WHEN LEARNING HAPPENS THROUGH A CYCLE OF INVENTION, DESIGN AND DIGITAL FABRICATION AS STUDENTS BRING THEIR IDEAS TO LIFE

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Abstract

NEWTON is a large European Union project which develops state-of-the-art STEAM content (Science, Technology, Engineering, Art and Math) and innovative technological-based solutions for technology-enhanced learning (TEL) and validates them with diverse target audiences, which include primary, secondary, university and special learning students in experiments and pilots deployed in multiple locations across Europe. These technologies involve not only adaptive and personalised multimedia and mulsemedia delivery, augmented reality and virtual reality (AR/VR) support for special learners, virtual labs and gamification but also digital fabrication technologies, which are used in conjunction with different learning approaches including self-directed, game-based and problem-based learning methods. Fab Lab Madrid CEU, the digital fabrication laboratory based at CEU University participates in the NEWTON project which is now involved on the real-life validation that includes pilots and experiments targeting over 1000 students and forty teachers/lecturers from different schools, including schools with special learning students, universities and vocational institutes in seven European countries.

The current paper describes some of the experiments carried out in Fab Lab Madrid CEU using 3D printing technologies in coordination with CEU Sanchinarro School, ISEP CEU (Instituto Superior de Estudios Profesionales), Fundación Oxiria and EPS CEU (Escuela Politécnica Superior). Experiments involve the participation of primary school students, students with special needs and high-school students and target the use of the Fab Lab for STEAM subjects as a support tool oriented to fabricate small-scale prototypes to demonstrate and prove the concepts developed by the students in theoretical classes using a hands-on approach. All them provides students with a personalized learning environment that assist them during the whole fabrication and experimentation process establishing a clear link between theoretical concepts and their practical implementation.

Participants learn by designing and creating objects of personal interest. Empowered by the experience of making something themselves, they gain deep knowledge about the machines, the materials, the design process, and the engineering that goes into invention and innovation. In this educational settings, rather than relying on a fixed curriculum, learning happens in an engaging, personal context, one in which students go through a cycle of invention, design, prototyping, reflection, and iteration as they find solutions to challenges bringing their ideas to life. The goal is to show the effectiveness of the Fab Lab environment as a learning tool to develop among students problem solving, collaborative skills and team commitment bringing emotion and motivation into design activities and raising their interest for Science, Technology, Engineering, Math, Art and Design.

Keywords: Fab Lab, inclusive education, digital fabrication, technology.

1 INTRODUCTION

Nowadays, education in schools and high-schools is limited with formal education requirements, content standards and end-of-year examinations. Non-formal education provided in Fab Labs and Makespaces is allowing to remove some barriers complementing the formal education with STEAM initiatives that includes the integration of technology and engineering into science and math curriculum, the promotion of engineering design through mathematics and science classes, the participation of K-12 students with different students and educators that work on the same field on project-based learning using digital fabrication technologies to enhance their learning environment.

The NEWTON project developed in Fab Lab Madrid CEU is involved on the integration of STEAM, looking for increase K-12 and high-school student's enrolment and motivation on subjects as science, technology, engineering, art and maths. The experiments carried out in the Fab Lab for the NEWTON project is contributing to this aim with activities and projects engaging K-12 learners, high-school

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students and students with special needs in STEAM pursuits through digital fabrication. The current communication describes some the experiments carried out using 3D printing technologies and innovative teaching methods. The goal is to show the effectiveness of the Fab Lab environment as a learning tool to develop among students problem solving, collaborative skills and team commitment bringing emotion and motivation into design activities and raising their interest for science, technology, engineering, math, art and design. In order to deeply explain the experiments and activities carried out in the Fab Lab, a brief introduction on how is the on-site learning experience in a Digital Fabrication Laboratory is explained hereafter.

