood and especially highly appreciated according to the results.

Considering organizational issues (see Fig. 2), the communication with the organizers and the information provided before the school were highly appreciated, as happens with the support provided by mentors, although with some minor proportions of disagreement. Accommodation and lodging received slightly lower punctuations, although in our opinions all participant students should have borne in mind that a university residence is not a congress hotel. To sum up, it is necessary to note that more than 82% of students considered the design school a rewarding experience.

The closing ceremony was the moment for announcing the opening of the "UBORA Design Competition 2018", giving also appointment to the "UBORA Design School 2018", to be held in Pisa from the 3rd to 7th of September 2018, following the paces of present experience. Authorities from the Spanish and Italian Embassies attended the Closing Gala Dinner at Safari Park Hotel in Nairobi, where professors, researchers and representatives of all participant institutions signed the "*Kahawa Declaration: A Manifesto for the Democratization of Medical Technology*". In this joint declaration of the UBORA and ABEC partners a clear commitment to the promotion of the democratization of medical technology, as a key for achieving universal equitable healthcare, is expressed. The whole text of the Declaration can be found at: http://ubora-biomedical.org/kahawa-declaration.

4.2 Complete development of medical devices following open-source approaches

Projects were developed thanks to a tight schedule control and an adequate delimitation of boundaries for each stage of the "conceive-design-implement-operate" engineering-design process for fulfilling the tasks in just one week. In fact, Monday was devoted almost completely to introducing the school and presenting the teams, so Tuesday was

