DESIGNING, TESTING AND ADAPTING TO CREATE A DISTRIBUTED LEARNING PROGRAM IN OPEN DESIGN AND DIGITAL FABRICATION

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Abstract

Science, Technology, Engineering, Arts and Mathematics (STEAM) education is perceived as difficult and many students either do not choose or give up studying these subjects. NEWTON is a large European Union project which develops STEAM content and innovative solutions for technology-enhanced learning, validating them with diverse audiences, which include primary, secondary, university and special learning students in pilots deployed in multiple locations across Europe. These technologies include digital fabrication tools in conjunction with different learning approaches as self-directed, game-based and problem-based learning methods to increase learner quality of experience improving learning programs.

This paper describes a small-scale pilot leaded by Fab Lab Madrid CEU and deployed at Madrid based CEU Montepríncipe School, that will be also run at St. Patrick's School in Dublin (Ireland) and Liceo Scientifico G. Da Procida in Salerno (Italy) in a second stage. It targets the use of a digital fabrication laboratory for STEAM education, as a support tool for students to test remote access to digital fabrication facilities and effectiveness of a Fab Lab to develop among students problem solving, bringing emotion and motivation into activity designs and raising their interest for Science, Technology, Engineering, Arts and Mathematics.

Keywords: Fab Lab, digital fabrication, education, technology, open design, STEAM education.

1 INTRODUCTION

The number of students enrolled in scientific disciplines across Europe has been dwindling lately. The rate of European graduates in Science, Technology, Engineering, Art and Mathematics has dropped since 2000 [1]. This disengagement is mainly due to the fact that students perceive STEAM subjects as difficult and get easily dissuaded. To address this concern, the European Union Horizon 2020-funded project NEWTON [2] was launched in 2016 to build a pan-European learning network platform that supports fast dissemination of learning content. The project develops STEAM content and innovative solutions for technology-enhanced learning, validating them with diverse audiences, which include primary, secondary, university and special learning students in pilots deployed in multiple locations across Europe. These technologies includes digital fabrication tools in conjunction with different learning approaches as self-directed, game-based and problem-based learning methods to increase learner quality of experience improving learning programs.

To validate the effectiveness of the approach proposed in the NEWTON project, multiple small and large-scale pilots have already taken place in several European countries. Over thousand students from different educational levels, including students with special needs, participated in these pilot tests. This paper describes one of the small-scale pilots, leaded by Fab Lab Madrid CEU and deployed at Madrid-based CEU Montepríncipe School, that will be also run at St. Patrick's School in Dublin (Ireland) and Liceo Scientifico G. Da Procida in Salerno (Italy) in a second stage. The pilot targets the Fab Lab STEAM Program, which is focused on the use of digital fabrication technologies [3] to consolidate STEAM courses via remote access to digital fabrication facilities, helping students to develop creativity, problem solving and team-work and raising their interest for Science, Technology, Engineering, Arts and Mathematics.

2 METHODOLOGY

A combination of three diverse approaches [4] has been used for designing the Fab Lab STEAM Program: constructive alignment, the RASE (Resource, Activity, Support and Evaluation) model and

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universal design strategies. In our view, all are complementary. Constructive alignment provided a general approach to educational design, the RASE model helped on the integration of technology to improve student learning outcomes and finally, universal design approaches provided specific information on how to design inclusive and accessible activities for all.

Constructive alignment was used to define the learning goals and align them with teaching and assessment strategies [5]. It helped to select the course content and plan the learning activities so that success could be measured through assessment of a student's achievement of the learning outcomes. This approach has been a good solution to design the Fab Lab STEAM program because learning goals were clearly stated from start, so activities were designed to reach these goals and assessment tasks guided students toward these outcomes.

