Invited Review Article:
Where and how 3D printing is used in teaching and education

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Abstract

The emergence of additive manufacturing and 3D printing technologies is introducing industrial skills deficits and opportunities for new teaching practices in a range of subjects and educational settings. In response, research investigating these practices is emerging across a wide range of education disciplines, but often without reference to studies in other disciplines. Responding to this problem, this article synthesizes these dispersed bodies of research to provide a state-of-the-art literature review of where and how 3D printing is being used in the education system. Through investigating the application of 3D printing in schools, universities, libraries and special education settings, six use categories are identified and described: (1) to teach students about 3D printing; (2) to teach educators about 3D printing; (3) as a support technology during teaching; (4) to produce artefacts that aid learning; (5) to create assistive technologies; and (6) to support outreach activities. Although evidence can be found of 3D printing-based teaching practices in each of these six categories, implementation remains immature, and recommendations are made for future research and education policy.

Keywords: 3D printing, additive manufacturing, teaching, education, learning

1. Introduction

The adoption of additive manufacturing (AM) and 3D printing (3DP) technologies in industry is growing as new applications are found that take advantage of their functionalities. While technical advances continue to be made in terms of their productive throughput and quality, there are concerns that education and skills development lags these technical developments and that they may inhibit the technology's wider adoption [1–6]. Despite these concerns and a longstanding call for evidence of educational activities [7], there is currently an absence of a comprehensive and accessible literature review of how 3D printing technologies are being used in the education system.

Addressing this deficit, this paper synthesizes prior research spanning a wide range of educational disciplines through asking two questions:

1. Where is 3D printing being used in the education system?
2. How is 3D printing being used in the education system?

To answer these questions, a review of academic literature is conducted that explores the application of AM and 3DP technologies in teaching and education. Within the education system, it is observed that the majority of AM and 3DP equipment adopted for teaching purposes is the low-cost, consumer grade 3DP rather than the more sophisticated AM equipment that is used for the fabrication of advanced prototypes and final products. Accordingly, the term 3D printing (3DP) is used throughout this article, even though we recognise that in some cases the course or program may describe AM technologies.

The use of digital fabrication technologies such as 3DP to support education is far from new. The disciplines of architecture and engineering were early adopters of rapid prototyping technologies [8–12], and a variety of benefits have been identified arising from the incorporation of these technologies into teaching. For example, they can facilitate learning, develop skills, and increase student engagement [13]; inspire creativity, improve attitudes towards STEM subjects and careers, while also increasing teachers' interest and engagement [14]. This literature review extends our understanding of 3DP in the education system, describing the benefits and challenges of using 3DP in teaching within six use cases, and providing clear directions for future research through a list of 44 research questions.

2. Literature review process

Literature reviews provide a foundation for future empirical research. They can help reveal the current status of knowledge related to a focal topic, describe the quality of current research, situate research findings, and provide rationale for future research directions [15]. In drawing together research in teaching and education, this literature review follows in the footsteps of others in the domain of 3DP and AM, which have focused on providing literature reviews of AM processes, materials and applications [16]; hybrid AM processes [17]; AM and nanotechnology [18]; AM management [19]; AM trends in construction [20]; and the societal impact of AM [21].

A literature review is a process of material collection, descriptive analysis, category selection and material evaluation, leading to the identification of patterns, themes and issues within the literature [22]. The literature review presented in this paper followed such a process and was conducted in two distinct stages. In the first stage, an initial scan of academic literature related to teaching and education was conducted. This involved a search of Scopus, EBSCOHost and Google Scholar using combinations of the search terms “3D printing” and “additive manufacturing” in combination with “teaching” and “education”.

During this material collection phase 44 academic articles were identified and acquired. A preliminary analysis of these papers revealed that 3DP was being adopted across the K-12 school spectrum, and in universities, libraries, makespaces, and special education settings. Through a category selection process, five categories were found in relation to the research question of “How is 3D printing being used in the education system?” We define these five categories as use cases. They were:

1. To teach students about 3DP;
2. To teach educators about 3DP;
3. To teach design and creativity skills and methodologies;
4. To produce artefacts that aid learning;
5. To create assistive technologies.

Reviewing these 44 articles it was also revealed that the literature on 3DP in teaching and education spanned multiple, disconnected clusters of literature. The articles were drawn from journals and conferences that spanned the disciplines of architecture [9,12,23]; computing [24,25]; ergonomics and human factors [26–30]; engineering [11–17]; healthcare [18]; library studies [19–22]; medicine [23–25]; and technology [26–28]. In a final cluster of education, articles were found in journals and conferences that linked education to medicine [31]; STEM [32]; science [14,33–37]; and technology [13,38–40].

In the second stage of the literature review a systematic process was taken to broaden and deepen the collection of material from the dispersed literature sources. The bibliographies of the original articles were mined for relevant citations and the same keyword searches were conducted within the journals and conference proceedings of all the articles collected. This process of bibliographic search followed by publication and conference keyword search was conducted iteratively until no further articles could be identified. In total, this search led to the identification and acquisition of 280 articles. These articles comprise the review presented in Sections 3 and 4, with the analysis of these articles leading to a revision of the original five use cases to the six described in this paper.

As a literature review it is important to define clear boundaries to what is included and what is not. The focus of the literature review is the application of 3DP in teaching in the education system. The scope of the education system is considered to include primary, secondary and tertiary education. This includes K-12 teaching that spans elementary, middle and high schools, and further and higher education institutions. Work published before September 2017 is included within the review.

Excluded from this review are academic articles describing the application of 3DP for research purposes in the education system; the use of 3DP for teaching in non-educational institutions, such as in-company training and skills development; self-led education; and the creation of 3D models where no physical object is 3D printed [41–43]. Furthermore, only academic literature is reviewed. Non-academic sources excluded from this literature review include descriptions of Master’s programs and graduate certificates focusing on 3DP and AM such as those offered at the National University of Singapore [44], PennState [45], University of Maryland [46], University of Nottingham [47], and University of Texas at El Paso [48]; online resources describing educational 3DP projects such as MakeSchools [49] and Create Education [50]; and educational resources provided online by 3DP companies such as Formlabs [51], Stratysys [52], Thingiverse [53], and Ultimaker [54].

3. Where is 3D printing being used in the education system?

This review begins by first describing *where* 3DP is being used within the education system. The sections that follow summarize the four main pedagogical environments in which 3DP is being used: (1) schools; (2) universities; (3) libraries; and (4) special education settings. Each of these sections includes short overviews of how 3DP is being used within these settings.

3.1 3D printing in schools

The papers related to the use of 3DP in schools and children's education cover the full spectrum from primary/elementary [33,55–58], through middle school [59–62], to secondary/high school [63–70], and also includes combinations of the three [24,71–82]. However, given that there are relatively few papers specifically considering primary and middle school, these are clustered together with secondary and high school for the purpose of this discussion.

In their commentary on the engineering design curriculum in schools, Bull et al. describe how engineering design projects involving physical prototyping such as 3DP can provide a foundation for improving the understanding of science and mathematics [72]. The majority of papers in this body of literature support this view, being examples of how 3DP is being used to support STEM education in schools. For example, in the sciences, 3DP was used to introduce atomic structure in Grade 10 chemistry classes, with a positive correlation found between its integration into teaching and student learning [74]. Meanwhile in physics, Japanese high schools students learned about audio frequency through creating 3D printed police whistles [66]. In technology and engineering, students were introduced to the construction of 3D printers [75], computational thinking through a combination of Minecraft and 3DP [69], and design thinking through a 3D printed city planning game, Kidville [77]. Other studies focusing on design described how students developed skills in creativity [64,65], technical drawing [70], and product design and development [57,63]. Specific instances of the latter can be found in real-world cases of creating prosthetic hands, in elementary schools [33] and high schools [76]. A study of a transmedia book project in a project-based learning environment found that using 3DP increased mathematical achievement in students [59], while understanding of geometry was improved through the fabrication of three dimensional shapes [58,62]. STEM integration has been sought through using 3DP in K-12 teaching in paleontology, where students learned about the giant extinct shark carcharocles megalodon through 3D printed reproductions of its teeth [80]. Furthermore, 3DP is being used as part of a variety of STEM outreach activities in schools. These are discussed in Section 4.6.

Beyond STEM education, studies have demonstrated how oral presentation benefits can arise from using 3DP [26], and how 3D printed visualizations can aid spatial education, with the rotation ability of ten year old boys particularly promoted [55]. This latter study, along with many of those described above, highlight the advantages of 3D printed artefacts relative to virtual, screen-based artefacts; they allow self-directed construction and capacity for independent and introverted work, as well as improving physical tactility and the observability of the physical artefacts created [24].

The inclusion of 3DP in school curricula is also positive from another pedagogical perspective as it can provide opportunities for different learning styles to be practiced, including experiential learning and failure [71]. In a study of two Greek high schools, it was found that the use of 3DP enabled different learning styles to be practiced, with this particularly useful in engaging certain students: *"We have seen that students, who were otherwise indifferent (according to them and their teachers) about their project class, when given proper stimulation and the necessary tools can choose what to* *learn themselves through exploration […] Then proudly share their results with others while they acquire knowledge instead of dry information out of textbooks"* [65].