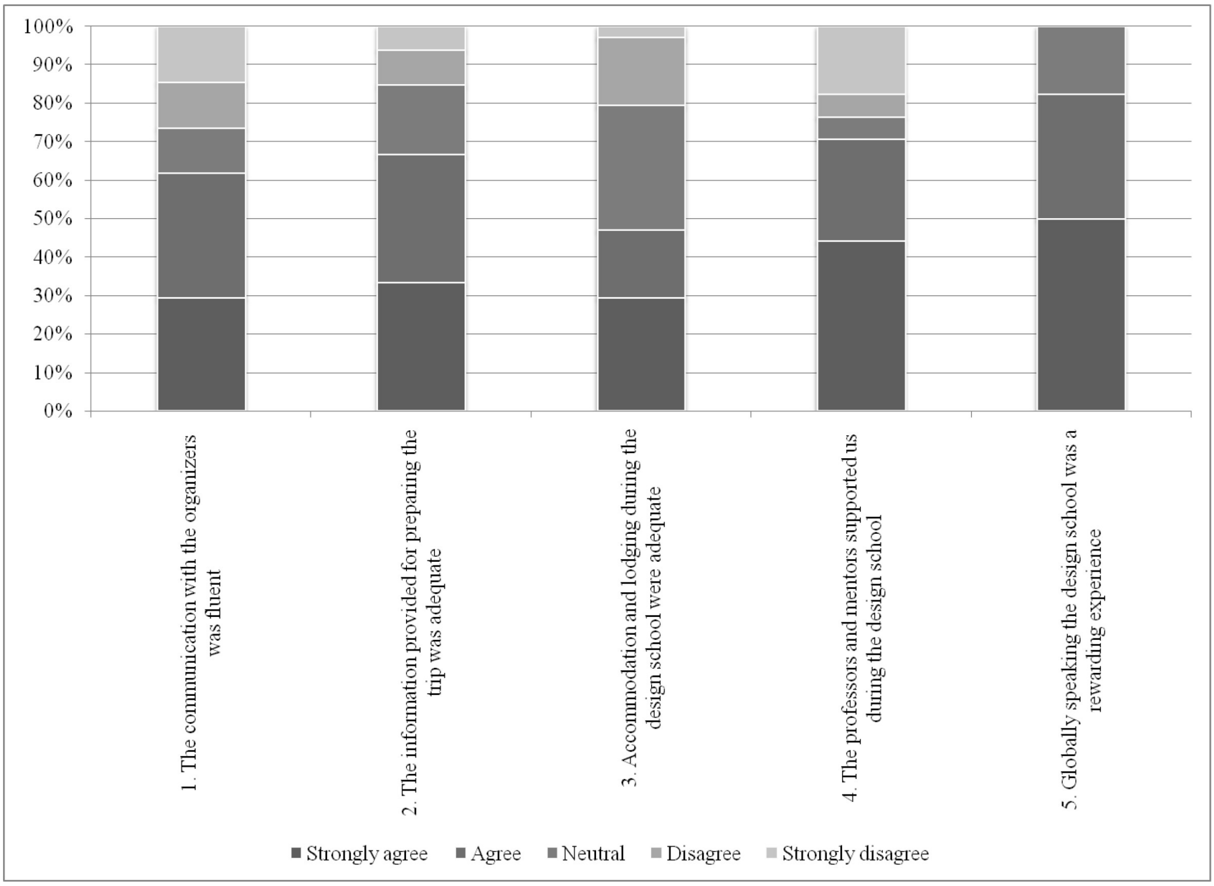

Fig. 2. Summary of results regarding students' opinions about organizational issues.