A Fab Lab[1] is a platform for learning and innovation comprised of fabrication and electronics tools, wrapped in open source software and programs that include laser cutter machines that makes 2D and 3D structures, vinyl cutters that produce graphics for making imprintables, large high-resolution CNC milling machines for building furniture and prototypes, 3D scanners and printers and a suite of electronic components for on-site rapid circuit prototyping. Users learn by designing and creating objects of personal interest. Empowered by the experience of making something themselves, they gain deep knowledge about the machines, the materials, the design process, and the engineering that goes into invention and innovation[2]. In these educational settings, rather than relying on a fixed curriculum, learning happens in an engaging, personal context, one in which students go through a cycle of imagination, design, prototyping, reflection, and iteration as they find solutions to challenges or bring their ideas to life.[3]

Digital fabrication[4] goes from the design to the fabrication; it begins with digital design and ends with an output from a fabricating machine. That implies that students interested into prototyping something, no matter with technology is used, should follow this workflow. First of all, students should learn how to use software that helps them to design. After that, they use the software to make their own design (an object, a model or a prototype). Thirdly, students should learn how to use a machine to prototype their designs. 3D designs could be fabricated with a laser cutter, a vinyl cutter, a CNC machine or a 3D printer. Finally, students should prototype their own designs, assemble all the pieces and test the final object.

The activities and experiments designed for the NEWTON project involves different lessons that are related to Fab Lab technologies: laser cutter, vinyl cutter, 3D printing and CNC technologies. Each lesson is configured as a quest that allows students a fixed goal to achieve, made up from a series of linked challenges that multiply the feeling of achievement. Challenges help to keep students interested, testing their knowledge and allowing them to apply it. Overcoming challenges make them feel they have earned their achievement. Three different lessons have been planned. Each one will include three activities that will allow students to improve their level starting from a level for beginners and then, acquiring and intermediate level before they reach the advanced level.

The first lesson is related to learn 3D printer technologies and allow students to reach the following goals. First of all, they learn geometry, 3D modelling techniques, surface analysis and how to export and import models to and from different file formats. Also, they learn how to visualize their designs using axonometric and perspective views. Secondly, they will produce 3D objects and pieces from a 3D printer that will be used, once the pieces are assembled for building a prototype.

Related to their level on this lesson, students are required to do different activities. Beginners are asked to 3D print the pieces for a chess set using a 3D printer and PLA filament. 3D printing technology is attractive for making complex objects easily, personalizing designs according to the mastery of the student on using a computer aided design software. The challenge for this activity is to design and fabricate a chess set. To that end, students have to start designing the shape of the pieces considering the limitation of the technology and the scale. Each student is in charge of one piece (king, queen, rook, knight, bishop and pawn) and the final set includes the whole pieces.

Intermediate students are requested to fabricate ceramic vases. Each student is responsible for some parts of the ceramic vases and should work in coordination with the whole group to scale the parts,

[1] Gershenfeld, Neil (2005). *FAB. The Coming Revolution on your Desktop*. Basic Books, New York.

[2] Gershenfeld, Neil (2012). "How to Make Almost Anything. The Digital Fabrication Revolution". *Foreign Affairs*, 91/ 6, Council in Foreign Relations, New York.

[3] Blikstein, Paulo (2013). *Digital Fabrication and 'Making' in Education: The Democratization of Invention in FabLabs*. J. Walter-Herrmann & C. Büching (Eds.), Bielefeld: Transcript Publishers.

[4] Anderson, Chris (2012). *Makers, the New Industrial Revolution*, Crown Publishers Group, New York.

prepare the necessary files and 3D print them using the proper parameters. Advanced level students have to design and fabricate a mini-rocket using 3D printing technologies. It involves to learn physics and maths concepts for the definition of the mini-rocket shape; spatial reasoning; form analysis to slice a model into smaller parts that later will get attached and finally, navigating the 3D design environment using measurement tools, units, scale and Boolean operations. Students are expected to learn theoretical concepts during the game, as well as the technology of additive processes, slicing and G-code to prototype their design files. They have to work in groups: each group of three students will design and fabricate one mini-rocket. There will be a competition at the end to test which mini-rocket goes higher. Competition gives students a chance to prove themselves against others so it can be a way to win rewards, but above all it can be an activity where new friendships and relationships born.

The second lesson is focused on learning CNC technologies and allows students to reach the following goals. First of all, students acquire knowledge on 2D drawing techniques using plans, sections and elevations of a 3D model, in order to be engraved or milled in a CNC machine. Secondly, they learn how to design and build objects using a CNC machine. Using wood as the main material, they explore the fabrication of experimental prototypes, test geometries and pursue creative solutions. Finally, they explore the interaction between digital manufacturing and craftsmanship, combining techniques of woodworking, engraving or printing using latest computer controlled machines.