However, in her conclusions arising from her 25 month autoethnographic study of a Grade 9 woodworking course at Lakeside High School in Melbourne, Australia, Nemorin warns that 3DP *"ought to be approached as a method of teaching and learning with the same pitfalls and obstacles that previous new digital technologies have brought into the school setting"* [67]. These pitfalls and obstacles include the *"frustration, physical fatigue, mental exhaustion, tedium and occasional panic"* that can occur during the protracted learning stages of a 3DP-focused design project [68]. The project observed was only sustained *"through the vast amount of personal enthusiasm, organisation and support from one motivated and interested teacher, alongside sporadic episodes of student attention, effort and energy"* [68]. Thus rather than reshaping the classroom into a more democratic peer learning environment, established teacher-student expertise dynamics were reinforced. This highlights the significant role that teachers have in shaping the experience of 3DP's first use, with the need for teachers to receive continuing professional development so that their expertise remains up to date [65,73]. In addition, other challenges that have been identified include issues of student technological literacy and attitudes towards new technologies [65,67]; costs, even when open source [65], and integration into the curriculum and instructional standards [73].

3.2 3D printing in universities

In tertiary education, the adoption of 3DP is greatest in universities, and there are comparatively few reports of the technology's adoption in other continuing education and further education institutions. Within the articles reporting on the use of 3DP in universities, literature can be found that describes the acquisition of subject knowledge through the creation of 3DP systems, scientific models and test models; the use of 3DP during project-based learning; the integration of 3DP skills development into the curriculum through its incorporation in existing courses and the introduction of new courses; and external engagement beyond the university. This section provides brief summaries of each in turn.

There are several accounts of the construction of open source RepRap 3D printers being incorporated into engineering curricula. Their construction acts as the focal point of a mechatronics design project at Philadelphia University, Jordan [83]; is part of senior capstone projects supported by the Princeton / Central Jersey Section (PCJS) of the Institute of Electrical and Electronics Engineers (IEEE) [84]; and is used to introduce 3DP to industrial engineering and business masters students at the University of Applied Sciences Offenburg [85]. In this last case, students first built the 3D printer before downloading and fabricating 3D models [85].

A significant use of 3DP at universities is in the sciences, where 3D models are created to support student learning in the lab or classroom [35,86–88]. This application of 3DP to produce models as visual learning aids is discussed in more detail in Section 4.4. In a similar vein, 3DP can be used to create test models for experiments. This also includes test specimens for learning about the mechanical properties of materials; 3D printed polymer test models have been demonstrated to be appropriate for this purpose in engineering curricula [89], and mechanical tests have been incorporated into an undergraduate capstone research course in the Mechanical Engineering Science Department at the University of Johannesburg [90]. Elsewhere, MSc graduate students in the Faculty of Mechanical Engineering at the University of Belgrade used 3D printed components during fan and turbocompressor experiments [91], and fourth year aerospace engineering undergraduates at Technion – Israel Institute of Technology created different configurations of wing spoilers, and measured their effects using 3D printed models in wind tunnels [92].

3DP has also become a popular tool in robotics teaching, with it being a low cost means of supporting the development of educational robots [93–99] and haptic devices [100]. Using a 3D printed chassis for low-cost open source robotic platforms enables students to modify the robot, and to be distribute these modifications to other students [98].

3DP can be used to enable project-based learning [101–106] and the use of 3DP in projects is the subject of numerous papers (see Section 4.1.2 and examples in Section 4.3). Examples include the University of Modena and Reggio Emilia, where second year mechanical engineering undergraduates used 3DP as part of a project to design and create an eye-tracking system [107], and the State University of New York, where student engagement was improved through the integration of 3DP into a semester long "Introduction to MEMS" design module [108]. During the MSc in Mechanical Engineering at Politecnico di Torino it was found that incorporating 3DP in a project-learning environment improved student attitudes towards mechanical engineering. In particular, it was found that the use of 3DP provided positive student feedback in relation to student motivation, understanding, interest and education [109].

Learning styles were explored during a two year study of 3DP adoption in the second year of an industrial design degree [110]. It was found that using 3D printed artefacts to demonstrate theoretical concepts *"can favor different groups of students, according to their preferred learning styles active, reflexive, theoretical and pragmatic. The higher the applied methodological diversity in higher education, the more efficient is learning for most students"* [110]. Furthermore, students are able to assimilate, apply and describe new knowledge more effectively, with the conclusion that *"Students become more responsible, motivated, involved and reach higher levels of learning, in that it caters to the diversity of their learning styles"* [110].

Similarly, at Griffith University's Product Design Studio, the integrated adoption of 3DP into the first year teaching syllabus has had three main benefits: (1) it has promoted student-centred learning and led to observable improvements in student work; (2) it has changed the relationship between students and lecturers as eLearning has taken place; and (3) it links students' learning to their ethical responsibilities in the world, such as environmental sustainability. The second point is an important one as student-centred learning involves the balance of power within the learning experience shifting from the lecturer to the student. Traditionally, the lecturer would have significant practical expertise to impart to the students; however this is often not the case with a novel technology such as 3DP. In addition, the novelty of the technology means that internet resources are more accurate and up-to-date than the limited number of 3DP publications. Given the pace of 3DP developments, Loy comments that *"the student is as likely – more so as a cohort – to be bringing new information on the spread of the technology to the classroom as the lecturer"* [34]. This means that the lecturer will be learning alongside the class, acting less as a leader and more as a mentor to the class. Experiences at Griffith University indicated that a 'flipped classroom' approach as part of a blended learning strategy was positive for both lecturers and students [34].

The need to explicitly learn 3DP skills has led several universities to either incorporate training into existing course offerings or to create new courses to introduce the topic. Examples of the former include the University of North Georgia's Department of Computer Science and Information Systems, which has integrated 3DP into a computer graphics course so that students can develop modelling, scanning and rapid prototyping skills [111]; in undergraduate engineering courses at Tsinghua University's Department of Mechanical Engineering [112]; in graphic design courses at

Universidade Estadual de Londrina, Brazil, where the incorporation of 3DP into student courses led to interest from other parts of the university into the use of 3DP [113]; and at City University of HK, where 3DP has been included in a classic instructional design theory course for first year engineering students [114]. In this last case, student feedback about the course experience was identified as being broadly positive, but dependent on the student's prior experience with 3DP and their area of expertise/major [114].

There are multiple opportunities for students to acquire 3DP skills at the Missouri University of Science and Technology, with 3DP skills development opportunities available in courses focusing on design and basic CAD modelling; product modelling; rapid prototyping; integrated product development; as well as in advanced level courses [115]. Meanwhile at Colorado State University-Pueblo, 3DP is being used in industrial engineering and mechatronics programmes, and integrated into 12 courses in total [116]. Uses of 3DP include direct learning of 3DP skills during rapid prototyping and functional part manufacturing, along with 3D visualizations and specimens for testing the mechanical properties of materials. Commenting on what they believe to be the significant benefits of integrating 3DP into the undergraduate engineering curriculum, the Program Director lists: *"Creation of functional parts in the first year of study by various engineering majors, quick verification of designs early in the curriculum, fast turn-around times from "imagination to implementation," the decreased need for students with the well-developed machining skills, connections with other sciences and mathematics through 3D built objects, and increased lab safety"* [116].

There are also several examples of programmes explicitly created to introduce and educate students about 3DP. These are discussed further in Section 4.1 and include MIT's graduate and advanced undergraduate course, which was created to teach the fundamentals of 3DP, and which is open to multiple faculties [117]; the University of Texas at Austin and Virginia Tech's introduction of undergraduate and graduate 3DP courses, which cover the science of 3DP, the principles of "design for additive manufacturing", and apply this learning through problem-based and project-based pedagogies [118]; and the Metropolitan State University of Denver, where the Mechanical Engineering Technology (MET) Program has introduced a semester-long direct digital manufacturing elective for upper level undergraduates from industrial design, mechanical and manufacturing concentrations [119]. Alongside student learning, there are instances of 3DP being introduced in universities to support educator learning [120,121]. These applications are discussed in more detail in Section 4.2.

3.3 3D printing in libraries

The papers which consider the library as a place in which 3DP occurs cover libraries in schools [122], universities [123–136] and community colleges [137], along with public libraries [138,139], medical libraries [140], and libraries in general [141–147]. The topic of 3DP adoption in libraries sits within a larger debate about the nature of libraries in a digital era. Those critical of 3DP being used in libraries argue that it is an *"exotic cutting-edge technology-based service and a mere extravagance or an unnecessary expense for what might only be a select number of patrons"* [144]. According to the sample of papers reviewed here, this is the minority view, with the majority of articles positive in their attitudes towards the incorporation of 3DP into library services. A more representative statement is that *"In most organizations, the library is a logical choice to house technology that has many potential users. By providing space and expertise for 3D printing, libraries can offer a valuable service to their organizations while raising awareness of the other services they offer as well"* [140].

As a physical space, libraries provide opportunities for collaboration and knowledge exchange between library users, librarians and educators [128,148], and reduce barriers to participation [141]. This accessibility has seen the rise of makerspaces within libraries as creative spaces in which 3D printers, among other digital fabrication technologies, are available to library patrons [123,127,128,130,133,145,147,148], with such spaces encouraging creativity and experimentation [131,138,142,147]. While the majority of such makerspaces are being created within libraries, there are also numerous instances of makerspaces being established independently of libraries [149,150].

In universities, the neutral, non-departmental space allows interactions between students from different faculties [124–127,133] and extra-curricular use [142]. As Van Epps et al. explain: *"The library is often seen as a non-disciplinary or cross-disciplinary space on campus, where access to the materials and services is available to all users. By bringing 3D printing into our libraries, access to 3D printers moves beyond gated access for a few to general access for all"* [132]. While access may be improved, the awareness of this access to non-traditional library services such as 3DP can limit their uptake in university libraries [129,131,151]. Awareness can be raised by running introductory 3DP workshops [133,151] and pop-up maker technology workshops [130], and identifying local advocates such as design class instructors, 3D visual researchers, and design-oriented student groups [125].