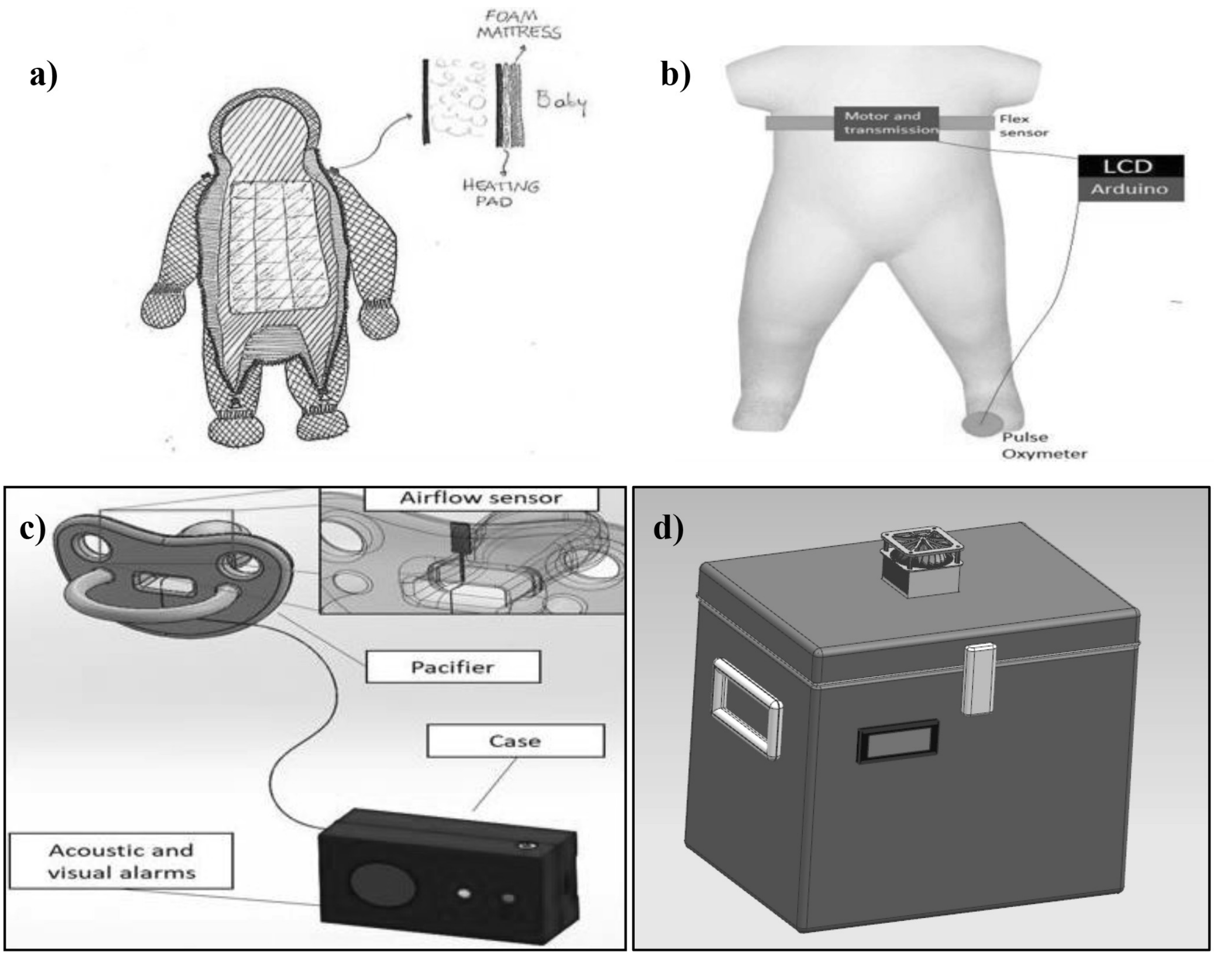

Fig. 3. Examples of the different biomedical devices developed within the UBORA Design School 2017. Some results from the "conceive" and "design" phases: *Concepts*: (a) Monitored warming suit. (b) Resuscitation device for neonates. *Designs*: (c) Instrumented pacifier for detecting SIDS. (d) Portable cooler for vaccines.

dedicated to conceptual tasks, Wednesday to design issues, Thursday to implementation aspects (prototyping and testing) and Friday to the operation of the devices (final presentations and tests before the jury).

The conceptual stage was limited to precisely defining the medical need, analyzing existing solutions, specifying and classifying the medical device, proposing alternative product ideas and evaluating them for selecting the adequate "concept". The design stage was devoted to obtaining basic CAD geometries of the different components, selecting materials, designing electronic circuits, defining joining forms, selecting commercial components (i.e., sensors and actuators) and briefly describing possible manufacturing processes towards production (see Fig. 3). The implementation phase included the prototyping of electronic circuits using prototyping boards and Arduino kits and the rapid manufacture of mechanical components by 3D printing, either using the real CAD geometries or resorting to scaled conceptual prototypes (Fig. 4). Mounting and testing was also part of this phase. As for the operation stage, in our case, it was limited to preparing reports and presentations of the devices and presenting them before the jury and their co-participants. The degree of completeness achieved can be compared to that of one- or even two-semester long CDIO experiences, which is extraordinary in our opinion.

Regarding the development process and the success of the CDIO stages lived through with the medical devices, students' perceptions about their progresses and results were also noteworthy (see Fig. 5). Again, more than a 70% of participants considered the project-based learning experience satisfactory according to their expectations, although in this case around a 15% were not so satisfied. In this regard, it is necessary to mention that sometimes PBL experiences are a bit frustrating for students, especially when prototyping and testing stages are involved, as they tend to focus on the product and final prototyping result (and prototypes do not always work as expected).

