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3D Printing in Education. Theoretical Perspective and Classroom Experiences

Impresión 3D en educación. Perspectiva teórica y experiencias en el aula

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ABSTRACT

3D printing in universities uses printers that enable the three-dimensional printing of objects. A teaching methodology based on the printing of models is implemented that can be taught interactively and progressively to a wide range of students, from primary and secondary education and vocational training through to undergraduate and postgraduate studies, particularly in the STEM fields of education (Science, Technology, Engineering and Mathematics). The resources used in 3D printing can be integrated in different fields of science as part of a teaching approach based on interdisciplinarity and the application of scientific and mathematical knowledge. This study aims to disclose the role of 3D printing in education, its characteristics, advantages and disadvantages, as well as illustrate various educational experiences on different levels, providing a reference framework that sets out the current situation in terms of its use. Educational experiences using 3D printing obtain meaningful learning thanks to manipulative experimentation, the fostering of motivation to learn, and improved educational results. Students learn while they experiment and have fun, creating a desire to continue acquiring knowledge that is relevant on both a professional and personal level.

KEYWORDS: ICT; 3D printing; higher education; new methodologies; makerspaces.

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RESUMEN

La impresión 3D en el ámbito universitario utiliza impresoras que permiten realizar impresiones tridimensionales de objetos y ponen en práctica una metodología de enseñanza mediante la impresión de modelos que se pueden enseñar a un amplio colectivo de estudiantes, de forma interactiva y progresiva, desde Primaria, Secundaria y Formación Profesional hasta los estudios universitarios y de posgrado, especialmente en la educación de las áreas STEM (Science, Technology, Engineering and Mathematics). Los recursos utilizados en la impresión 3D se pueden integrar en diferentes áreas de las ciencias en un enfoque de la enseñanza basado en la interdisciplinaridad y aplicabilidad de los conocimientos científicos y matemáticos. El presente trabajo pretende dar a conocer el papel de la impresión 3D en la educación, sus características, ventajas y desventajas, así como ilustrar varias experiencias educativas en distintos niveles, proporcionando un marco de referencia que expone la situación actual en cuanto a su uso. Las experiencias educativas utilizando la impresión 3D obtienen aprendizajes significativos gracias a la experimentación manipulativa, el fomento de la motivación para aprender y mejores resultados educativos. Los estudiantes aprenden mientras experimentan y se divierten, se genera un deseo por continuar adquiriendo conocimientos aplicables tanto en el ámbito profesional como personal.

PALABRAS CLAVE: TIC; impresión 3D; educación superior; nuevas metodologías; *makerspaces*.

1. Introduction

In recent years, the integration of technologies in classrooms and in all teaching and learning processes has been a significant step forward in the field of education. These elements offer numerous different scenarios and possibilities and they evolve on a daily basis, creating new elements that give rise to a wider variety of tools and methodologies.

Objects, materials, machines or tools that, until recently, had been thought to belong to other knowledge areas, are now applicable to education, enabling us to harvest their full potential. Thus, robotics, augmented reality and 3D printing are being increasingly introduced in educational processes. This final element is going to be the focus of this study, which aims to disclose the role of 3D printing in education, its characteristics, advantages and disadvantages, as well as different educational experiences at varying levels to provide a reference framework that sets out the current situation.

3D printing involves the use of a printer that allows objects with volume, that is, three-dimensional objects, to be printed. These objects are created from specific designs produced using CAD (computer-aided design) programs (Moreno et al., 2016).

There is considerable variety when producing three-dimensional designs, which can be pieces with all kinds of forms or shapes. Education, as stated above, has not pioneered the use of this element; rather, it was the more technical scientific fields, such as architecture, engineering or industrial design, that first used it (Mpofu et al., 2014; Ford and Minshall, 2019). Today, the field of medicine uses this technique to manufacture prostheses (Sanz-Gil, 2017); geography, to create relief maps (Šašinka et al., 2018; Oswald et al., 2019); technical drawing, to make parts that can be manipulated; and art, to reproduce works (Saorín et al., 2017).

Likewise, in the field of education, 3D printing as a teaching resource is gaining momentum. This is due to teaching and learning processes being understood as makerspaces, that is, spaces for construction and creation where the digital aspect is of particular importance. Thus, students actively participate in practical problem solving (Ford and Minshall, 2019).

The objective of employing this technique within education lies in the revival or recycling of traditional classrooms as creative spaces that address the future needs of students and educate them through experiential learning (Popescu et al., 2019).