Related to their level on this technology, students are required different activities. Beginners are asked to do a tactile map for children with visual disabilities. CNC technology is attractive for making communication tools for the visually impaired and blind, due to its obvious benefits in offering a raised surface that goes far beyond what Braille alone has to offer. The challenge for this activity is to design and fabricate a tactile map of the area in which the Fab Lab is located among all the participants. Rather than making the tactile map simply aesthetically appealing and correct to scale, the map has to be optimized for clarity and the practical needs of people who are visually impaired. It should not be a true to life version of the area but a map that contain the following roads of all size; pedestrian roads higher than others (because they are more important for the blind); buildings; railways; the location of the Fab Lab marked with a cone and a North-East corner marked to indicate correct orientation. Students learn to identify components of a laser engraving and cutting system; describe vector images to learn how the CNC machine mills them and set power and feed rate appropriate for engraving.

Intermediate students are requested to combine engraving and cutting techniques. Students should learn how the CNC machine engrave; use 2D software to create designs for engraving and finally, set power and feed rate appropriate for different processes. To that end, the intermediate challenge will consist on design and fabrication some product design that should be assembled to generate a collaborative project. Finally, advanced students are involved on a woodworking project and the exploration of joints that allow assembling a large prototype. To learn this, students are required to fabricate an architectural model made by some parts that should be tabbed into the material and that require removal and filing. Each student should build part of the structure and the enclosure using wood. The generated parts will need connecting, clamping, filing, and sanding. There will be a hands on workshop where the easy to assemble prototype has to be built. The use of a CNC requires layers and sequencing when planning cuts, carving, drilling and milling as well as layering for sequence of drilling, milling and cutting.

The third lesson is designed to teach students how to use laser and vinyl cutter technologies and allows students the following goals. First of all, use 2D vector programs so that students can fabricate their designs using the laser cutter or the vinyl cutter. Secondly, learn the endless possibilities of laser and vinyl cutting technologies. Among the list of objects that can be generated it includes printmaking plates, screen-printing stencils, drawn designs and laser paper cuts.

Related to student's level using this technology, students are required to carry on different activities. Beginners are requested to design and fabricate a pop-up mini book. Laser cutter could be used for making paper folding models starting from a design created in a 2D vector software. A laser-cut design made by each student should be cut and then, folded into a pop-up before it is adhered to the page of the book. Through this activity, students are expected to learn a variety of functions related to cutting, half cutting, dotted line cutting and folding lines which will help to finish the production of the pop-up mini book. Intermediate students are planned to work with a vinyl cutter that should be used to produce graphics for T-shirts. On this activity, students learn graphic design tools that allow them to draw their design in a computer aided design software before cutting it with the vinyl cutter and adhere it to the T-shirt using a heat press. Also, they learn how the imprinting process works and what it is needed to get started doing imprintables with CAD cuttable T-shirt graphics, as well as how to use vinyl & transfer tape in order to get a good final result.

Finally, advanced students are requested to build a press-fit kit, starting from the use of a computer aided design software that allow designing a structure before cutting the parts using a laser cutter to manufacture and assemble an expandable model with compatible and interchangeable joints that allowed different configurations. Thanks to this activity, students are expected to learn advance tools for laser cutting, cause all the pieces of the press-fit kit must fit together without using glue, nails, screws or other fasteners. They have to adjust the joints to fit together in a precise way depending on the material thickness that they use. Each group of three students should be responsible for a part of the final model, so they have to work with the rest of the groups to make the joints of their model compatible. There is a hands-on workshop where all the models will be assembled.

The experiments and activities described in this communication are focused on the first lesson devoted to learn 3D printing technologies to introduce students to STEAM subjects.

2 METHODOLOGY

The experiments and activities proposes a methodology inspired by Neil Gershenfeld's ideas of Fab Labs[5] as tools for improving people skills to design and produce their own things. Students learn by designing and creating objects of personal interest. Empowered by the experience of making something themselves, they gain deep knowledge about the machines, the materials, the design process, and the engineering that goes into invention and innovation. In this educational settings, rather than relying on a fixed curriculum, learning happens in an engaging, personal context, one in which students go through a cycle of invention, design, prototyping, reflection, and iteration as they find solutions to challenges bringing their ideas to life[6].