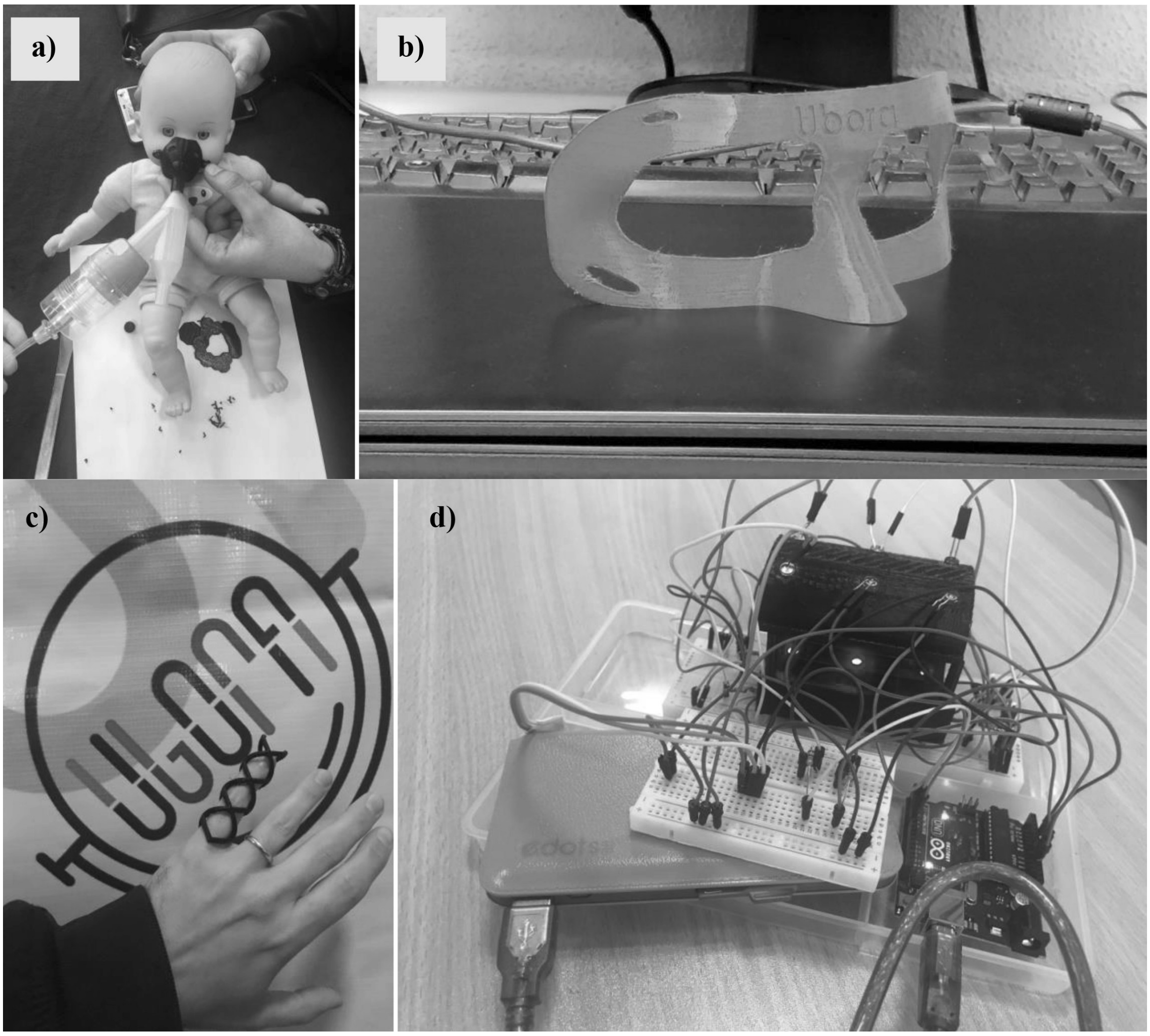

Fig. 4. Examples of the different biomedical devices developed within the UBORA Design School 2017. Some results from the "implementation" and "operation" phases: (a) CPAP device for babies. (b) Protecting splint for broken nose. (c) Splint for articular problems. (d) Phototherapy device for infant jaundice (conceptual scaled prototype of instrumented cradle).

However, in our opinion, the final result is not as relevant as the whole teaching-learning process, which in our case has been highly gratifying both for students and teachers, as can be understood from the global analysis of the presented surveys, from the design and prototyping results previously shown and from all the informal discussions among teachers, mentors, students and international stakeholders.

4.3 Impact on the promotion of students' professional skills

Probably the more relevant data gathered with the online surveys, especially for us as professors and from the perspective of the actual impact of the teaching-learning experience, are those linked to students' perception about their promotion of professional skills thanks to the UBORA design school. We opted for asking about the set of ABET professional skills, which cover most skills needed for engineering professional practice and are almost coincident with those from the CDIO standards. Results are summarized in Fig. 6 and are very positive indeed. We can objectively declare that, in just one week of intensive project-based learning experience following the CDIO approach (let's call it "express CDIO" model), students performed teaching-learning activities covering the whole spectrum of ABET professional skills. To highlight just some examples, around a 90% of students considered that the experiences lived had helped them to communicate more effectively and around a 85% of students clearly confirmed that the projects helped them to apply academic knowledge to real life. The impact of engineering solutions and the need for lifelong learning were also clearly perceived by students, possibly thanks to the inspiring keynote speeches and to the activities performed during the school using modern engineering tools, many of which were novel for them.