The use of tangible objects or models as a teaching resource has always been one of the most frequent practices in education. Recently, however, and with technology acquiring considerable importance within education, these models are now made using digital tools.

In this context, emphasis must be placed on a closely related term, 3D modelling. It is the step prior to three-dimensional printing; using specific apps on a digital device, whether that be a tablet, computer or mobile phone, models of different elements can be designed or transformed until the desired outcome is achieved before printing. In short, it increases the possibilities of creating and adapting the future model to suit the requirements (Cervera et al., 2015).

Therefore, a three-dimensional object can be created in two different ways, in both digital and tangible form; they are good options that can complement each other.

Creating digital models outweighs some of the disadvantages associated with material objects, such as breakages. Likewise, having the model in digital format enables it to be disseminated, replicated as many times as desired, reproduced and simultaneous visualised on various devices, stored and transported, among others.

The use of digital models, as well as three-dimensional models in the field of education, is becoming possible thanks to the affordable prices currently available. In this sense, different applications that have lowered the cost have had a significant influence, as both teachers and pupils can access them free of charge (Carbonell et al., 2016).

2. Advantages and Disadvantages

2.1. Disadvantages

The use of tangible models to help students visualise educational structures in three dimensions has been a cornerstone of general education, particularly in science, for a number of years. The classic anatomical, biological, botanical and mechanical models, and so on, were reused by different generations of students across the globe. However, conventional modelling kits were limited in terms of the types and accuracy of the models and structures that could be used for construction.

To mitigate these limitations, and in the early phases, CAD systems consisted of tools to display two-dimensional (2D) or three-dimensional (3D) graphics that involved complex design processes before they could finally be manufactured, often by hand (Vidal and Mulet, 2006). Today, however, the majority of current educators were trained before advanced CAD programs and solid modelling packages for 3D printing became widely available, while those teachers who recognise educational advantages in 3D printing must frequently learn about varying techniques that are often beyond their area of expertise or turn to virtual training sources (YouTube, e-learning, etc.) (Veisz et al., 2012).

The lack of training has led some educators to sketch preliminary designs and undertake manual calculations to complete the conceptual design and development phase, lengthening the preparation process. The recent development of 3D printing technology has enabled the creation of a much wider variety of structures for teaching; however, they are not easy to implement. Creating the files necessary to print complex structures tends to be technically challenging and requires the use of various software programs that are not always easy to operate and are written in highly technical English (Jones and Spencer, 2018).

Furthermore, not all educators and students have the resources or technical skill to create these files and, therefore, they are discouraged when attempting to use 3D printing in the classroom. In general, 3D printing requires access to databases with the necessary resources, such as UniProt or PubChem for chemical, biological or human structures. With these databases, basic structures of molecules, cells or chemical structures can be created internally on the teacher's computer or easily obtained online from said databases. However, it is difficult to store refined prototypes or erase errors in the design in these databases.

To correctly operate the programs and databases, 3D printing requires time availability, a range of materials, and access to installations or local or online providers with the necessary printers and economic resources to obtain tangible models for a large and adequate number of students. Furthermore, although commercial 3D printers are becoming increasingly cost effective, their adaptations to software do not always enable them to be used for the variety of disciplines required in the classroom.

A common criticism of 3D printing techniques is that they may lead to the educator/designer focusing on the details instead of the underlying principles (Utterback et al., 2006). It is written that "sketching by hand allows a designer to capture an idea quickly; it concentrates on the essentials rather than on bells and whistles" (Utterback et al., 2006).

This is supported by assessing the information required by a CAD system to generate a representation of an object in comparison to the amount of information required to design the prototype.

2.2. Advantages

Nevertheless, set against these disadvantages, simple methods have been developed to easily generate the files needed to print nearly any previously filed structure in 3D using the National Institutes of Health Print Exchange server (http://3dprint.nih.gov/) (or simple alternatives), among others (Coakley et al., 2014).

This is a complete and interactive open website for searching, browsing, downloading and sharing files for 3D printing. This file base allows users to quickly and cost-effectively browse the options to print different structures in a range of materials using local and online shops, as well as internal 3D printers by means of rather simple protocols.

The simplification of the hardware and software tools required for 3D printing means that the technology is becoming accessible to even non-experts. The diversity of interests in 3D printing, together with the wide distribution of the printers themselves, means that there is a host of opportunities to use 3D printing at all levels of education (Miller, 2014).