In their 3D printing and scanning pilot projects at Dalhousie University Library, Groenendyk and Gallant explain how the library sought *"to take the knowledge-sharing, innovation-driven ideals of hackerspaces and bring these into an academic library setting"* [126]. The library sought to make 3DP accessible to students beyond those in engineering and architecture that already had access. The 3D printing and scanning technologies were purchased on the basis of affordability and usability. In addition, the librarians hoped that the 3D scanner would enable various scientific and cultural artefacts to be digitized and archived online. *"In creating this collection the Libraries will help to provide online exposure for both student and faculty work, as well as ensure that the 3D information collected remained preserved and freely available"* [126].

Librarians themselves play a critical role in the integration of 3DP into the school or university. As Mark Ray, Chief Digital Officer of Vancouver Public Schools commented: *"School libraries can serve as test beds. As others follow our lead, teacher librarians can play a valuable role, supporting educators for whom this brave new world represents change and uncertainty"* [122]. As a central resource, library staff not only help support those coming into the library but educators looking to incorporate 3DP into their teaching practice. One such example comes from a collaboration at LaGuardia Community College between a librarian and an educator to produce a biological model for in-class teaching [137]. While the time available and expertise of library staff to provide such services is a limiting factor [124,138,141,145], providing librarians with training around the use of 3DP technologies can help them overcome their lack of expertise and their discomfort when interacting with library users [126,128,146]. Such basic training is necessary to in turn be able to provide student training [131,145], as well as ensure that library staff can maintain 3DP equipment and troubleshoot equipment malfunctions [124,126,128,136]. As technologies continue to evolve, so too will librarianship skills need to evolve in parallel [138].

Other issues of noted concern were those associated with the operational of 3DP equipment, health and safety, and intellectual property. Operational issues highlighted include the cost of 3DP consumables, particularly for those with highly limited budgets [122], along with access hours, staffing and supervision of 3DP use [145]. Concerns regarding the health and safety consequences of using 3DP in libraries have led to PLA filaments being recommended for use rather than ABS; fabrication using PLA produces approximately ten times fewer ultrafine particles than ABS [124,152]. A final issue of note that has been considered in this literature on 3DP in libraries concerns intellectual property (IP), and the potential for library users to infringe upon existing copyrights when designing, modifying and producing 3DP artefacts. Academic librarians have pointed towards the need for acceptable use policies to be developed that cover IP and 3DP in libraries, alongside raising patrons' awareness of the IP issues associated with the use of 3DP [138,143,153].

3.4 3D printing in special education settings

3DP is being used in special education settings for those with visual, motor and cognitive impairments. Within these settings there are several examples of 3DP being used by students with visual [14,40,154–156], motor [28,33,76] and cognitive [56,157] impairments, along with combinations of the three [27,158,159]. The use of 3DP in such settings is enabling the creation of custom adaptive devices and educational aids, while also enabling greater student engagement with STEM subjects [27,56,159]. The use of 3DP to create assistive devices is discussed in greater detail in Section 4.5.

Using 3DP in special education settings is not without its challenges, as described in Buehler et al.'s two year investigation into its applications [27,28,157,159]. In one of their studies, cognitively-impaired students were given tutorials on using Tinkercad software before being encouraged to create their own 3D designs [27]. However, the combination of task difficulty and limited time meant that most students did not create their own designs, instead printing or modifying designs from open-source sites. Student interest in completing custom designs appeared to decrease due to the challenge of using the software, with difficulties observed in changing views and manipulating objects. Furthermore, the ability to design in three dimensions was particularly challenging for students with high support needs. Other adoption challenges arose from the occupational therapists who worked with the students. While enthusiastic about the potential of 3DP, they were concerned about the effort required on their part to learn how to use the software; *"they currently see the task of 3D design and printing to be someone else's work, and see themselves as consumers of that work"* [27].

4. How is 3D printing being used in the education system?

After considering *where* 3DP is being used in the education system, this section summarizes *how* 3DP is being used within it. The sections that follow describe the six main ways in which 3DP is being used: (1) to teach students about 3DP; (2) to teach educators about 3DP; (3) as a support technology during teaching; (4) to produce artefacts that aid learning; (5) to create assistive technologies; and (6) to support outreach activities.

4.1 Teaching students about 3D printing

In the first instance, 3DP is being used to teach students about 3DP and develop 3DP skills. An important distinction between this literature and others concerns the active and passive integration of 3DP into curricula. Active integration involves the development of courses and projects which have an explicit focus on the teaching of 3DP skills. In contrast, passive integration involves the use of 3DP during courses and projects to support the teaching of other subjects [160]. The former is the focus of this section, while the latter is the subject of Section 4.3, in which the development of 3DP skills may occur as a by-product or side benefit of teaching other subjects.

4.1.1 Teaching university students about 3D printing

The majority of these papers provide accounts and summaries of experiences introducing 3DP into curricula in universities. These include the creation of courses, projects and workshops, with almost all falling within the domains of design and engineering. The curricula into which this 3DP teaching has been actively integrated is summarized in Table 1. In these accounts, the stated learning objectives of the introduced 3DP teaching content ranges from the very brief and general [85,109,111,113–115,161,162] to the more detailed and specific [117–119,163].

Subject	**Source(s)**
Computer graphics	[111]
Design and manufacturing with polymers	[162]
Engineering design	[118]
General engineering	[114,163]
Graphic design	[113]
Industrial engineering and business	[85]
Informatics	[164]
Mechanical design and manufacturing processes	[117]
Product and industrial design	[34,165]
Product development	[166]
Product realization	[115]

Table 1. Summary of university courses into which 3DP teaching has been actively integrated

In broad terms, 3DP courses are being introduced to encourage creative experimentation [34,113,114]; enable product innovation and entrepreneurship [113,115]; support the integration of technical knowledge from other courses [115]; and facilitate multi- and interdisciplinary approaches [113]. More specifically, the stated objectives of these courses is to develop a range of technical and non-technical 3DP-related skills. These learning objectives are summarized in Table 2.

Learning objective	**Source(s)**
Appreciate the advantages and disadvantages of 3DP technologies	[119]
Appreciate the differences between 3DP and conventional manufacturing processes	[117,167]
Evaluate the performance and functional constraints of 3DP for specific applications	[117–119,162,163]
Learn and apply 3DP post-processing techniques	[163]
Learn and apply design for 3DP principles	[85,109,117,119,162,163,166]
Learn and use 3D scanners	[117,119,163]
Recognise business opportunities for 3DP	[163]
Recognise current and future 3DP applications	[117,163,167]
Recognise important 3DP research challenges	[118]
Understand and recognise the causes of errors and irregularities in 3DP parts	[118]
Understand the complete 3DP sequence of designing, fabricating and measuring parts	[115,117]
Understand the fundamentals of 3DP and its basic operating principles	[85,117,118,161,163,167]

Table 2. Learning objectives of 3DP-focused courses

Among these courses there are several detailed accounts of how new 3DP courses are being introduced and what they cover [114,117,119,163]. At MIT a 14-week additive manufacturing course was introduced in which 30 students participated. During the first five weeks of the course, students gained an overview of the 3DP industry and technology landscape. They were introduced to the fundamental 3DP technologies of FDM, SLA and SLS/SLM, and a variety of scanning techniques. Lab sessions on FDM and SLA were held in parallel with the lectures, with each involving pre-processing, printing, post-processing and inspection stages. Following these introductory classes, two group exercises gave students opportunities to apply their new knowledge. These exercises involved the design of a 3DP-based bridge and a more open-ended innovation project. Alongside these open lab sessions, further special topic lectures were organized with industry and academic experts. These topics included bioprinting; computational design; design for additive manufacturing; digital assembly; economics of additive manufacturing; entrepreneurship for additive manufacturing; machine controls; micro- and nanoscale additive manufacturing; and printed electronics. Student feedback was reported to be positive for both the lecture materials and the two projects, albeit with some concerns raised about the time demands and open-ended scope of the innovation projects. In reflecting on this feedback, the authors recognized the importance of setting clear project objectives during the early part of the course in order to establish appropriate workload expectations. They also identified that introducing SLS/SLM equipment to the teaching laboratory would improve future courses. Furthermore, it was recognized that courses such as this provide collaborative research opportunities with industry, and the potential for tailoring separate curricula for professional development [117].

In another detailed course description, a seven-step pedagogical model was developed for introducing 3DP teaching into an engineering-oriented general education course at the City University of Hong Kong [114]. This model draws on Gagne's conditions of learning instructional framework [168]. The model was used as the basis for teaching the course in 2013/14 and 2014/15, with 89 and 28 students participating in these courses respectively. Approximately half of these students were from the College of Science and Engineering, with other significant participation from the College of Business and the College of Liberal Arts & Social Science. Analysis of student feedback indicated positive impressions on the understanding of 3DP technology and ease of use of CAD software with tutor guidance, and that using 3DP in the learning task improved their motivation and the development of innovative ideas. However, there was greater variance in student perceptions of the workload and difficulty of the learning task; this was thought to derive from the weaker technical backgrounds of non-science and engineering students [114].