Regarding the integration of technology to improve student learning outcomes and satisfaction, the RASE model [6] which is focused in resources, activities, support and evaluation, has been essential for designing the program. The use of technology resources, such as video tutorials and demonstrations to learn about digital fabrication tools were planned, as well as remote access to the Fab Lab machines through a cloud hub application. Besides, hands-on workshops on the use of digital fabrication technologies (collaborative activities) were designed and on-line support was provided during the workshop through teachers, Fab Lab instructors and active students that become 'instructors' during the workshop (support). Finally, on-line feedback from instructors and teachers during the workshop (evaluation) were carried out to engage students on the activities.

Finally, it is worth to mention the universal design strategies used to design the program, which are closely aligned with the concepts of equity, diversity, accessibility and inclusivity that provides specific tools on how to design inclusive and accessible activities for all. Fab Lab STEAM Program includes some of the UDL principles, such as diverse ways of providing students the learning content and to support learners to communicate ideas through different means. We also planned some methods to improve engagement of students, such as providing them more feedback during the class and being clearer about the goals to achieve, so that students might be able to develop their self-regulatory skills.

2.1 Learning Goals and Objectives

Fab Lab STEAM program has two main goals: first of all, consolidating STEAM subjects through using Fab Lab technologies as a support tool that can provide students with a personalized learning environment, in which they can put into practice the different theoretical concepts acquired in class; and secondly helping students developing skills and capabilities such as creativity, problem solving and team work. In doing so, we believe that we can raise students' interest in STEAM subjects.

Specifically, the small-scale pilot carried out at Madrid based CEU Montepríncipe School has five objectives. First of all, raise the motivation of students on STEAM courses and the potential of digital fabrication to help learners to gain a greater understanding of Geometry and Arts & Crafts. Secondly, explore if Fab Lab technologies could help in developing new skills in the fabrication of products [7] in a way that conventional approaches have failed to do. Thirdly, test if the learning that was achieved on the design and fabrication of ceramics through the implementation of Fab Lab technologies (3D printers) was retained by learners and they were able to apply on the design and fabrication of other ceramic products. Fourthly, demonstrate that Fab Lab technologies [8] can be used as a learning tool, through which it is possible to create a working educational environment [9] to show students practical applications of theoretical concepts acquired during their conventional classes at school. And finally, test if the virtualization of Fab Lab machines allowed students to remotely engage Fab Lab activities and to learn the Fab Lab workflow [10] to design and fabricate their own products.

2.2 Pilot Procedure Stages

In order to achieve the main objectives previously stated, Fab Lab instructors and teachers counted on the support of a Pedagogical Assessment Committee (PAC) created for the NEWTON experiments and pilots, who advised us in the procedures to follow, which included four stages.

The first stage was related to the preparation of the pilot which was managed through a collaborative tool called Trello. Thanks to this application, teachers were informed about the procedures to follow and got access to all the information, videos and tutorials required during the pilot's deployment. They were in charge of downloading and installing free software applications needed to design and fabricate ceramic vases: FreeCAD and Ultimaker Cura. To that end, video tutorials and text tutorials were provided explaining step by step how to download and install both programs. Besides, teachers and instructors could get access to documents, forms and questionnaires to be used during the data collection.

During the second stage, consent from student's parents on their participation in the small-scale pilot was obtained. Also, students were informed about the research, so that they had the opportunity to express their agreement or lack of agreement to participate in the pilot. Besides, students filled in the questionnaires and pre-tests approved by the PAC to be assessed after the pilot deployment. Three questionnaires were handed-out before starting the pilot: a Demographic Questionnaire, a Knowledge Pre-Test on Learning to investigate the participants' level of knowledge on the subject and finally, an Affective and Motivation Questionnaire regarding traditional technology classes.

The third stage involved the pilot deployment and was organized in four main activities. During the first one, students were required to 3D design geometric shapes using free 3D software; the second activity focused on the preparation of the design files to be 3D printed; the third one involved the use of a cloud hub application to send the files to a 3D printer and finally, the last one was related to the fabrication and assembly of the final product.