This methodology can take 3D printing to a wider audience, helping disseminate its use in science education, and it can also be used by students in self-directed learning exercises. In modern pedagogy, education systems using the 3D printing model can support and visualise the design as it is developed, stimulate creativity, improve administrative management of the resources necessary to operate the appropriate hardware and software, enable collaborative work, and interactively design with the student user (figure 1).

Teaching methodology based on the printing of 3D models can be introduced to a wide range of students, interactively and progressively, from primary and secondary education (students aged 6 through 16) and vocational training to undergraduate and postgraduate studies, particularly in the STEM fields of education, integrating different areas of science in a teaching approach based on the interdisciplinarity and applicability of scientific and mathematical knowledge.

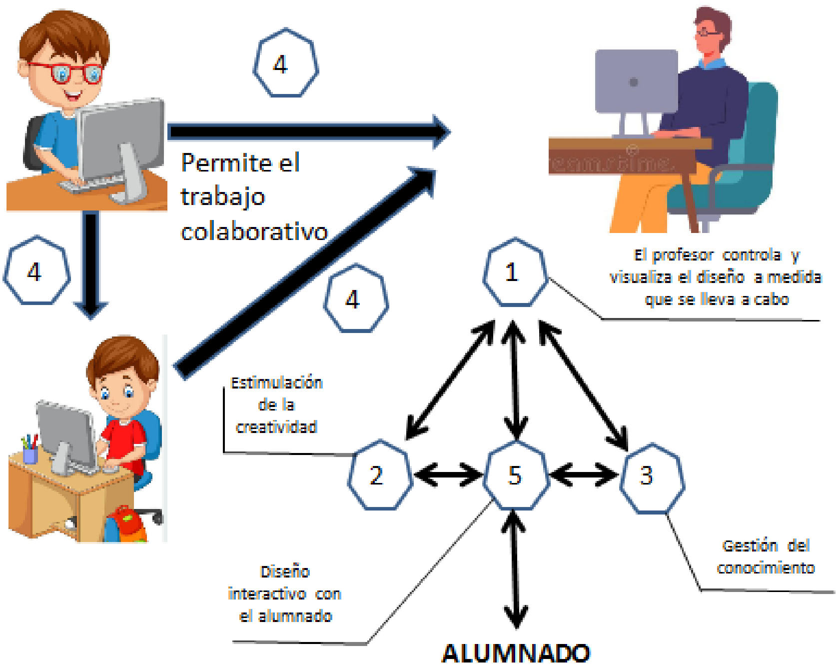
The projects and activities proposed under the 3D approach aim for the application of scientific and mathematical knowledge in a context linked to technology and tangible and practical three-dimensional engineering.

In the educational context, 3D printing enables students to explore the relationship between form and function in living tissue using three-dimensional printing since the way in which structure relates to function, through space scales, from the individual molecule to the complete organism, is a central topic in biology. Thanks to 3D printing, the following question can be reversed: Does function follow form?

In other words, it enables a practical or experimental approach to the architecture of living tissues, with the hope that the structure created leads to the desired function, offering students a new learning experience (Miller, 2014).

Figure 1

Elements of the 3D design system



Source: Modified from Vidal and Mulet, 2006.

The accuracy of samples printed in 3D is comparable to the original samples in many biological fields, including anatomy (McMenamin et al., 2014). This alternative focus to produce anatomically precise reproductions offers many advantages over plastination: it enables multiple copies of any studied specimen to be produced quickly on any size scale, and it can be adapted for any educational centre in any country, avoiding cultural and ethical issues, such as those associated with the teaching of medical science using real specimens.

3. 3D Printing in Education

In recent years, a new technology has emerged, 3D printing (Sanz-Gil, 2017), which is defined as:

> A suite of technologies that creates a tangible product from a digital model. This technology is considered a sort of additive manufacturing due to it producing objects in 3D from the successive application of layers of a specific type of material (Ortega, 2016; cited in Zavaleta, 2019: 35).

There are different 3D printing technologies; however, the most widely used in academic settings is fused filament fabrication (FFF) or fused deposition modelling (FDM) (Beltrán-Pellicer and Rodríguez-Jaso, 2017).

With each passing year, the idea that education professionals have in relation to the active role of students in the classroom changes, as experience has shown that meaningful learning is fostered when students are involved in their learning process. That is why the area of technology is taking on an increasingly central role in the field of education, showcasing new resources, such as 3D printing, which develops different skills in the learners, including organisation, creation, imagination, logical reasoning, and so on (Zavaleta, 2019). As regards the figure of the teacher, 3D printers enable a wider range of possibilities when designing and expanding activities that will increase student interaction with the technologies, enabling them to assume a lead role in their learning process (Johnson et al., 2016; cited in Blázquez-Tobías et al., 2018).