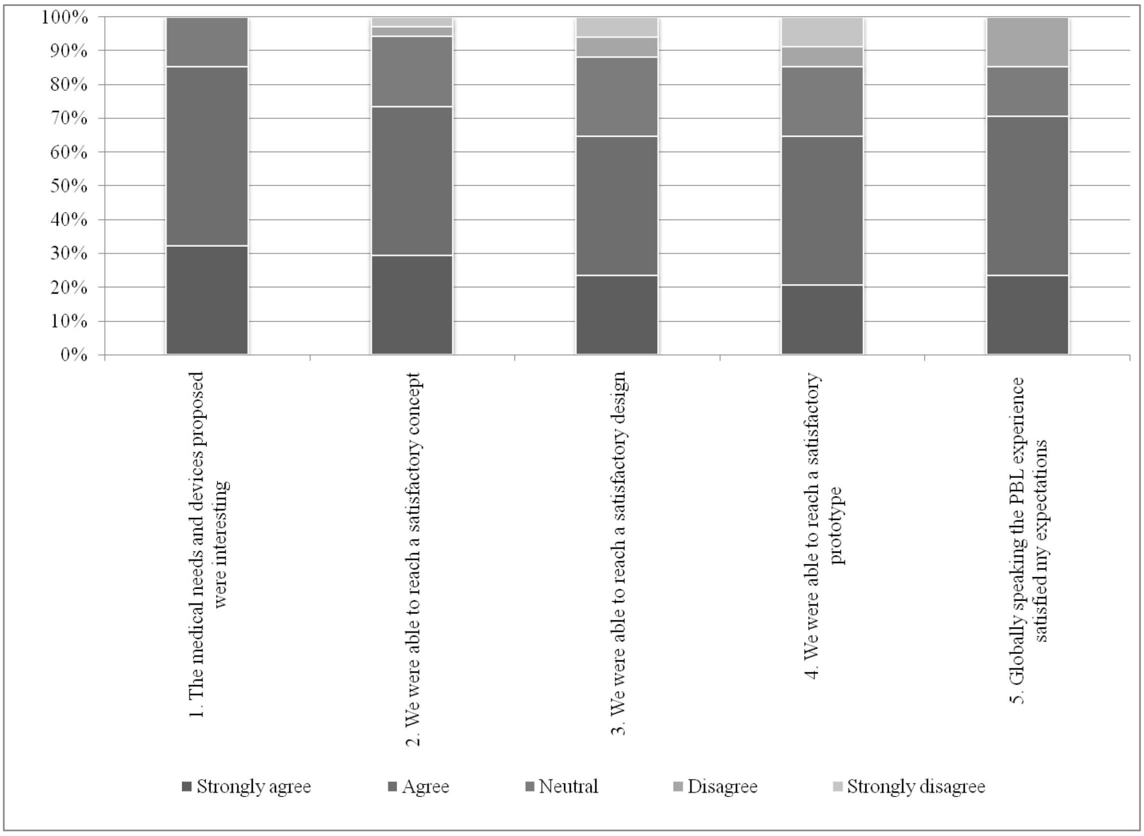

Fig. 5. Summary of results regarding students' perceptions about the biodevices developed.