The learning experience includes two sessions. The first one includes a theoretical introduction to teach some concepts related to design and math that are applied on 3D design. The second one is a workshop to allow students to fabricate their designs working in groups. Along the way they are requested to document and explain their way to approach to each part of the design and fabrication and to discuss it with the instructors and classmates.

2.1 Goals and objectives

Main goals for the NEWTON experiments and activities carried out in the Fab Lab are listed below:

- Motivate students in STEAM courses through the use of digital fabrication technologies.
- Combine the formal education taught in the school with non-formal education provided in a Fab Lab.
- Understand the practical application of theoretical concepts taught in the school's core subjects.
- Understand how the basic principles of digital fabrication are applied in diverse fields as art, engineering or science.

Specific goals for the NEWTON experiments and activities carried out in the Fab Lab are listed below:

- Operate equipment in a Fab Lab following safety protocols.
- Design something in a Fab Lab using a specific process under close instructor guidance.
- Work with a group to follow multiple common design process steps (e.g. defining the user, brainstorming, prototyping, iterating, etc.).
- Draw a basic design using 2D vector graphics
- Draw a basic design using a 3D design or a computer aided design software.
- Safely virtually operate a digital fabrication machine.
- Fabricate objects of students' own designs using multiple digital fabrication processes.
- Identify the design problem, investigation, or challenge.

[5] Gershenfeld, Neil; Gershenfeld, Alan; Gershenfeld, Joel Cutcher (2017). *Designing Reality: How to Survive and Thrive in the Third Digital Revolution,* Basic Books, New York.

[6] Lorenzo, Covadonga (2017). *La fabricación digital y su aplicación en el ámbito de la educación superior universitaria. El laboratorio de fabricación digital FabLab Madrid CEU*, CEU Ediciones, Madrid.

– Formulate questions that reveal important aspects of design process including problems and challenges.
– Understand information to answer general questions about Fab Lab equipment and design process.
– Explain the effectiveness of a provided solution to a design problem, or a given approach to meet a digital fabrication challenge.

2.2 Participants

Experiments and activities for the NEWTON project at Fab Lab Madrid CEU have been carried out in coordination with CEU Sanchinarro School, ISEP CEU (Instituto Superior de Estudios Profesionales), Fundación Oxiria and EPS (Escuela Politécnica Superior) at CEU University. Experiments involve the participation of primary and secondary schools, students with special needs and high-school students and target the use of the Fab Lab for STEAM subjects as a support tool oriented to 3D design and fabricate small-scale prototypes to demonstrate and prove the concepts developed by the students in theoretical classes using a hands-on approach. All them provides students with a personalized learning environment that assist them during the whole fabrication and experimentation process establishing a clear link between theoretical concepts and their practical implementation.

3 CASE STUDIES

To deeply explain the activities related to learning STEAM subjects through 3D printing technologies an overview of the experiments carried out at the Fab Lab are provided hereafter.

3.1 Primary school students: design and fabrication of a chess set.

This experiment includes the design and fabrication of chess sets, as well as a redesign of a chess set for the visually impaired. Thanks to this activity, students learn how to design and fabricate daily objects as well as how to improve them to enhance social inclusion.