During the fourth stage of the small-scale pilot, post-questionnaires were distributed to teachers and students to collect information to be used during the data analysis. To fully understand student's impressions and get in-depth information about the participants' experience, two forms were handed-out after the pilot: an Affective and Motivation Questionnaire regarding STEAM and a Learner Usability Evaluation to assess student's level of usability and enjoyment of the Fab Lab technologies. Furthermore, to gather accurate information during the pilot deployment, teachers collected data through observation taking notes and pictures. Observing group interaction provided valuable information to be used for implementing the activities that didn't work as it was expected, as well as thinking about new ones that could improve the learning processes. Through observation, it was possible to recognize possible improvements not easily described by participants on the questionnaires. Besides, in order to gather qualitative information regarding usability that was very specific to the pilot, there was one focus group at the end of the activity to ask students additional questions. Finally, to determine the student's state of skills, Fab Lab instructors checked the pieces fabricated by participants. This allowed to know about the level of students on digital fabrication to evaluate if they acquired all the skills on 3D printing that were expected and to rethink new ways of improving activities

3 CASE STUDY

The Fab Lab STEAM small-scale pilot was deployed at CEU Montepríncipe School in Madrid, Spain. A group of secondary school students of thirteen years of age took part in the pilot test: five boys and five girls working together to design and prepare the files to be 3D printed. The pilot was carried out over two days, each of which consisted on a four hours long session divided in four main activities.

3.1 Activity 1: Designing Ceramic Vases (3D Modeling)

The aim of the first activity was the design of ceramic vases using a 3D modeling software after exploring diverse types of geometries. To that end, it was used FreeCAD, which allowed teaching the basic principles of construction and visualizing the designs in the 3D space. The design of geometries that were transformed afterwards into ceramic vases put emphasis on the use of geometry in practice. At the same time, the fabrication of 3D models by students was meant to increase their imagination and perception through logical reasoning and deductive thinking, helping them to expand both, mentally and mathematically.

The ceramic vases proposed to be designed and fabricated during the pilot included geometries that were not easy to understand by secondary school students, as the hyperbolic paraboloids (hypars). Hypars are ruled surfaces and can be created using only straight lines, even though they are curved. In fact, hypars are doubly ruled and one of only three curved surfaces than can be created using two distinct lines passing through each point. The vases proposed are designed with fragments of hypars based on a square and a triangle. The geometry starts with two squares or triangles rotated 45 or 180 degree angles that create star-shaped projections in plan. Using the square sides or half the sides of the squares it is possible to create fragments of hyperbolic paraboloids that make up the faces of the ceramic vases. As the hypars are built using straight lines, these surfaces are appropriated to be fabricated quickly with a 3D printer, which works extruding the shapes by mean of summing up layers.