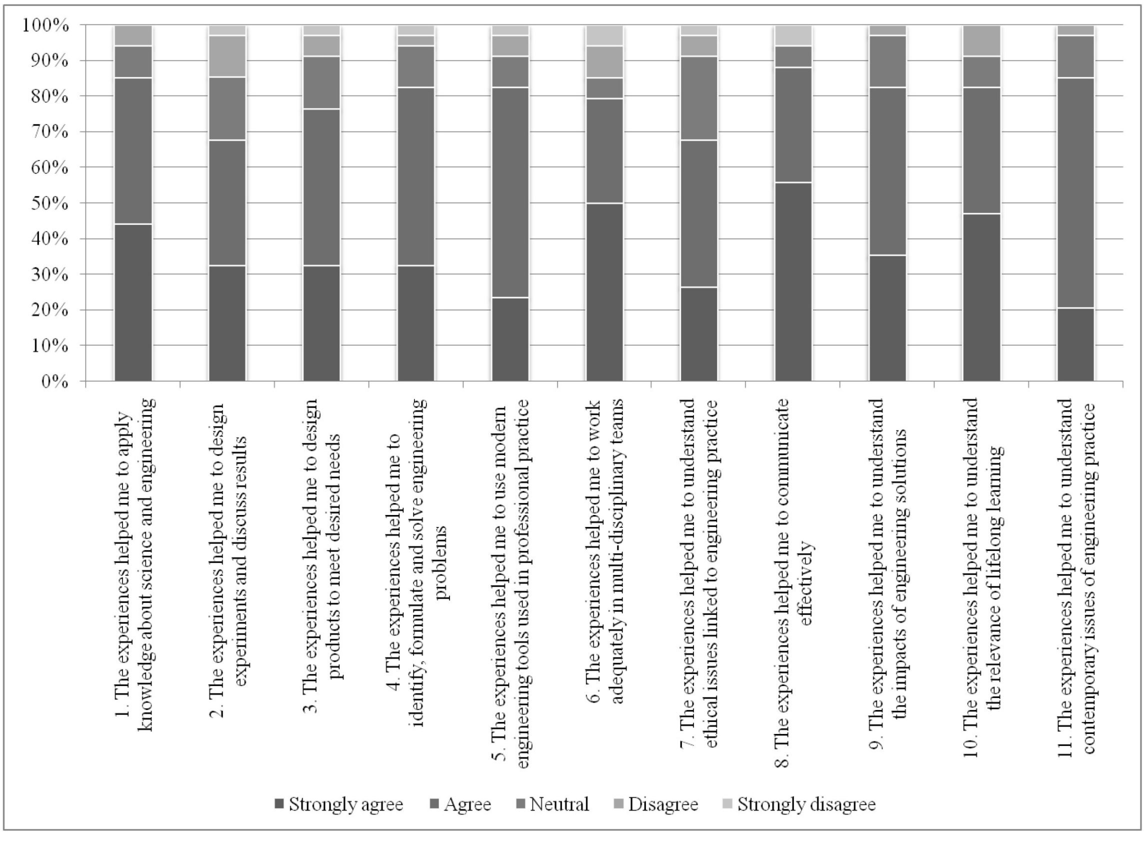

Fig. 6. Summary of results regarding students' perceptions about their improvement of professional skills (following the list proposed by the ABET).

5. Discussion: lessons learned, main challenges and future proposals

5.1 Lessons learned: Keys for successful implementation

In project-based learning experiences, especially when applying the holistic CDIO model, both students and teachers learn together. As professors, the presented results and comments from students are a source of motivation towards the future and we also took home many learned lessons, especially regarding keys for successfully implementing "express" PBL experiences in international contexts. Among the more relevant aspects for an adequate accomplishment we should highlight: the need of advanced and coordinated planning, the relevance of a methodic student selection process, the importance of a complete agenda with tight time control, the essential role of motivated mentors and the provision of complete and clear information regarding desired objectives and proposed activities. Table 2 includes a summary of lessons learning in a schematic way, hoping it may be useful for colleagues facing similar challenges.

5.2 Main challenges and aspects to improve

Some generic challenges and difficulties, which can be encountered in this "express CDIO model" or in similar project-based learning experiences with tight temporal constraints, have been already presented (together with an analysis of possible causes and proposed solutions) in Table 2. Here we concentrate on the more relevant and difficult to tackle ones, according to the experience presented in this study and to the special features of the UBORA EU project, which we expect to correct for forthcoming editions of the "UBORA Design Schools", the following one in Pisa, Italy, in September 2018.

The more relevant challenge we now face is the long-term sustainability of the "UBORA Design Schools", as these international educational experiences, requiring mobility of students and professors from across the World need some sort of funding or sponsorship for performing in adequate conditions. After the two first ones, funded by the UBORA EU project, we expect to have generated enough international impact, so as to make these experiences clearly sustainable. Among the options we consider for the needed sustainability, we would like to

Table 2. Summary of lessons learned: Typical problems and challenges, their possible causes and some proposed solutions for successful implementation of "express" CDIO experiences