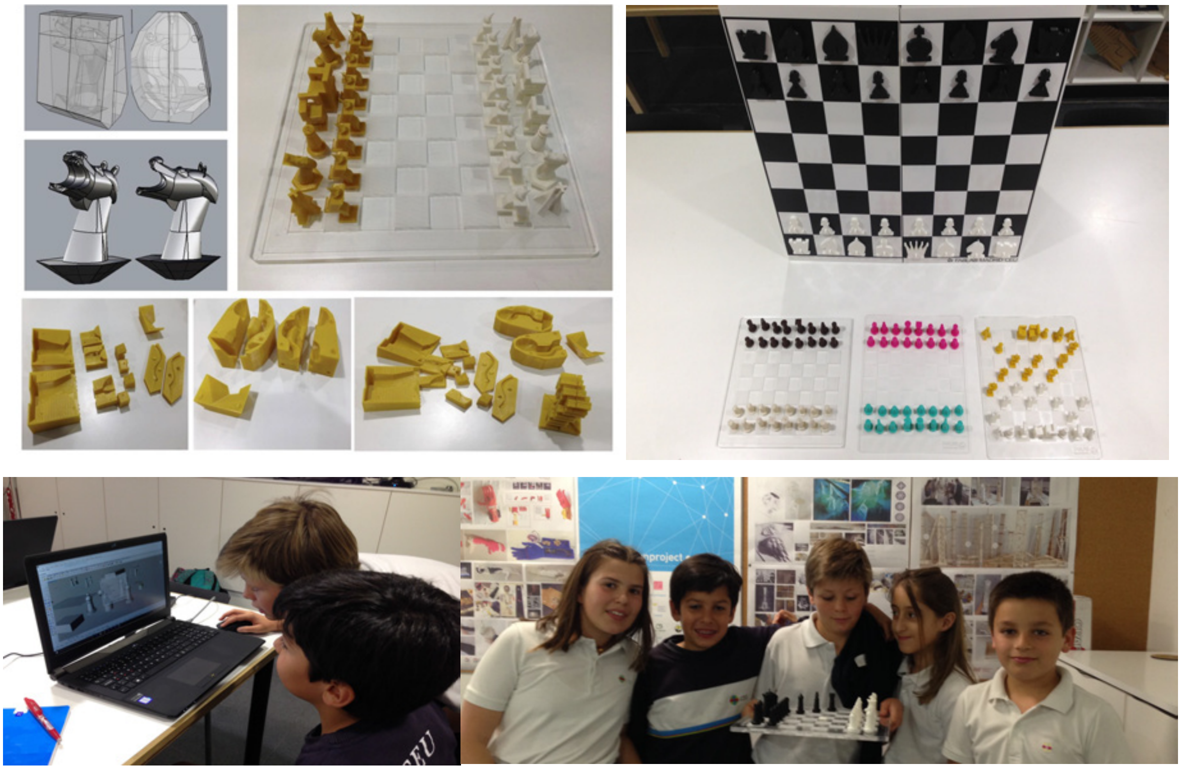

Figure 1. CEU Sanchinarro students designing and fabricating a chess set. Fab Lab Madrid CEU.

The learning experience includes two sessions. The first one is a theoretical introduction to teach some concepts related to design and math to be applied on the design of chess sets. The second is a workshop to allow students to fabricate their designs working in groups. Students used different technologies to design and fabricate the chess sets. Designs were made using Rhinoceros and Autocad to get the 2D and 3D designs. Some pieces of the chess sets were made using 3D printing technology. Some others were fabricated after 3D printing the molds of the chess pieces. The chess set redesigned for the visually impaired includes some other 3D printed parts attached to the original chess pieces. At the end of the second session, a competition was held using the chess sets encouraging the participation of students and instructors.

Chess has proved to be an excellent way to integrate children with disadvantages. Chess require a mental workout, thinking ahead, planning, being systematic, and determining the outcomes of certain moves becoming a single most powerful educational tool that could enhance learning, especially for the disadvantaged. So a chess competition is not only about promoting cognitive skills and academic achievement but is increasingly oriented towards social goals. All the chess sets has been donated to St. Helene Orphanage in Kenskoff (Haiti) where teachers are exploring the possibilities of chess as a learning tool for the motivation of the students as chess is not only about promoting cognitive skills and academic achievement but is increasingly oriented towards these social goals.

3.2 Secondary school students: design and fabrication of a mini-rocket

The experiment carried out with secondary school students was focused on the design and fabrication of a mini-rocket using 3D printing technologies.[7] This involved five sessions. The first one was focused on teaching physics and maths concepts for the definition of the mini-rocket shape. Theoretical concepts about a space rocket launch were shown to be applied on the design of a real mini-rocket that was launched on the last session of the experiment. Students learned also all the parameters involved on the launch to be considered on the design as the high, trajectory, etc. The second session was devoted to use a 3D design software to model the rocket pieces. Students learned concepts as spatial reasoning; form analysis to slice a model into smaller parts that later were attached and finally, navigating the 3D design environment using measurement tools, units, scale and Boolean operations.