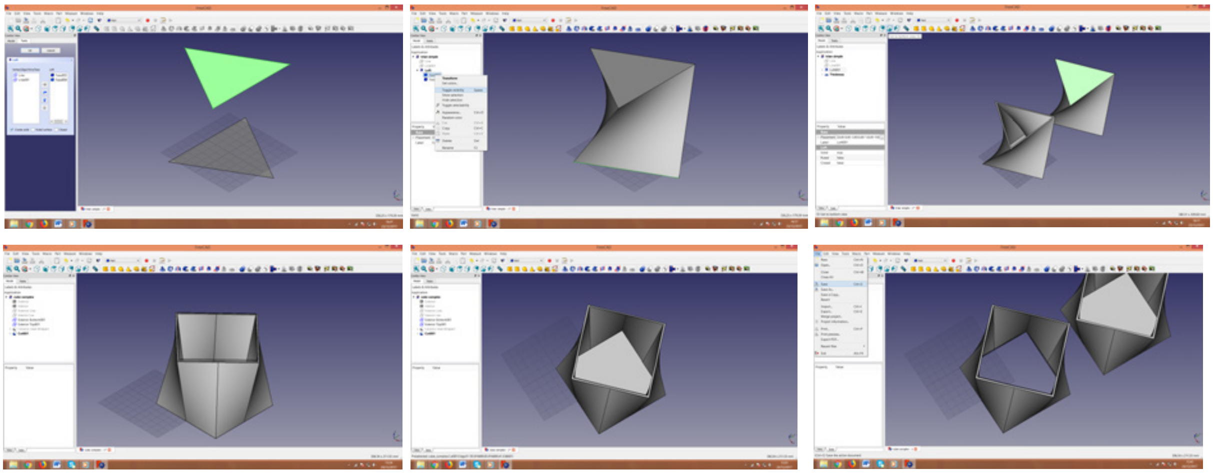

Figure 1. 3D designs of ceramic vases using FreeCAD.

Before starting designing the geometries, students learned about FreeCAD interface identifying the 3D view area; the tree view, which shows the hierarchy and construction history of all the objects; the properties editor, which allows to view and modify properties of the selected objects; the report view (or output window), which is where FreeCAD prints messages, warnings and errors and the workbench selector, where it is possible to select the active collection of tools to be used according to a specific task. After that, they started to design their ceramic vases based on simple shapes: triangles and squares. They were provided with paper-based and video-based tutorials which explain how to work in different workbenches, how to visualize the 3D model from different views (top, botton and front view as well as axonometric views), how to create primitive objects and transforming them or how to do Boolean operations. They also learned how to change dimensions and assign properties to the created items in order to get a 3D model that could be 3D printed. Finally, they learned how to save the original design files and how to export the stereolitographic files from the 3D design to be prepared for 3D printing in Ultimaker Cura, the 3D printer slicer application.

3.2 Activity 2: Preparing Designs to be Fabricated (3D slicing)

During the second activity students were required to prepare their designs to be 3D printed. Each ceramic vase consisted of three parts: the bottom, the middle and the upper one. Students grouped together and select one of the three parts of the vase to prepare the file to be printed. To that end, they used a 3D slicer application called Ultimaker Cura. They were provided with tutorials to learn how to import stereolitographic files, how to prepare the print set up and assign the model parameters as quality, infill, material, speed or support. They also learned how to create a profile from the settings used to prepare the files and how to save the file as G Code to be 3D printed.

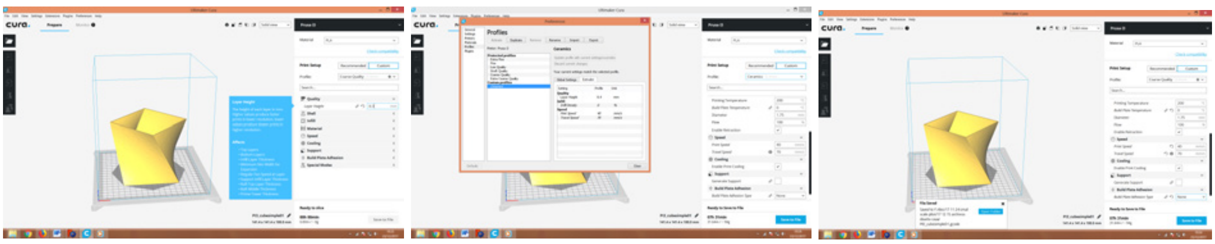

Figure 2. 3D slicing of ceramic vases using Ultimaker Cura.

3.3 Activity 3: Sending the Files to the Fab Lab Machines

The third activity was focused on the fabrication of ceramic vases using a 3D printer. Students learned how to send the files from their schools to a 3D printer located at Fab Lab Madrid CEU. The designs were submitted to the Fab Lab using the cloud hub platform developed at CEU San Pablo University. It relies on cloud, Internet of Things and Industry 4.0 technologies and protocols to implement the concept of Fabrication as a Service [10]. More specifically, it is a complex real-time distributed hardware/software infrastructure that provides a software abstraction layer to the digital fabrication equipment and exposes it over the internet as a web service. The platform implements real-time inter and intra Fab-Lab communication protocols that allow several Fab Labs to be networked and monitored. Every time a fabrication request is delivered to a Fab Lab via the application, the Fab Lab manager is notified and can analyze and approve the design for fabrication using ad-hoc web interfaces. As soon as the fabrication process ends, the system automatically notifies the users that the design has already been fabricated.