At the Metropolitan State University of Denver, the Mechanical Engineering Technology (MET) Program has introduced a semester-long direct digital manufacturing elective for upper level undergraduates from industrial design, mechanical and manufacturing concentrations. Over 16 classes, students are introduced to 3D scanning, solid modelling and CAD; a range of AM technologies and equipment; post-processing; safety; sustainability issues; and current and future applications. During hands-on lab sessions, students are introduced to digital file conversion, formatting and mesh manipulation; print variables; design for AM using FDM, SLA, powder bed fusion, and direct metal printing; and 3D scanning and reverse engineering. Analysis of pre- and post-surveys showed significant increases in student's learning outcomes, with improvements to their awareness of the types of AM technologies available, the geometries that could be fabricated and the factors in AM, alongside their ability to design a product for AM, and their overall confidence in using these technologies. The challenges of running this course include the logistics of fabricating components outside class time, the need for continuous lab supervision, and the current lack of an appropriate textbook to support teaching [119].

At Mercer University, a senior level elective course on AM is offered to students from all engineering disciplines. This 16 week long course begins with reviews of product design and CAD, the basic principles of AM, and the generalized AM process chain, before exposing students to a range of different AM technologies. During a range of open-ended labs, students conduct a comparative study of additive and subtractive manufacturing; practice reverse engineering with different 3D scanners; cast 3D objects; and design, make, market and sell a product in a rapid prototyping challenge. The course concludes with classes on design for AM; rapid tooling; applications of AM; business opportunities; and future directions. A final course assessment by faculty and student peers found that students taking this course averaged greater than four points on a five point Likert scale against the Accreditation Board for Engineering and Technology (ABET)'s student learning outcomes. These outcomes covered the ability to design and conduct experiments; analyze experimental data; design systems, components or processes under realistic constraints; function in multidisciplinary teams; communicate effectively; and use techniques, skills and tools for engineering practice. For future courses it was recommended that students receive additional training in CAD and 3D scanning [163].

The creation of 3D models is an important precursor to 3DP. In a study of their use in university teaching, three approaches to the acquisition of 3D designs were tested [169]. In the first approach, students downloaded existing designs from a database. In this way students were made aware of the technical capabilities of 3DP, the materials used, the design constraints, and the variety of potential application areas for 3DP. The second approach involved independent design. It was commented that *"students were turned from passive consumers (database users) into active and creative users grappling with the possibilities and limits of the 3D printing process"* [85]. Consequently, students gained significant experience of 3D modelling for 3DP, in terms of the geometric design, stability and colour scheme. Finally, the third approach involved 3D scanning, with students learning about the possibilities and limitations of 3D scanning, along with how to prepare this captured data for 3D printing. Testing out each of these three approaches meant that *"students are then able to learn how technical hardware specifications impact on part design and how these limits might be overcome"* [85].

The diverse technical backgrounds of students entering 3DP courses combined with the diverse technical nature of 3DP can create challenges for educators. Balancing breadth and depth is an issue due to the many design, engineering, material science and computing topics that make up 3DP. This diversity of topics highlights the importance of multidisciplinarity during courses. While challenging to teach, it has been found that projects comprising students with complementary disciplines produced more novel and sophisticated 3DP prototypes, and that *"while rooted in mechanical engineering and materials science, AM education is truly multidisciplinary. As a result, educational programs to AM processes and applications should embrace this context"* [117].

4.1.2 Teaching university students about 3D printing through project-based learning

A final stated learning objective is that of giving students hands-on experience of 3DP. This is primarily being achieved through project-based learning [170,171], in which students collaborate in groups and develop 3DP skills. Such project work features prominently in the courses documented. Descriptions of these projects found in many of these papers [109,113,114,161,162,167,172], but only a few detailed accounts [115,117,118].

In MIT's additive manufacturing course, project-based learning was practiced during two distinct projects [117]. In the first project, students worked in teams of 3-4 to design and build a bridge using desktop FDM and SLA machines, and stock polymers. This challenge required students to integrate their freshly acquired knowledge of the 3DP design and build process with prior knowledge of solid mechanics and material science, then conduct experiments to evaluate the mechanical performance of 3DP-fabricated components. In a second project, the capstone that spanned the entire semester, small teams were created based on common interests and multidisciplinary. During the capstone, students were challenged to identify and justify an opportunity for the creation of a 3DP application, before going on to use the skills they had been taught in designing and prototyping this application. Through this project seven concepts were developed, with the advanced nature of these projects seen in that several teams had discussions with the MIT Technology Licensing Office around filing provisional patents [117].

At the Missouri University of Science and Technology, a course on “Rapid Product Design and Optimization” introduced the design and production of rapid prototyping and 3DP. During the course, students worked on a sponsored project to develop a concept prototype. The projects involved creating CAD models, converting these models into 3DP-ready STL files, fixing any errors in the STL files, producing physical models, and post-processing these models. A further project-based course on integrated product development allowed these projects to be further advanced [115].

Both project-based learning and problem-based learning approaches are adopted during 3DP teaching at the University of Texas at Austin and Virginia Tech. Through a semester-long design project, groups of three to five students worked to identify, design, make and test a product appropriate for 3DP. Based on a formal problem statement, groups conducted a customer needs analysis, generated concepts based on these needs, and selected one of these concepts for more detailed design and embodiment. Through an iterative design process they arrived at a CAD model and 3DP-ready STL file of their final design before fabrication and final presentation [118].

Examples of other less detailed examples of project-based learning can also be found [109,113,114,162,167]. In the first of these, students used a concurrent design approach to create a “gerotor”-type gear pump during mechanical engineering projects at Universidad Politecnica de Madrid. Following the introduction of the challenge, student groups developed conceptual and detailed designs in CAD software, before prototyping using SLA 3DP, and then conducting assembly and functional tests [162]. Meanwhile at the Department of Management and Production Engineering (DIGEP), Politecnico di Torino, students worked in teams of five on an integrated computer-aided environment for design, engineering and manufacturing (CAD/CAE/CAM) project that spans three compulsory courses [109]. In a graphic design project at Universidade Estadual de Londrina, Brazil, the teaching team worked together with a group of five students. The collaboration led to the creation of an assistive device for young children with upper limb amputations, with this design being entered into the Designoteca-sponsored “3D Printing Challenge” [113]. At Austin Peay State University, a capstone project built on three previous 3DP courses so that students could apply their learning in an organization setting role play [167]. Finally, at the City University of Hong Kong, groups of 5-6 students worked together on a “smart living” challenge. This involved student groups creating a 3DP-ready CAD model, which was then fabricated by the instructor [114].

4.1.3 Teaching students about 3D printing in schools and libraries

Outside of university courses, student teaching about 3DP is also occurring during K-12 school teaching [56,65,122,160], and in libraries and makespaces [124,126,128,131,145]. In the former category, a study of two Greek high schools had the learning goal of introducing students to the concept of 3D design and the basic operation of 3DP. A group of 15 16 year olds in one school and a group of 18 15 year olds in another worked on a project that involved 700 minutes of instructor time. During these projects the students were introduced to basic 3D modelling software and the 3D design process. Following experimentation in open source CAD software, they produced 3D printed artefacts through a trial and error process, before reflecting on the lessons learned through their 3DP experience. One notable challenge with running these courses was found in terms of the different levels of technological literacy and engagement among the students; this heterogeneity created an uneven classroom and required instructors to adapt to the various needs of students. Other challenges arose from the freedom given to students to design artefacts of their own selection, as significant instructor attention was necessary when technical design problems arose, along with the cost of acquiring 3D printers [65].

An afterschool program open to third and fourth grade students was held at an elementary school in Baltimore. Separate program streams of 16 sessions were run for each grade group, with approximately 15 grade 3 students and 10 grade 4 students participating in each workshop session. The objective of this program was to help support academically vulnerable students, reinforcing fundamental skills such as arithmetic and reading. 3DP was included within this program as a form of enrichment; it was hoped that introducing students to 3DP would engage them and stimulate interest in STEM subjects. Sessions were project-based and focused on students needing to engage in problem solving. Doing so led students to complete entire iterative design cycles, going from initial concept development, through low fidelity prototyping, to 3D printed prototypes. Through doing so students developed an understanding of the basic capabilities and limitations of FDM 3D printers, as well as practicing their communication skills while working in project teams. It was observed that using 3DP enabled students to go beyond abstract concepts to produce tangible outcomes, creating engaging experiences that exceed skills acquisition alone. Alongside the benefits of incorporating 3DP, a number of barriers to disengagement were also observed. These included access to shared 3D printing equipment and the maintenance of this equipment; the prohibitive cost of 3D printers, even ones that are generally considered to be “low-cost”; limited practice time; and the challenge of onboarding new students throughout the program. Among the recommendations, it was suggested that further peer learning be incorporated into teaching in order to reduce the burden on teaching staff, as well as including a mixture of structured and unstructured projects in lesson plans [56].

Cost and instructor effort were also concerns expressed in a reflection on an introduction to 3DP course for grade eight and nine students at a high school in Steffisburg, Switzerland. Held over 16 90 minute lessons, students sketched, 3D modelled and 3D printed buildings for their own city before presenting their finished work in the final class. Running the course required significant investment of time on the part of the instructors, both in the planning and setting up of the course, and in the administration of 3DP jobs when the course was underway. However, the benefit of introducing students to 3DP was that they remained highly motivated throughout the project. It was reasoned that the presence of the 3D printer, the availability of free software tools such as Tinkercad and Sketchup, and the opportunity to express their creativity, combined to provide this motivation [70].