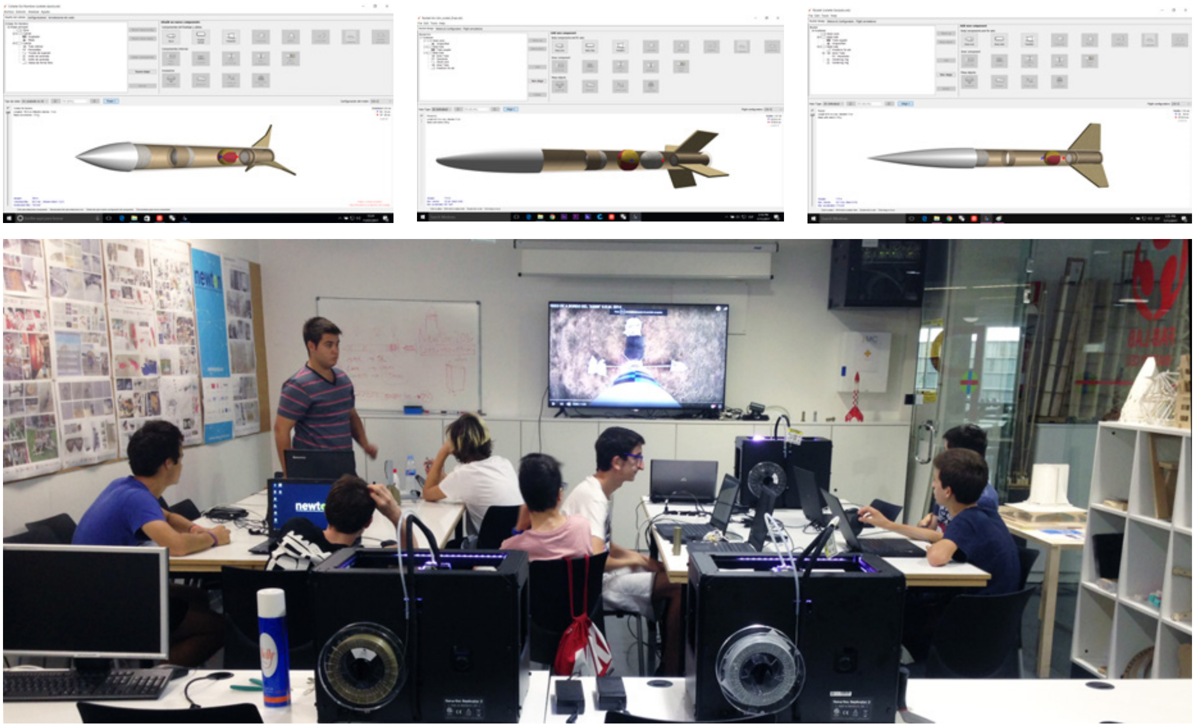

Figure 2. 3D Design and fabrication of mini-rockets. Fab Lab Madrid CEU.

[7] Lorenzo, Covadonga (2017). "Improving Learning Process through Digital Fabrication Technologies". *EDULEARN, 9th International Conference on Education and new Learning Technologies Proceedings*, IATED Academy.

During the third session students manufactured all mini-rockets using 3D printing technologies learning the technology of additive processes, slicing and G-code to prototype their design files. They made some printing tests before printing the final pieces and assembly the mini-rockets working in groups: each group of three students designed and fabricate one mini-rocket.

On the fourth session, students had to work on testing the rockets launching to decide the load and installing the motors, the accelerometer and the parachute. Finally, on the last session, a competition was held to test which ones goes higher and also to check their trajectory. All mini-rockets were launched at the Loring airdrome in Madrid. Competition gave students a chance to prove themselves against others so they could win rewards, but at the same time they had to work as a group making friends and enjoying the championship.

3.3 High-school students: design and fabrication of ceramics.

The experiment involved a group of high-school students[8] and aspiring designers on the design and fabrication of ceramic vases. During the experiment they learned how the study of geometry could help them to apply to the design and manufacture of products. Each student designed a ceramic vase using complex geometries as hyperbolic paraboloids or rotating shapes. Then, students had to learn how to prepare design files on a 3D slicer software, assigning the parameter for a new PLA filament with sandstone and binding polymer that creates a ceramic surface finishing. Once the G-code files were ready, they learned how to use a 3D printer to get the pieces and test the original designs.