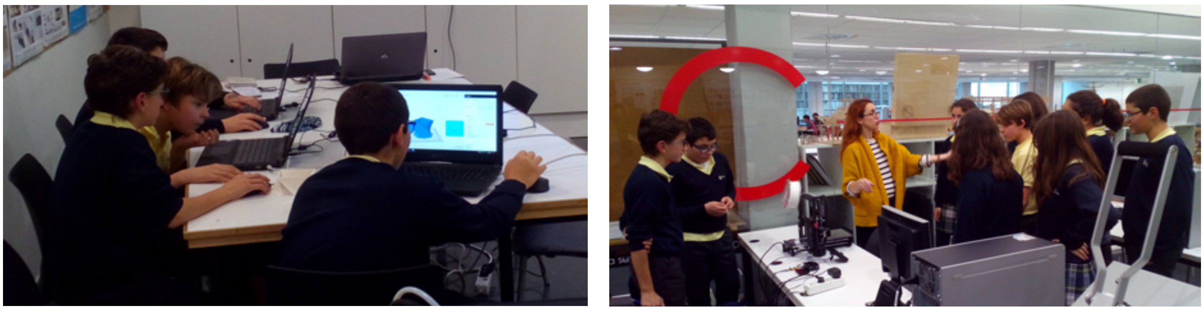

Figure 3. CEU Montepríncipe School Students preparing their files to be 3D Printed and collecting their ceramic vases to be assembled.

3.4 Activity 4: Fabricating and Assembling Ceramic Vases (3D printing)

Students learned how a 3D printer worked and how the machine prints a 3D model starting with the G Code file. The 3D printing process turns a whole object into tiny slices, then makes it from the bottom-up, slice by slice. Those layers stick together to form a solid object. Basically, after receiving the files through the cloud hub, the 3D printer built up the ceramic pieces by repeatedly printing over the same area, in a method known as fused depositional modeling (FDM). Working entirely automatically, the printer created the pieces over a period of three hours by turning the 3D drawings into lots of two-dimensional, cross-sectional layers. Instead of using ink, as in a conventional printer, the 3D printer deposited layers of molten plastic (PLA) that fused layers themselves together. To create a ceramic surface finishing a new material with sandstone was used during the pilot. Varying the extrusion temperature, the surface changed its texture so the combination of the complex geometries and the various possibilities of surface finish featuring this new material allowed students to create innovative ceramic pieces.

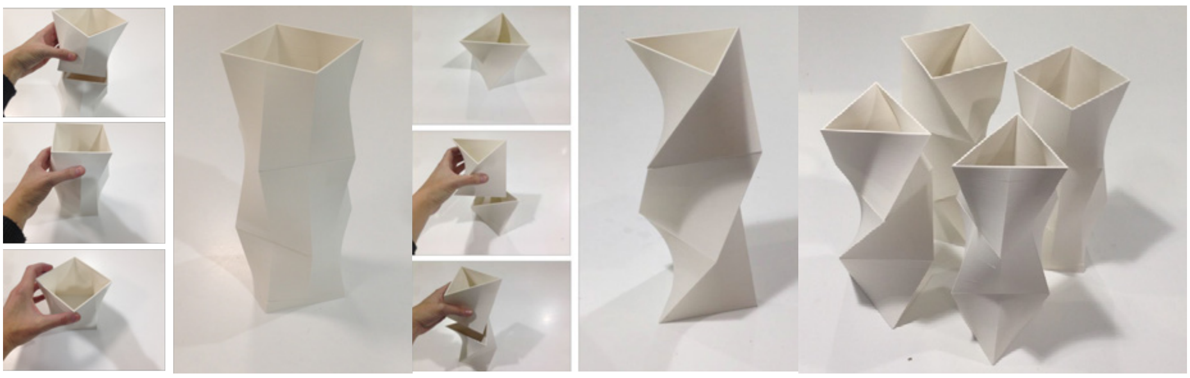

Figure 4. 3D printed ceramic vases fabricated by CEU Monteprincipe School students.