Recognising the need for age-appropriate educational models, a series of pilot programmes for introducing 3D visualization technologies into K-12 education have been described, with 3DP one of these technologies. It was found that for grades K-4, “show, touch and tell” type technology demonstrations and presentations from STEM professionals to groups of 2-8 students were the most effective. Meanwhile, another pilot programme involved the embedding of 3D printers into schools was aimed at grade 9-12 students who required live education opportunities. Pilot schools were selected due to having a “For Inspiration and Recognition of Science and Technology” (FIRST) robotics team who had a clear practical need for the 3D printer, as well as being able to ensure the facilitation and maintenance of the equipment. A dedicated educator to oversee the printer's operation was also seen as essential [160].

One major downside to using 3DP in a school teaching environment is the speed of 3DP and the time it takes for larger prints to be created [56,122]. As Plemmons comments *"it is unrealistic to think that students will sit and watch the entire print take place while they are missing instruction in their classroom"* [122]. One strategy he uses in his elementary school classes is to have the whole class only watch the beginning of the print so they are part of the printing process.

Finally, as was described in Section 3.3, 3DP is being provided in libraries and makespaces [126,145]. Providing 3D printers in libraries gives students the opportunity to learn about 3DP as part of extracurricular activities. Librarians use multiple methods to train students, including demonstrations and workshops, as well as online tutorials and videos. The range of training methods provides students with multiple ways by which they can access 3DP education [145].

4.2 Teaching educators about 3D printing

Despite potential benefits, there are many barriers to the integration of new technologies into the education system. Along with institutional, cultural, assessment and resource barriers, these include teacher attitudes and beliefs, and teacher knowledge and skills [173]. As a new digital fabrication technology, 3DP is not immune to these integration challenges; Bull et al. remark that in the school system *"the current generation of teachers is not well positioned to take advantage of these capabilities"* [72]. As they see it, this lack of readiness derives from the fact that *"Many teachers do not fully understand engineering, engineering habits of mind, or design thinking. This expertise is not currently provided in teacher preparation programs"* [72]. Others believe that teachers are not receiving sufficient guidance on the use and maintenance of 3DP [150]. This speaks to a more general need in the education system of teaching educators about 3DP, supporting their professional development, and enabling their ability to teach others about 3DP.

Reflections and discussions on realising these objectives can be found in the literature, with small clusters around informing educators about 3DP during their teacher training [61,120,121,174,175]; informing active educators as part of professional development [26,174,176–179]; and informing library professionals [145,146].

In this first cluster, early childhood educators [120] and technology and science educators [121,174] were the recipients of 3DP teaching during their teacher training. During a Master's level programme at James Madison University, preservice early childhood educators were introduced to 3DP during a 2-hour workshop in their "Creativity and the Arts in Early and Elementary Education" course. However, rather than provide detailed guidance to student teachers on how to use 3DP and instruct others in its use, the experience was instead aimed at encouraging student teachers to critically evaluate new technologies, including the appropriateness of 3DP for young children, and the rationale for incorporating the technology into early childhood classrooms [120].

During a Master's degree in Applied Science Education at Michigan Technological University, RepRap 3D printers were used during a two-week course that introduced students to the design-build-test process. Post-course feedback from 18 completed surveys rated the course highly. Furthermore, two high school biology teachers who were participants in the course also attended a two day workshop to build a 3D printer. They were able to do so and to go on to use it to 3D print scientific apparatus for use in their classrooms [174].

A more comprehensive programme to teaching future educators occurs during the "Advanced issues in teaching design and manufacturing" course at the Technology Education Laboratory at Technion University in Israel [121]. Spanning a whole semester, each week students had two hours of lectures and two hours of laboratory classes. During lectures, students were introduced to theories of learning in the context of technology education, with the students themselves tasked with delivering short lectures on aspects of teaching design and manufacturing. Examples of these lectures include 3DP in design education; user-centred design; student engagement in design and manufacturing; and fostering creativity in learning design and manufacturing. During the laboratory classes, students practiced aspects of CAD and 3DP. Finally, a teaching assignment made use of “conceive, design, implement and operate” (CDIO) learning practices in response to a real-world educational problem from a grade ten mechanics class. Through this assignment student teachers learned about the benefit of using 3DP models as teaching aids and ice-breakers. Noting how 3D printed artefacts engaged their class, one student teacher commented: *“The pupils said that the printed models were very cool. They enjoyed holding the model, examining it and even took photos of the models”* [121].

In a two day workshop, a group of 10 pre-service teachers and 13 in-service teachers learned about 3D modelling and 3DP, and began to explore how these technologies could be integrated into their curricula. Within this group, nine teachers chose to focus on the application of 3DP in history and social sciences. This led to four projects being conceived and delivered in middle school classrooms on themes of world geography, US history, and American government and civics. Educators initially found the Tinkercad design software difficult to use, and also found it challenging to imagine what artefacts to produce that tied into the curriculum. However they found that having access to content and technical support during the project was helpful [61].

This workshop spans the first and second clusters, which cover pre-service and in-service teacher education respectively. Several other professional development initiatives for middle and high school educators can also be found [26,176–178]. An initiative at the College of Computer and Information Sciences at King Saud University (KSU) in Saudi Arabia, involved a 3-day workshop on introducing new computing technologies to high and middle school computer teachers. 3DP was one of several new computing technologies introduced during 90 minute sessions, alongside mobile application programming, Internet of Things, and robotics. During the session on 3DP, the technology was introduced, the main steps to producing 3D printed artefacts were explained, and participants discussed the potential use of 3DP in the teaching and learning process. The perceived difficulty of integrating 3DP into teaching can be seen from 3DP scoring the lowest of the four technologies in a survey of post-workshop intentions; 57% of participants strongly agreed or agreed that they intended to integrate 3DP into their teaching, in contrast to 90% of participants for mobile application programming, 87% for Internet of Things, and 73% for robotics [176]. In another initiative, a three day instructional workshop was run at East Carolina University as a professional development activity. Focusing on 3DP, seven participants were introduced to the fundamentals of the technology [177].

During the three day “Emerging Technologies and Technicians” workshop at St. Petersburg College, participants were introduced to 3D modelling and 3DP, alongside reverse engineering, quality assurance and other machining processes. The 24 participants were largely community college and university faculty, and gained hands-on experience of these methods. In a workshop exit survey, 85% of participants intended to incorporate workshop materials into their teaching, with several participants reported to have done so [178]. Meanwhile, a 3.5 day training workshop involved 22 middle school and high school teachers from Michigan [26]. Workshop participants worked in pairs to construct a RepRap-based open source 3D printer, and discussions of how incorporating the technology into teaching could benefit students. The experience of building the 3D printer was reported to have given participants *"a sense of empowerment"* and a belief *"that their students would be empowered by the ability to design, build, and create unique physical objects using OS3DP"* [26].

The final cluster describes educating library professionals about 3DP, set within the broader context of libraries as digital makerspaces [145,146]. Of the three clusters, this one exhibits the least evidence of formalized educational initiatives, with Williams and Folkman commenting that *"as of 2016, the concepts of making and the skills needed to run these spaces are as uncommon as instructional design courses in foundational librarianship programs"* [146]. Without formalized education about 3DP, librarians have often needed to be self-taught, with Moorefield-Lang describing necessary attitudes of *"Trial and error, experimentation, going with the flow, patience, and time"* [145]. For such individuals, peer learning has been necessary, either in physical space or on social media, with visits to other schools, libraries, makerspaces and museums helpful in learning about how 3DP could be integrated into their libraries. The overall attitude is that *"While this technology is becoming more prevalent, having a spirit of investigation and little fear of failure is important"* [145].

The importance of library staff having the technical skills in 3DP and other maker technologies, and the confidence in those skills, was the focus of an initiative at the University of North Carolina at Greensboro (UNCG) Library that involved librarians from across the state [146]. Through a programme of online resources, events and workshops, librarians were introduced to a range of digital making technologies, including 3DP. The hands-on workshops with equipment received the most positive feedback from participants and were found to be the most successful as they provided *"a safe, encouraging, "okay to fail" environment which embodies the maker movement in practice"* [146].

In addition to these teaching initiatives, other workshops and curricula have been proposed. In the former, a National Science Foundation-funded Innovative Technology Experiences for Students and Teachers (ITEST) project plans to run two week workshops with educators in grade 4-12 STEM subjects. The aim of these workshops is to introduce educators to Internet of Things (IoT), building automation and 3DP technologies, and then support them as they integrate these technologies into their curricula [180]. Elsewhere, a teaching curriculum has been developed and proposed for use at Korea National University of Education. This curriculum makes use of the ADDIE (analysis, design, development, implementation, and evaluation) approach to introduce 3DP to pre-service educators over 250 minutes of instruction [175].

4.3 Using 3D printing during teaching

In Section 4.1, a distinction was drawn between the active use of 3DP in the classroom, instructional laboratory or library to learn about 3DP and develop 3DP skills, and the use of 3DP in such settings to learn other subjects. The focus of this section is the latter application, in which students are using 3DP to learn about other subjects.

The predominant subjects in which 3DP is being used in this way are the STEM subjects of design and mechatronics engineering. In design, 3DP is being used within teaching courses to introduce students to product and engineering design processes, making use of its functions as a rapid prototyping and low-cost production technology [10,11,33,34,77,90,102–107,161,181–204], as well as architectural design [205]. The application of 3DP in combination with 3D scanning is a specific emphasis in design courses focusing on reverse engineering [206–210], while 3DP also features in CAD/CAM courses [211–214], and concept-based teaching in green manufacturing [215].

3DP is frequently used in design projects. The range of artefacts created during such projects is highly diverse and examples are included in Table 3. In addition of these artefacts, 3D printers themselves have been built during integrated engineering design [216–220] and mechatronics and instrumentation [221] projects.