A group of about eight students enrolled to the experiment looking for increasing high-school students motivation through the design of a technologically rich environment that could offer them direct access to the university facilities and innovative methods that prioritize ideas over skills or knowledge. The Fab Lab and the digital fabrication tools helped to change the student's misconception that learning is related to acquire knowledge and skills, to a new definition of learning that involves bringing their ideas to life thanks to the use of new programming languages and technologies.

Figure 3. 3D Design and fabrication of ceramic vases. Fab Lab Madrid CEU.

[8] Lorenzo, Covadonga (2017). "Digital Fabrication as a Tool for Teaching High-School Students STEM at the University". *IDC 17, Interaction Design Conference Proceedings*, Stanford, California.

The experiment was designed for those high-school students that were finishing up their junior year of high school and were thinking about their future. The aim was to motivate them to finish their studies and explore the possibilities of studying a career at the university and more specifically, it was focused on those students that were interested on a career in the design and building professions. The idea was to take advantage of the university facilities as a kind of dynamic laboratory of design speculation.

3.4 Students with special needs: design and fabrication of flowers.

Thanks to Fundación Oxiria and ISEP CEU a group of students with special needs attended to the experiment at FabLab Madrid CEU. The challenge was the design and fabrication of 3D flowers using a 3D Printer and open software. To that end, students started designing the shapes through simple geometries and Boolean operations. Later on, they learned how to prepare the files to 3D print their own designs at the Fab Lab and finally, assemble all the pieces to get a bouquet of flowers.

All the students with intellectual disability came from the Fundación Oxiria and all are studying a title on Floristry Technician on the ISEP CEU. The aim of the experiment was to show them the applications of new technologies in their field so that they can introduce 3D printing technologies on their everyday work as florists. The experiments was a success and they all understand and use fluently new digital fabrication technologies with wit and interest.

Figure 4. 3D Design and fabrication of flowers. Fab Lab Madrid CEU.

4 CONCLUSIONS

After the experiments and activities, results of the evaluation process showed a high degree of satisfaction among students who were included in the activities and experiments, as it was showed on the questionnaires. Many of the comments made by the students were related to their satisfaction with the experiment as: “It has been very good and I liked it a lot”, “Very cool”, “I have learned more than I knew”, “I want to come back” or “It has been magic”. Some others were related to the use of Fab Lab technologies, as “I love 3D”, “I have learned how to apply the new technologies to the Art” and finally, some others comments were focused on the design processes as “I have created and I have learned and developed my creativity” or “We have applied our knowledge of geometric shape”.

During all the experiments and activities carried out for the NEWTON project, Fab Lab technologies have been proved to be part of the future of education, allowing students to design and fabricate their own products and prototypes to test theoretical concepts taught during the school’s core subjects, through the combination of the formal education taught in the school with non-formal education provided in Fab Labs, where all the necessary tools can be found and use safely[9].

The experiments carried out at Fab Lab Madrid CEU focused also on the application of the basic principles of digital fabrication in diverse fields, as product design, art, engineering or science to demonstrate that Fab Lab technologies are useful to strengthen and deepen all the theoretical and practical school's core subjects. Experiments were also carried out with students that came from different backgrounds: primary school, secondary school, high-school and students with special needs to prove that it is possible to use Fab Lab technologies starting from scratch with students from any level and also, that it is possible for all kind of students to operate equipment in a Fab Lab following safety protocols if they are guided and taught by instructors under the supervision of teachers while design prototypes using multiple digital fabrication processes.

All these experiments and activities also allowed students to work in groups following multiple common design process steps, as defining the user, brainstorming, prototyping or iterating. They had also identified the design problem, investigation and challenges involved on design and fabrication processes. During these processes, students have learned to formulate questions that reveal important aspects of design process including problems and challenges, as well as explain the effectiveness of a provided solution to a design problem, or a given approach to meet a digital fabrication challenge.

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[9] Lorenzo, Covadonga; Lorenzo, Epifanio (2017). "On Active Learning and Sharing through Digital Fabrication", *ICERI 17, 10th International Conference of Education, Research and Innovation Proceedings*, IATED Academy, 2017.