4 RESULTS

According to the design objectives, our aim was to measure student’s response to the lesson, rating their perceptions about the quality and impact of Fab Lab technologies, as well as their opinion about how their use increased their knowledge, skills and motivation. We were also interested into analyze whether the participants were able to use digital fabrication techniques [11] with confidence during the lesson and if they felt ready to design and prototype by themselves using the skills learned.

After the analysis of pre-test and post-test questions it seemed clear that students have demonstrated to know the workflow that occurs in a Fab Lab [12] to fabricate objects through a proceeding that involves design in computer software, prepare the files for a 3D printer in a slicer application and afterwards, use an on-line platform for sending the files to a 3D printer located at the Fab Lab. They have also answered correctly the questions related to the technologies that can be found in a Fab Lab and all the concepts related to 3D printers.

Related to the 3D modeling workflow, students finished their designs with minor problems during the pilot, but it seems that when students were asked to name the operations that they did using the software to get the surfaces, some of them forgot the names of commands used in FreeCAD. Besides, although students also learned about parameters related to 3D printing objects, as the temperature of the extruder, the infill or supports needed to prepare the files, some of them could remember the technical terms for explaining these concepts and didn´t answered correctly the question related to it.

According to the information gathered from the questionnaires, it seems that students felt highly motivated to learn Fab Lab technologies before starting the pilot. Thanks to the information gathered from the demographic questionnaire, it seems that students liked learning Science, Technology, Engineering, Art and Maths. It is worth to mention that no any student answered negatively to this question. 70% of students stated that STEAM courses were not boring, although regarding STEAM lessons at their school, 70 % of them said that they would change them. Besides, 90% of students answered that they would like lessons to be more active. All pointed out that they would like to use more technology in the classroom, so it seems that they might feel highly motivated with the use of technologies to learn STEAM courses at school. In relation to the use of technology, 90% of students stated that they use smartphones and a percentage of 60% said that they use it every day for different purposes: to search on internet, play games, communicate with friends and family, do school work and homeworks. All of them have access to a PC or laptop at home and they seem to use it for the same purposes. The frequent use of technology by students explains why they felt familiarized with laptops during the whole pilot.

After the pilot, students stated on the post-questionnaires that they did not find Science, Technology Art and Maths boring (70%), although they have also stated that these courses should be more active (100%) and also, that they would like to use more technology in the classroom. It seems that the use of Fab Lab technologies increase the idea that STEAM classes should be more active at school.

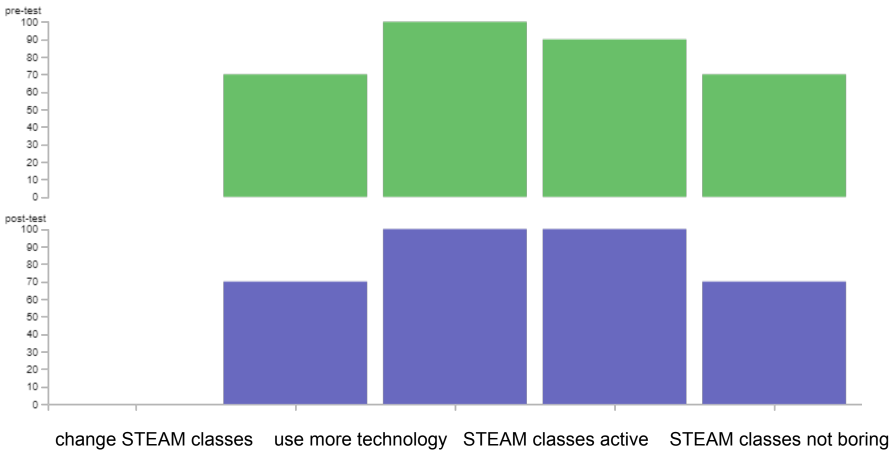

Table 1. Pre-test and post-test results regarding STEAM classes.