Problems and challenges	Possible causes	Proposed solutions
International schools are complex to organize and manage (logistical issues).	Moving more than 50 persons from across the World to the specific campus is always a challenge.	Plan in advance and count with the support of specialized staff and volunteer students.
Student diversity of backgrounds and disciplines limits collaboration.	Students from different degrees, countries and ages tend to have different backgrounds, so some degree of training in advance may be needed.	Provide some additional time for presentations, employ social networks, make them spend free time together. . . Select students on the basis of merit.
Students do not work or communicate efficiently.	They do not like assigned tasks or are not adequately motivated by mentors.	Always promote communication and detail the teaching-learning objectives.
Mentors do not support in a balanced way.	Not all mentors are used to employing project-based learning methodologies or the CDIO approach is unfamiliar.	Perform specific training courses for engineering educators. Involve more partners within the CDIO initiative.
Some (bio)devices are too complex (& expensive) to be designed in one week.	If not adequately selected, proposed devices may be too complex. Sometimes design and simulation programmes are too expensive.	Employ open-access software and student licenses. Simplify geometries and provide rapid training tutorials. Define the boundaries of the project.
Some (bio)devices are too complex (& expensive) to be fabricated in one week.	Sometimes the overall size of the final device is too large or the materials and components too varied and costly.	Employ low-cost 3D printing, paper rapid prototyping and cheap electronic kits for conceptual prototypes.
Working during a whole week with a 8:30–23:00 agenda can be stressing for students and mentors.	Developing an engineering project living a complete CDIO cycle in 5 days requires extreme dedication.	Provide enough coffee breaks and some special leisure or cultural activities for changing scenery and relaxing a bit.
The complete experience is too expensive for long-term sustainability.	Mobilizing so many students and mentors is truly expensive and requires funding and logistic support.	Find sponsorship involving universities, organizations and companies. Perform some of the activities online.
The role of assessment and the assessment procedures are unclear in extra-curricular experiences.	Individual exigency and assessment in a team-based experience, especially if lasting only a single week is very complex and is not compulsory in extracurricular activities.	Incorporate these experiences to the plans of study as complementary courses with a value in credits and requiring assessment. Resort to peer-evaluation and methodic surveys.

mention the potential of UBORA and the UBORA e-infrastructure as teaching-learning environment for collaborative project-based learning in the biomedical field, which may receive sponsorship from universities making use of this online environment. Besides, the open-source medical devices developed in the framework of UBORA may be in some cases offered as low-cost kits for teaching-learning purposes, whose related incomes may be also used to sponsor the UBORA Design Schools. Finally, Higher Education centers worldwide may be inspired by the UBORA community and may wish to involve their students in these mobility actions, providing stipendiums to some selected students focused on the biomedical field. Another minor but still worth mentioning challenge is linked to the unequal dedication and motivation of students and mentors, especially in these extra-curricular experiences, which in our design school led sometimes to minor percentages of absenteeism, although not leading to any dropouts. We believe that following the suggestions included below most of these aspects will be significantly enhanced.

5.3 Future proposals

In the immediate future we will try to focus on the training of engineering educators, for generating a cohort of devoted mentors for these express CDIO experiences, especially in the biomedical field, which will help us improve the already motivating results. Apart from that we believe that enabling the possible recognition of these "UBORA Design Schools", once adequately valued in correspondence with the ECTS (i.e., 3 ECTS for the global dedication of around 75 hours that students devoted to the preparation of the school and to the intense week of collaboration), may help to attract students and additional support from our universities.

Finally, we will devote ourselves for making these "UBORA Design Schools" sustainable and to generate enough momentum and sponsorship from universities, consortia, organizations and engineering companies for being able to implement at least one in Kampala in 2019 and one in Madrid in 2020. As for the longer term, the role of already created consortia (i.e., ABEC and UBORA), the continued support of UNECA and of the EU Commission and the impact of innovative mobility schemes and projects (i.e., ABEM: https://www.africanbmemobility.org) will prove fundamental for transforming BME and its education towards open-source approaches linked to equitable access to healthcare technology.

6. Conclusions

This paper has described an international Euro-African teaching learning experience, the "UBORA Design School" (first edition, 2017), in which engineering students (working in teams) have lived through the complete development process of innovative open-source medical devices, following the CDIO approach, during an intense week. A total of 39 students from 14 universities and 9 countries, have participated in the experience, conceiving, designing, implementing and operating 8 medical devices, intrinsically safe and compliant with international regulations, for addressing relevant health concerns linked to childhood and maternity. This integral teaching-learning experience has helped to promote their professional skills and to plant the seed towards a future generation of biomedical engineers, who will collaborate as members of the "UBORA Community" by using the UBORA e-infrastructure, which has been also presented. The presented analyses of results help to validate the relevance of the proposal and the possibility of performing highly-intense or "express" project-based learning experiences, in which a whole CDIO cycle can be fulfilled in just one week of international collaboration when counting with adequate planning, relevant teaching-learning objectives, motivating sessions and continued mentoring sessions and support from devoted professors.

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European Commission

UBORA: Euro-African Open Biomedical Engineering e-Platform for Innovation through Education

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