Artefacts	**Source(s)**
Biomedical devices	[202,222]
Bridges	[223–225]
Desk lamps	[105]
Exoskeletons	[226]
Home appliances	[191]
Microfluidics	[188]
Model cars	[103,227]
Musical instruments	[187]
Orthotics	[228]
Quadcopters	[229]
Robots	[194,230]
Rockets	[102]
Unmanned aircraft system wings	[231]
Whistles	[196]

Table 3. 3D printed artefacts created during design projects

Meanwhile, its application for rapid prototyping is also finding use in mechatronics [83,101,108,203] and the mechatronics sub-category of robotics [78,93–100,230,232–239]. As previously commented in Section 3.2, 3DP has become a popular tool for creating low-cost educational robots as it allows modifications to be easily made to the design of the robot chassis/body and for these modifications to be shared with others.

Elsewhere in STEM subjects, examples of 3DP being used to directly support teaching can be found in creating experimental test artefacts for aeronautical [91,92,240], mechanical engineering [241–249] and structural [250] engineering; developing computational thinking [69]; and supporting teaching in biology [35,86,137]; physics [66]; chemistry [74,251,252]; and mathematics [58,59,62]. Documented examples from outside of STEM can be found in English [132] and history [61] teaching.

A range of benefits have been described in these accounts. These include the way that incorporating 3DP into teaching can bring excitement and realism into the classroom [10,33,161,216], raising student engagement and motivation [33,102,104,105,108,223,224,252], and interest in the subject material [137,231]. The use of 3DP has been observed to improve the iterative design process and shorten design-test-revise cycle times [90,181,183,185,201,202,247], exposing students to CAD [103], while reducing the cost of creating prototypes [183,187] and experiment components [90]. Furthermore, there are indications that using 3DP can improve student confidence in terms of oral presentation when demonstrating their 3D printer and communicating their learning [26], improve their creative flexibility [197] and critical thinking [215], as well as build on skills in virtual making to build confidence in physical making [34]. Most significantly the use of 3DP during teaching has been reported to improve student understanding, with these benefits arising during a range of subjects and settings (Table 4).

Subject	Topic(s)	Educational context	Source(s)
Biology	Biological molecules	Community college	[137]
Chemistry	Atomic structure	High school	[74]
	Protein structures	Upper division undergraduate	[253]
Design	Co-design and sustainability	Lower division undergraduate	[34]
Engineering	Foundations of engineering	Undergraduate	[223–225]
	Material properties	Undergraduate	[245]
	Computer-aided simulation and design	Lower division undergraduate	[241]
	MEMS design	Upper division undergraduate and postgraduate	[108]
Mathematics	Geometry	Middle school	[59,62]
Pharmacology	Enzyme and ligand structures	Upper division undergraduate	[87]

Table 4. Subjects in which the use of 3DP has improved student understanding of a topic

There is also some evidence that exposure to 3DP during these subjects may also improve attitudes towards 3DP [35,183,245]. As one student commented when electing to use 3DP to create biological models, *"I feel using the 3D printer to design and create a project allowed me to learn a lot more about the subject than I otherwise would have. However, the most valuable part of this project was the skill set I gained in learning how to operate 3D software and upload and print these designs"* [35].

Incorporating 3DP into the teaching of other subjects is not without problems, with various challenges noted. These include students struggling with 3DP when they don't have experience with 3D modelling [108]; problems arising in the modelling and printing process that need educator support [137]; 3D printed materials not performing as expected [183], particularly in experimental settings [90]; the time it takes for 3D models to print [122,253]; and the costs of 3D printing [35].

4.4 Using 3D printing to produce artefacts that aid learning

While the previous section described how students are using 3DP to learn about a range of different subjects, this section describes the use of 3D printed artefacts that are brought into the educational setting by educators, and which have been fabricated by those educators or third party suppliers.

It has been commented that educational tools *"could be printed to assist educators in almost every discipline"* [5,160,254]. This review has found evidence that 3DP is already being used to produce artefacts to aid learning in a number of subjects. Table 5 provides a summary of the types of artefacts being created. It is apparent that 3DP artefacts are being used to support teaching in anatomy [31,36,255–270] and chemistry [271–288] the most.

Subject	3D printed artefact(s)	Source(s)
Anatomy	Airway models	[270]
	Bones	[31,263,267,289,290]
	Femoral artery	[262]
	Heart	[258,260,261]
	Limb sections	[262,268]
	Lungs	[290]
	Oral surgical model	[269]
	Orbital dissections	[257]
	Prosected human cadavers	[36]
	Skeletal tissues	[255]
Arts	Cultural heritage models	[291]
Biochemistry	Macromolecular structures	[292]
Chemistry	Atomic structure	[293]
	Copolymer nanostructures	[282]
	Crystals	[273]
	Crystal structures	[280,285,287,288]
	Free energy surfaces	[276]
	Hydrogenic orbitals	[274]
	Molecular structures	[281,284,286,288,294]
	Orbitals	[279,294]
	p orbital isosurfaces	[272]
	Potential energy surfaces	[271,276,277,283]
	Reaction progress surfaces	[275]
Dentistry	Cavities	[295]
	Prosthodontic models	[88]
Geosciences	Digital terrain models	[14]
Mathematics	Geometric models	[296–302]
Paleontology	Extinct shark teeth	[80]
Physics	Mechanisms	[303]
	Mie scattering apparatus	[304]
Zoology	Marine biology specimens	[305]
	Nematodes	[306]

Table 5. Summary of subjects in which 3D printed artefacts are being used to support learning

Whatever the subject, a significant benefit of using 3D printed models as learning aids is that *"the simple ability to rotate a physical object can often bring new elements into view for evaluation that would not be detectable using digital models alone"* [14]. There are also subject specific benefits. The advantages of using 3D printed models in anatomy teaching include *"durability, accuracy, ease of reproduction, cost effectiveness, and the avoidance of health and safety issues associated with wet fixed cadaver specimens or plastinated specimens"* [36]. Purely in cost terms, it has been estimated that 3DP models are 10-20 times less expensive than plastinated alternatives created from cadavers [257]. Furthermore, using 3D printed replicas means that students can examine them without damaging the originals [31], while also reducing demand for human body parts, and allaying ethical and legal concerns regarding the use of cadavers [256]. Similar benefits have been described in zoology, where the ability to replicate the textures and mechanical features of original specimens to a high level for hands-on student learning is advantageous [305].

There have been several investigations of the application of 3D printed artefacts in anatomy teaching, with these comprising surveys of student attitudes and experimental tests of student learning. During an investigation into the use of a 3D printed upper limb in teaching, 15 medical students reported that they felt the anatomical features of the model were accurate, but that the models produced were best used in combination with plastinated prosections to aid learning [268]. A survey of 211 anatomy students, found that 3D printed models of a femur, fifth rib and cervical vertebra helped their overall understanding of the structure of bones, as well as improving their learning interest [289]. Elsewhere, in a cadaveric comparison study of 3D printed temporal bone models by ten postgraduate surgical trainees there were mixed attitudes towards the use of 3D printed simulations as a replacement for cadaveric specimens. While the study reported that trainees found the internal structures of the 3D printed models very similar to cadaveric bones and were in unanimous agreement that such models should be integrated into resident education, the trainees disagreed that the models could completely replace the cadaveric bones [267].

Several experiments have also been conducted that explore the effectiveness of 3D printed artefacts toward student learning. In one study, a 22-part one third scale model of the lower limb and posterior compartment musculature was used in a limb anatomy class. The class was divided into two groups, with one studying dissection specimens and the other studying 3D printed models. Analysis revealed no meaningful differences between the knowledge gained by the two groups [262]. In another study, 29 premedical and medical students were introduced to the concepts of ventrical septal defects and used high-fidelity 3D printed hearts to develop surgical incisions and suturing skills. Statistical analysis of pre- and post-seminar questionnaires showed that use of the 3D printed models enabled significant improvements in terms of knowledge acquisition, knowledge reporting, and structural conceptualization of ventrical septal defects [260]. The effect on learning has also been investigated through analysis of test performances of 127 first year medical students during a "Heart, Lungs and Blood" module. In this study, 61 students were part of a control group that used only anatomical images during module tutorials, while 66 students were part of an intervention group that studied 3D printed models during these tutorials. The use of 3D printed models was found to support learning; average test scores for those in the 3D printed model group were 14.4% higher, with this result statistically significant (P=0.001) [290]. In another study, 52 undergraduate medical students explored the use of cadaveric materials and 3D printed models in self-directed cardiac anatomy learning. Of the 52 students, 18 used only cadaveric materials, 16 used only 3D printed models, and 18 used a combination of the two types. Statistical analysis of pre- and post-test scores showed significantly higher post-test scores for the group that only used 3D printed models. Furthermore, significant improvements to this group's test scores were found, while there were no significant improvements to the other two groups [261]. These findings support earlier propositions that when dissection specimens are not available, that 3D printed models *"offer a novel, accurate and effective substitute"* [36].

The low cost of producing pedagogical aids using 3DP has also been recognized by those in chemistry. One estimate of the cost of 3D printing molecular structures designed using freeware CAD software found that they cost less than one fiftieth the price of commercially available models [274]. As in anatomy, studies have begun to explore the effectiveness of using these 3D printed visual aids to support teaching [287,294]. An end of course survey of over 180 undergraduate students on an organic chemistry course found that the use of 3D printed molecular models in lectures was welcomed by students. 79% of students agreed that using 3D printed molecular models in lectures was an improvement over 2D images used in slides course materials, while 72% of students agreed that seeing the models helped their understanding of molecular structure and bonding [294]. Meanwhile, analysis of the introduction of 3D printed crystallographic models into a 300 level general education course on nanoscience and nanotechnology found the models to have a significant benefit to comprehension and knowledge retention. The average test score of a study group (n=7) that used 3D printed models was 47% higher than a control group (n=7) that did not [287].