On the basis of the foregoing, it is worth mentioning the relevance of the teacher's role when selecting the methodology and digital content to be studied in the teaching and learning process (Moya, 2013). In relation to this digital content, there are numerous programs that enable modelling and 3D printing to be carried out.

3.1. 3D Applications and their Educational Use

Today, 3D printing is an affordable educational technology given that its cost has been significantly reduced due to the waiving of the patents associated with the Reprap project (Blázquez-Tobías et al., 2018). Numerous materials can be used to print in 3D; however, thermoplastics (PLA or ABS) are the most widely used in the classroom due to their low cost and versatility (Evans, 2012).

Likewise, there are different 3D design software programs, for example, OpenSCAD (a highly versatile program for printing solid elements using software compatible with Linux, Windows and Mac) and FreeCAD (a widely used 3D design tool due to it being open and useful in any size imaginable); or lamination software, such as Ultimaker Cura 3D (the most popular 3D printing software in the world thanks to its simple workflow and ability to create personalised configurations). They enable objects associated with any knowledge area—mathematics, music, history, technology, and so on—to be printed, aiding students' understanding of the content related to the subject and fostering motivation, creativity and interest (Sánchez et al., 2016).

According to the latest Horizon Report, 3D printers are a technology that will have a significant educational impact over the coming years, leading students to learn by exploring through manipulation, in other words, learning by doing (Adams et al., 2017). Likewise, this report states that 3D printing enables the contextualisation of learning, becoming a resource suitable for working with students with special educational needs (SEN) as it can help them develop their creativity, motivation and established competencies, while working in a cooperative and collaborative way with the group/class.

Lütolf (2014) asserts that all students, from primary education to university students, have the ability to use 3D printers and design and laminating programs, taking into consideration that the complexity of the object to be designed and printed will increase with age. Furthermore, Lütolf clarifies that it is a safe resource to be used in the classroom.

Regarding the use that can be made of 3D printers in educational contexts, Johnson et al. (2016) point out the advantages of using this work methodology in project-based learning (PBL). In this sense, the first school 3D printing lab, with ten MakerBot Replicator+ printers, was opened in Bogotá in 2017. In the lab, students from nursery, primary and secondary education develop design and 3D printing projects that enable them to reinforce the learning objectives of different subjects: music, biology, history, mathematics and physics. Specifically, students in nursery education start out learning spatial dimensions, while those in primary and secondary education make sketches and models of different objects using 3D modelling software before printing them. This technology has enabled teachers to implement innovative projects in their study programmes while students improve their creative, planning, collaboration, communication and critical thinking skills (Rosales, 2017).

Another example is the FIRST Robotics equipment, which has implemented additive manufacturing (AM) technology due to it being particularly useful for printing parts and robots. AM objects facilitate the learning of challenging topics that are difficult to understand, such as biological and chemical phenomena. That is why the Center for BioMolecular Modeling at Milwaukee School of Engineering has used AM to create molecular structures and physical models of proteins, so that the molecular world becomes real when their students hold these models in their hands (Huang and Leu, 2014).

4. Educational Experiences with 3D Printing

A number of educational experiments have used 3D printing as a teaching resource given the multiple benefits that it offers for learning varying content in different educational stages and disciplines (Moreno et al., 2016; Popescu et al., 2019).

This teaching material, particularly in the case of engineering and areas of design, offers students the opportunity to face real problems and situations that they can interact with, analyse and find a suitable solution. This strengthens mechanical, spatial and associative skills, as well as meaningful learning, and develops creativity and self-learning. Furthermore, 3D printers enable three-dimensional models to be created that represent complex concepts and facilitate the creation of ideas and novel designs. This has been demonstrated in experiments such as those undertaken by Rua et al. (2018) in descriptive geometry on the mechanical engineering programme, where students had to learn to represent three-dimensional objects in two-dimensional spaces using geometric techniques. With traditional materials, spatial memory, abstraction capacity and association are not stimulated due to the lack of interaction with real objects. For this reason, by using 3D printing, life-size models could be made. The students used these models to identify forms and were able to easily comprehend the projections in two dimensions, as well as put together a 3D model to form all the parts.