The information gathered from the affective and motivation pre-questionnaire allowed us to analyze the interest of students in the Science classes provided in their school and their feelings about it. It seemed that they felt engaged in school lessons; although 60% of students replied they felt anxious. The same percentage answered that Science class was boring. However, all the students felt relaxed on the classes and enjoy them. 80% of students stated that science lessons are really interesting, although almost all (80%) agree on the idea of learning without textbooks. It is clear that students are interested into Science and Technology and complains are related to the way these lessons are taught at school.

According to the answers collected from the affective and motivation post-questionnaire, students also seemed to be interested (100%) in Fab Lab technologies. About their feelings while they were learning Fab Lab tools, all of them felt engaged. They didn´t feel anxious or worried about it (100%) nor even bored (100%). On the contrary, they felt relaxed and 100 % of students felt happy and enjoyed very much (20%) or extremely (80%) during the pilot. Obviously, the approach used on the pilot based on projects, where students learn while they experiment with technologies helped to engage students on the proposed activities.

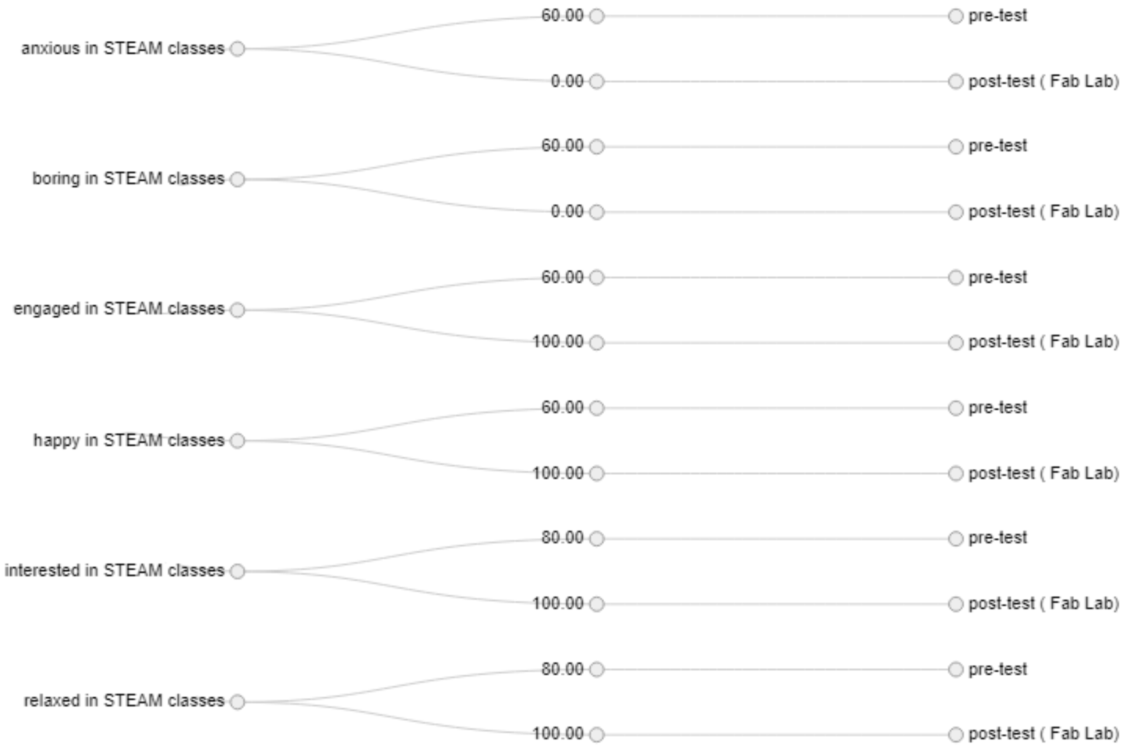

Table 2. Pre-test and post-test results regarding student's feelings.