Finally, evidence of the effectiveness of incorporating 3DP into teaching can also be found in dentistry. 3D printed prosthodontic models were introduced to a class of 22 fourth year dental students in a simulation to practice dental crown removal and preparation for new crown installation. The class was in strong agreement that the model is useful as a preparation for clinical courses and provides learning benefits, but had varying opinions on the realism of the model and simulation with 3DP limited in the colours and features that can be built into such models [88].

4.5 Using 3D printing to create assistive technologies

As previously described in Section 3.4, 3DP is being used in special education settings for those with visual, motor and cognitive impairments. There are two broad categories of application: (1) when the artefacts created using 3DP are for use by those needing assistive technologies [14,27,28,154,156–159,307–310], and (2) when the needs of those with special learning needs provides a real-world framing to student projects [33,40,76,174,190]. This latter category can be seen as a specific instance of the use of 3DP during teaching that was covered in Section 4.3. It includes the creation of tactile stories for the visually impaired as part of a middle and high school design and teaching class [40]; the development of a prosthetic hand in a school project by fourth graders [33]; and the production of the 3D printed e-NABLE prosthetic hand in a ninth grade programme [76].

To help visually impaired and blind students, 3DP is being used to create a range of tactile artefacts [309,310], including graphics to assist with the teaching of programming [156]; mathematics [307]; literacy [308]; picture books [155]; geoscience maps [14]; astronomical maps [311]; and history textbooks [154]. In this last case, educators and students agreed that the introduction of tactile history textbooks into a semester-long teaching class were useful, that the 3DP textbooks *"helped to clarify obscure meanings*" and also *"directly stimulated the students' imagination and reinforced their understanding and capacity for memorization"* [154]. Meanwhile student excitement and engagement was also found to increase when using tactile graphics to help teach programming, with students *"eager to touch the printer and observe its mechanics"* [156]. However the slow speed of printing and the brittleness of the tactile graphics created were issues, and the quality and durability of 3DP need to be improved for the tactile graphics to become more useful [156]. In other special education settings, 3DP has been used to help students with combinations of visual, motor and cognitive impairments. During the SHIVA project, disabled students used eye-gaze tracking or touchscreens to create three dimensional "totems" in the SHIVA software environment, with these totems then fabricated using 3DP. Through this process, students improved their understanding of spatial awareness and spatial relationships between objects [158]. Elsewhere it is recommended that the availability of assistive technology designs on online catalogues such as Thingiverse be improved, and that more connections and communication be made between designers and communities of users with disabilities [29].

4.6 Using 3D printing to support outreach activities

A growing number of universities are finding applications for 3DP in their outreach activities. While outreach from universities into middle and high schools is the most commonly described [115,116,150,312–319], there are also descriptions of 3DP being used in an outreach function to enable the professional development of teachers [150], librarians [130,146], and industry professionals [115,117,150], as well as engage with students in other universities [316], and adult learners [150].

Using 3DP to develop interest in STEM subjects is the main focus of university outreach activities in schools. As part of a STEM pathway initiative at California State University – Northridge, seven high school students were introduced to digital manufacturing and the engineering design process through 3DP. Running over eight weeks and involving three hours of instruction per week, students learned basic 3D modelling and 3DP concepts, implementing them during design-simulate-build activities [315]. A design-analyze-build-test process is also followed during the four-week long "Summer Ventures in Science and Mathematics" program sponsored by the State of North Carolina. The program included a bracket design challenge where participating high school students needed to design and 3D print the lightest bracket possible that fulfilled the challenge specification [246]. In collaboration with an industry partner, TimeOut 4U, Hampton University ran a pilot Advanced Manufacturing STEM after school program at Hunter B. Andrews PK-8 school. Over ten modules and fifty hours of activities, students learned about manufacturing and 3DP, and went through an iterative design process that led to the creation of 3D printed objects [316]. 41 high school students participated in 3DP-focused STEM workshops at Miami University [198], while a collaboration between the Missouri University of Science and Technology and the St. Louis Community College at Florissant Valley saw a series of NSF-sponsored "Discover Manufacturing Workshops". Held over five days, the aim of these workshops was *"to expose high school students and teachers to manufacturing technologies in the hope of directing and impacting their career choices"* [115].

3DP has also been incorporated into STEM outreach initiatives focusing on women and minorities. At the suggestion of the University of Florida (UF) student chapter of the Society of Women Engineers, the University of Florida Marston Science Library sought to engage middle school students in 3DP. During 90 minute sessions, students were introduced to Tinkercad, before designing and printing their own nametags. Almost 110 students, of which approximately 80 were female, have attended the sessions so far. Along with introducing students to 3DP, the workshops also helped promote the availability of the library's 3DP capabilities [314]. Elsewhere, a 3DP-based workshop was included as an activity at a Women in Engineering Summer Camp organized by the University of Dayton. This workshop contributed to the effectiveness of the whole camp, with 35 of the 36 female high school participants reporting that the camp had influenced their future college study plans [320].

Meanwhile, African-American students have been the target of two outreach initiatives. In the first, a two week-long "Generation Innovation" summer camp, African-American students in grades 6-12 were introduced to a variety of computing science topics. In 2013, 3DP was one of the topics included to a group of 30 students, with each designing and producing objects such as rings and keychains [321]. In a second initiative, 3DP was included in the Minority Male Maker program, a STEM-focused student engagement program for African-American middle school students. A survey of 480 participating students from 56 middle schools in four US states found that the program stimulated student interest in pursuing careers in science, design and engineering [322].

In other outreach initiatives, plastic jewellery has been 3D printed during Colorado State University-Pueblo's K-12 outreach, with high school students using 3DP to produce bracelet designs downloaded from Thingiverse [116]. Meanwhile, the Santa Clara University Maker Lab used a mobile maker lab for school visits and has engaged with other 500 middle and high school students to date. 3DP is just one of the fabrication tools to which students are introduced; it features in an "Exploring Flight" module where students use 3DP to make noseclips for balsa wood aeroplanes and test their effects on the balance of the planes [150].

Some studies also report on the effectiveness of these STEM outreach activities. The two-week Engineering Design and Manufacturing Summer Camp organized by the Georgia Institute of Technology saw 59 students from multiple US states participate on a distributed basis. Using 3DP as part of a create-build-design-operate process, it was reported that students had a strong satisfaction with the course content and approach, as well as a high degree of motivation for pursuing careers in engineering [317]. Working with high school students, faculty from the University of Texas at El Paso used 3DP to test the strength of redesigned LEGO components. The activities led to a reported 45% of the class gaining a positive impression of STEM as a career option [319]. An existing STEM summer program for high school students, the six-week long Cooper Union Summer STEM program, was revised to incorporate 3DP into a makerspace-oriented stream. The first two weeks of the program saw students introduced to a range of making technologies, including CAD and 3DP, as well as the engineering design process, before going on to apply their new skills in projects that lasted the remaining four weeks of the program. Among the 22 respondents to a survey on future study intentions, 17 indicated that the course had changed their study intentions, and that all 22 planned to go on to study science or engineering [323]. In an effort to attract high school students to STEM subjects, Texas A&M University-Kingsville brought 17 students from grades 11 and 12 to a month-long series of workshops in which they worked alongside undergraduate students to learn about 3D modelling and 3DP. This outreach activity was considered successful as after the workshops all 17 students submitted applications to Texas A&M engineering programmes [312]. In another week-long student camp with middle school students, the use of 3D printed modular robots was found to boost student confidence in the use of computers and robots [78]. In contrast, the inclusion of 3DP in a two-week computer science summer camp for middle- and high school girls found was found to be challenging due to the student's lack of spatial awareness skills [79]. Finally, an extracurricular summer camp for computational bead design introduced students to computing, digital modelling and 3DP. While qualitative survey data was positive about the experience, quantitative survey data among a small sample (n=17) was inconclusive about the relationships between 3DP application and changes in attitudes towards STEM [60].

Reports of planned activities can also be found. In one instance, a combined wind-turbine and PV demonstration kit has been developed at Roger Williams University using 3DP, with the intent of it being used for K-12 STEM outreach activities [318]. In another, the use of 3DP in soft robotics is planned as part of a large-scale initiative to increase female interest in STEM. This will be delivered to grade nine students taking a freshman-level technology and engineering course within the Engineering by Design program, seeing it taught in over 270 US school districts to about 100,000 students each year [313].

5. Conclusions

This article has summarized the existing research conducted into the application of 3DP in the education system. Through synthesising a diverse and fragmented literature of 280 articles, this state of the art review provides a clearer understanding of where and how 3DP is being used in the education system. A high-level summary is provided in Table 6. Given its historical roots as a rapid prototyping technology, it is unsurprising that 3DP's adoption is most mature in university engineering and design courses, and that dedicated 3DP courses are emerging from within these disciplines (Section 4.1). However, it's apparent from this review that 3DP has expanded beyond these roots; 3DP is being actively incorporated into a variety of other subjects (Section 4.3) and being used to produce artefacts that support learning (Section 4.4). Outside of engineering and design, other STEM disciplines are the most prominent adopters of 3DP, and are beginning to demonstrate how using 3DP can create cross-linkages between these subjects [39]. In non-STEM subjects, however, there are currently only a few documented examples of 3DP's adoption during in-class teaching.