In mathematics, 3D printing can also be very useful for understanding some abstract concepts, such as integration. This is a fundamental aspect of calculus, which is based on the concept of sum as an infinite sum of infinitely small areas or volumes. Thus, in an integral calculus class at the Faculty of Mechanical Engineering, a program was designed in OpenScad to generate 3D teaching material on Riemann sums, using rectangles made to scale.

Bonet et al. (2017), meanwhile, carried out a pilot study with the Automation and Electronic Engineering undergraduate students at the University of La Laguna, with the aim of analysing the influence of using 3D printers to boost creativity. The result showed a large increase in creativity, reaching values only obtained in purely creative degrees, such as Fine Arts.

Beltrán-Pellicer and Rodríguez-Jaso (2017) verified its educational effectiveness in the field of mathematics, particularly in geometry and probability reasoning.

Mesa et al. (2021) took this innovative resource to secondary school classrooms to demonstrate its effectiveness in engineering education, developing important aspects in students such as imagination, design and the making of robotic mechanisms through engineering design.

Plaza-González (2021) designed a complete project combining all the Technical Drawing content covered in the first year of Bachillerato (equivalent to Lower Sixth or Year 12), which culminated in printing the object designed in 3D. She considered printing in 3D to be fundamental for acquiring competences that enable collaboration with other disciplines, understanding the design processes of the professional world.

This resource is also used and proves to be highly effective with younger students. Blázquez-Tobías et al. (2018) affirm that these experiences can become more complicated depending on the development of the students' skills. In this vein, Daniel et al. (2021) implemented this tool in primary and secondary school classrooms for the purpose of studying various subjects with a cross-disciplinary approach. Various works of art were printed in 3D in Physical Education. Following a breakout exercise, the students, working as a team, then had to complete challenges and pass different tests in order to obtain a code that would let them achieve their goal: unlocking the padlock on a chest. By doing so, they sparked the interest of the students who, in a cross-disciplinary approach, learned content belonging to different areas without needing to use a textbook.

Gómez-Ruiz (2018) also developed an experience using three-dimensional models in primary education, proving its utility to favour educational inclusion, as these resources were highly useful for students who had difficulty recognising the three-dimensional nature of objects, as well as being fundamental for visually impaired students, who were able to recognise the different forms in 3D by manipulating the models. Thus, they created maps, planets and chemical elements using the school's 3D printer.

Within informal education, there are also experiences of using 3D printing such as that undertaken by Nolla et al. (2021) in the mathematics club at an Italian international school in Madrid, in which different activities were carried out in order to learn and study maths in more detail from another angle. The project "*Aeromodelismo y matemáticas*" (Aeromodelling and Mathematics) allowed students to try out a practical mathematics application in another discipline, by means of 3D printing.

5. Conclusions

This study on the use of 3D printing in the field of education has shown how this technology offers significant benefits in the student learning process. Among the numerous advantages, the attainment of meaningful learning thanks to manipulative experimentation can be highlighted, fostering in students the motivation to learn and improving educational results. Students learn through experimenting and having fun, generating in them a desire to continue acquiring knowledge which will be useful in the short and long-term future, on both a professional and personal level.

The use of 3D technology in education has been acquiring special relevance for some years now due to the recognition of the active role of students in their learning. These technologies are flexible and versatile and can be adapted to students, the educational stage, interests, needs or the subject being taught.

The advantage of offering students elements that are not available to them in their context and the ability to observe them from all angles for better study results in an increasingly widespread use of these models.

Likewise, throughout this article, it has been sustained that these models not only favour the understanding and development of theoretical and practical content, but also basic competences, such as the digital competence of both teachers and students. The numerous experiments that have been undertaken using this educational resource have made evident the development of some aspects: mechanical, spatial and associative skills, creativity, auto-learning, imagination and understanding of abstract concepts. It also increases the motivation of students, facilitates educational inclusion, enables cross-disciplinary learning and experimentation in classrooms, giving students the opportunity to learn in an active way, favouring meaningful learning.

There are, however, disadvantages to the 3D printing system, such as the operation of complex computer programs; databases that, although very extensive, are limited to the STEM fields; the fact that teachers are required to invest a considerable amount of time in understanding how to use the resources; and a greater focus on the details than on the underlying principles.

In the future, more empirical studies are needed that offer results on the cognitive development of students, their experience in the classroom and the use of 3D applications at different educational levels (Ford and Minshall, 2019). Introducing these technologies in other areas outside of the STEM fields would also offer an impetus (Gyasi et al., 2021).

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