Finally, the analysis of the Learner Usability Evaluation Questionnaire allowed us to analyze the satisfaction of the users during the pilot. 80% of students answered that they would recommend the use of Fab Lab technologies to a friend and the same percentage agreed or strongly agreed on the statement that these technologies are funny to use. However, only 50% of them replied that they felt they needed to have these technologies in their lives. In relation to the Fab Lab technologies, 80% of students strongly agreed on their satisfaction using them.

Students were also asked some questions to evaluate their knowledge on Fab Lab technologies after the pilot, as it was recommended by the NEWTON Pedagogical Assessment Committee. After the analysis of the information gathered during the focus group, it was clear that students knew the Fab Lab's workflow and understood how to fabricate objects through a proceeding that involves designing in computer software, preparing the files for 3D printer in a slicer application and afterwards, using a platform for sending the files to a 3D printer. They have also answered correctly the questions related to the technologies that can be found in a Fab Lab and concepts related to 3D printers.

The observational assessment allowed us to realize that during the pilot, students responded well when they were requested to use the Fab Lab technologies. They seemed to be familiar with the use of computers and highly motivated to 3D print their designs. Also, they understood and finished the tutorials related to 3D modelling, as well as the 3D slicer application with almost any help from the teacher. They seemed highly motivated on the use of new technologies and all agreed that it was really great to have the opportunity to send their files to the Fab Lab's 3D printer through an application using PCs of their school.

Finally, regarding the answers provided by the teacher to the a post-questionnaire it seems that the use of Fab Lab technologies increased the way she uses technology as part of her teaching practice. She is expecting to start using the cloud hub to 3D print designs developed for students during technology classes at school. She thinks the use of Fab Lab technologies could increase the work in teams during technology classes at school, if she managed to use a project based approach. It is worth to mention that she agreed on the idea that using technology clearly helped to engage students. Regarding the teaching practice, she stated that technologies could change the way she could implement some pedagogical approaches. Specifically, she replied it could slightly increase a problem-based learning approach and also the flipped classroom. Finally, in relation to the learner satisfaction, after the pilot she agreed that having used these technologies in the classroom motivated students that were fully engaged during the pilot.

5 CONCLUSIONS

After the pilot and once the analysis of results finished, there were some lessons learnt to share. The pilot achieved the main goals, as the motivation of students in STEAM courses through the use of digital fabrication technologies, showing that it is possible to apply theoretical concepts taught in the school's core subjects using new technologies and pedagogical approaches. Thanks to the pilot we could also combine formal education taught in the school with non-formal education provided in Fab Labs, making students understand how the basic principles of digital fabrication are applied in diverse fields.

Regarding the specific goals that we expected to achieve using Fab Lab technologies, it was demonstrated that students could virtually operate equipment in a Fab Lab (a 3D printer) following safety protocols through an application that allowed them to send their files from their school to be 3D printed at the Fab Lab. It has been a good opportunity for students that never had the chance to fabricate something by their own. However, students with a previous experience using a 3D printer preferred to manage physically 3D printers. In relation to the design processes, students where highly motivated by the fact that they were going to use open software free for downloading. They were pretty interested into learn how to design to keep practicing with FreeCAD and Ultimaker Cura at their school or at home. On the other hand, they felt that it couldn´t be possible for them to learn without the tutorials and under close instructor guidance.

In order to improve the experience and based on the lesson learnt, there are some proposals to be considered. For those students with a previous experience using a 3D printer, that preferred to operate it physically instead of virtually from their schools, we suggest the use of Virtual Reality during the workshop to make the experience more realistic. Regarding the need of instructors to guide the tutorials, a possible improvement could be the use of some other practices that complement the text tutorials and video tutorials as webinars or forums to interact with students.

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