As a literature review, this work is ultimately limited by what academics have chosen to research and document. Given pressures to publish and share knowledge, university academics have greater incentives to document their experiences than K-12 teachers and continuing/further education lecturers. The more substantial literature on the adoption of 3DP in universities may be a reflection of these differences in motivations, but is also suggestive of the more mature adoption of 3DP in universities. Within universities, 3DP is diffusing from engineering and design subjects into other disciplines, with university libraries often providing a centralized resource that enables students from other disciplines to gain exposure to 3DP outside the classroom. While there are a relatively large number of documented accounts of workshops, courses and curricula in engineering and design, descriptive papers providing similar accounts outside of these subjects, particularly in non-STEM subjects, are encouraged so that others may learn from and be inspired by 3DP's application. Furthermore, there are limited accounts of 3DP skills acquisition in continuing/further education settings, and we call for research that studies that describes and analyses the implementation of 3DP in vocational subjects.

Meanwhile in the K-12 system, when middle- and high school students are being exposed to 3DP it is primarily through university outreach activities rather than during their formal curriculum. There are currently only isolated pockets of 3DP adoption in K-12 teaching, with these appearing to be based on the educator's experience, confidence and enthusiasm towards 3DP. This is reflective of the currently limited exposure and training in 3DP received by educators (Section 4.2). For K-12 educators to develop the experience and confidence necessary to incorporate 3DP into teaching, more 3DP educational components need to be included in pre-service teaching, as well as an expanded range of workshops to inform in-service teachers. Improved access to teaching materials is also necessary alongside improving teaching skills, and a centralized resource for lesson plans and comprehensive curricula would help support teaching integration [324]. This issue of "teaching the teachers" is a pressing one but one that appears to have been overlooked in recently published recommendations around 3DP education [2].

While there is a wealth of online materials to support teaching, it has been noted that there is a lack of an appropriate textbook to support teaching [119]. There remains a need for additional teaching support materials that simplify the process of incorporating 3DP into teaching, both for curricula where 3DP skills development is the objective, and for incorporating 3DP into curricula to improve student engagement and subject knowledge acquisition. In addition, improving the availability and access to 3D models is also needed to support teaching. 3D models provide an entry point for introducing 3DP, demonstrating its capacity for modification and sharing, and supporting educators who want to produce teaching models but don't have the time or necessary expertise. While there is a rapidly growing number of 3D models available online, those available for education purposes are predominantly found for disciplines such as engineering and architecture where 3D modelling skills are most advanced, with a sparse number in other disciplines [325]. Through dedicated repositories such as the NIH 3D Print Exchange [326], 3D models can be shared. It is recommended that similar education-focused 3D print exchanges be created to lower the barriers to integrating 3DP into teaching, avoid the duplication of effort in modelling, and reduce the cost of creating assistive technologies and labware [325,327].

Pursuing such initiatives is worthwhile as the positive impact of using 3DP in teaching is gradually becoming known. As described in Sections 4.3 and 4.4, there is evidence that incorporating 3DP into teaching supports student learning, along with providing additional subject-specific benefits. While this body of evidence is growing, much of it is based on single course assessments or small student samples, and there are currently no standardized methods of evaluation [149]. Developing such methods and conducting further evaluation studies across larger populations are necessary in order to better substantiate the nature and magnitude of learning benefits that arise. The results of such studies would help answer the broader questions of how should 3DP be integrated into teaching and what institutional and national policies are necessary to realise this objective.

Beyond the formal education system described in this paper there are also wider questions about the application of 3DP in informal education. Students of all ages can learn about 3D modelling through online courses and tutorials, fabricate objects through 3D print-on-demand services and networks such as 3DHubs, and join fablabs and makerspaces that are unconnected to universities and libraries [328]. The democratization of education and making provides opportunities for self-directed learning. Accordingly, a better understanding is needed of how acquiring 3DP skills occurs outside the formal education system, and how learning from informal and formal education can be integrated.

As the previous paragraphs have described, there are numerous future research directions that scholars could pursue to advance our understanding of 3DP adoption and practice in the education system. Expanding on these possible directions and drawing on the works reviewed in Sections 3 and 4, a list of potential research questions is provided in Table 7. Categorized against the six use cases, we propose 44 potential research questions for further investigation. We hope that these questions will assist researchers embarking on empirical studies into the use of 3DP in the education system, and that developing answers to these questions will inform 3DP education policy.

		Where is 3DP being used in the education system?			
		Schools	Universities	Libraries	Special education settings
How is 3DP being used in the education system?	Teaching students about 3DP	3DP and 3D modelling are introduced to students during design and prototyping projects in class	The fundamentals of 3DP and 3D modelling are introduced to engineering and design students, who apply their skills during in-class projects	Improving access to 3DP equipment and services enables self-directed learning by students outside class	-
	Teaching educators about 3DP	3DP and 3D modelling are being introduced to in-service teachers	3DP and 3D modelling are being introduced to pre-service and in-service teachers	Training librarians enables them to operate and maintain 3DP equipment, and troubleshoot 3D modelling problems	-
	Using 3DP during teaching	Using 3DP during class projects to improve student engagement and understanding of STEM subjects	Using 3DP during class projects to improve student engagement and understanding of STEM subjects	-	Using 3DP to create custom adaptive devices and educational aids
	Using 3DP to produce artefacts that aid learning	-	3DP models enable hands-on learning in lectures and lab sessions, particularly in anatomy and chemistry teaching	-	-
	Using 3DP to create assistive technologies	-	-	-	Expands the range of student learning opportunities, particularly among those with visual impairments

	Using 3DP to support outreach activities	Using 3DP during university outreach programs improves student engagement with STEM subjects	-	-	-

Table 6. Overview of how 3DP is typically being used in different educational settings

Use category	Potential research questions
Teaching students about 3DP	• When and how should 3DP be first introduced into the classroom? • What types of projects are effective in introducing students to 3DP and engaging them in developing 3DP knowledge and skills? • What knowledge and skills should students acquire in introductory, intermediate and advanced 3DP courses? • What differentiates a 3DP course from an AM course? • How is 3DP being introduced and taught in vocational education? • How are 3DP equipment companies supporting the creation of 3DP curricula? • With the rapid development of 3DP technologies, what should be included in 3DP curricula so that students' knowledge and skills don't become quickly obsolete? • How can 3DP engagement be encouraged and disengagement reduced in classrooms with diverse levels of technological literacy? • How can peer learning be used effectively to support 3DP learning and engagement? • How much structure, supervision and resources are needed during 3DP-based projects? • What do students learn when they share their 3DP projects online? • How are individuals of different ages developing 3DP knowledge and skills through self-directed informal education? • How can libraries and makespaces provide a bridge between 3DP teaching in the formal education system and self-directed informal education?
Teaching educators about 3DP	• What types of training programs are used to introduce and educate pre-service and in-service educators about the use of 3DP in teaching? • How successful are these existing training programs at preparing educators for using 3DP in teaching? • What types of 3DP training programs are required for educators to develop the skills and confidence necessary to integrate 3DP into classroom projects? • How should 3DP training differ for educators at different stages of their careers (pre-service; different levels of in-service), in different educational institutions, and in different disciplines? • Where in the pre-service educator curriculum should 3DP training be added? • What are the metrics for measuring the success of educator training programs?
Using 3DP during teaching	• What are the barriers and challenges to educators incorporating 3DP into their teaching of other subjects? • What teaching resources and support do educators require to incorporate 3DP into their teaching and classroom projects? • How effective are the educational resources provided by 3DP equipment manufacturers at supporting educators using 3DP during teaching? • Where is 3DP being used to support teaching outside of STEM subjects?

	• Why does hands-on experience of 3DP in class lead to improved student understanding of subject matter? • How does this improved student understanding relate to the preferred learning styles of students (e.g. kinaesthetic, visual, social)? • How are student attitudes towards 3DP affected by using 3DP in other subjects and educational settings?
Using 3DP to produce artefacts that aid learning	• What are the educational benefits of 3D printed artefacts versus those produced using alternative methods? • How do these educational benefits vary across different stages of the education system and across disciplines? • Why do students learn better when using 3D printed artefacts? • Why have 3D printed learning aids been embraced in anatomy and chemistry more than in other disciplines? • What are the barriers to the further adoption of 3D printed visual aids in teaching?
Using 3DP to create assistive technologies	• What types of assistive technologies have been 3D printed? • What are the benefits and challenges of creating 3D printed assistive technologies in the classroom for students with different types of visual, motor and cognitive impairments? • How effective are 3D printed assistive technologies at supporting learning in special education settings? • What are the metrics for measuring the success of using 3DP to create assistive technologies in special education settings? • What support and resources are necessary for using 3DP to create assistive technologies in special education settings? • How does the creation of assistive technologies by non-impaired students develop empathy for the users of such assistive technologies?
Using 3DP to support outreach activities	• What models of 3DP-based outreach programs exist? • What are the characteristics of successful 3DP-based outreach programs? • Which are the most significant factors when designing 3DP-based outreach programs for different types of student audiences? • How effective are 3DP-based outreach programs at encouraging students to pursue higher education and careers in STEM subjects? • What are the metrics for measuring the success of 3DP-based outreach programs? • How can 3DP-based outreach programs complement the in-class teaching of 3DP? • How does the effectiveness of 3DP-based outreach programs change as 3DP is adopted more widely in the K-12 school system?

Table 7. Potential research questions relating to 3DP in education

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