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3D Printers in Engineering Education

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Introduction

The world is moving towards simpler, faster and more effective methods of chemical, component and material production, fuelled by the technological transformations of Industry 4.0 (see Lu, 2017). Accurate and precise approaches in manufacturing are revolutionising the design and operation of industry processes, with wide impact across product sectors (Despeisse et al., 2017). Within this transformation, the emergence of

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3D printing (3DP), and more generally additive manufacturing (Additive Manufacturing UK, 2017; Dickens, Reeves, & Hague, 2012; European Commission, 2014; U.A.M.S. Group, 2016), has played an important role, significantly improving design (prototyping) and efficient component production (Simpson, Williams, & Hripko, 2017). Accordingly, a need has arisen for training in the use of 3DP as a design, development and manufacturing tool.

Such printers are becoming increasingly common in education, as exemplified by the UK's Department for Education report on their use in schools for "enriching the teaching of STEM and design subjects" (Department for Education, 2013). Likewise, high-impact initiatives are being reported in higher education (HE) contexts, including prototype development, design exploration and component/molecular/process visualisation. Although initial HE applications have had a natural affinity towards mechanical and structural engineering programmes, diverse and cross-discipline applications in areas such as medical and bio-engineering (e.g. tissue scaffolds), food processing (e.g. food printing) and more generally chemical product engineering are rapidly emerging. Moreover, the integration of 3DP into engineering curricula is leading to an interest in pedagogy, and specifically innovative approaches to enhance teaching quality and the student learning experience. How the technology can be used effectively in teaching and learning contexts, whilst maintaining its accessibility to students and teachers that do not have rigorous knowledge of computer-aided design (CAD) software, remains a challenge.

The focus of the research reported in this chapter is to explore literature, evidence and student perspectives on the value of 3DP in engineering education. Specifically, the following research question is being considered: what benefits do students perceive of 3DP in engineering education? A novelty of the work has been to consider 3DP use in engineering education contexts outside that of the mechanical/structural disciplines, i.e. a move away from the usual *printing of a design prototype* common in mechanical engineering design. As such, the study should be of broad relevance to educators across the disciplines.

Educational Use of 3D Printers

An extensive literature review on the use of 3D printers in education has been recently published by Ford and Minshall (2019). In addition to school and university classroom/laboratory settings, the authors also identify their growing use within library and special education settings. For example, libraries are "a logical choice to house technology that has many potential users…[and offer]…a valuable service to their organisations while raising awareness of the other services they offer as well" (Hoy, 2013). Across education levels, 3DP is allowing students to discover new interests in technology, and is similarly providing educators with new methods of engaging students. It has also provided a medium to facilitate student creativity (Bøhn, 1997; Horowitz & Schultz, 2014; Paio, Eloy, Rato, Resende, & de Oliveira, 2012; Stamper & Dekker, 2000), and empower pupils to physically create objects that aid their understanding. At the early stages of education, 3DP is also exposing children to technology, potentially changing attitudes towards study and work in science and engineering. As importantly, and valid across the education sector, 3DP can provide opportunities for low-cost component production for teaching purposes (Blikstein, 2013; Bull, Chiu, Berry, Lipson, & Xie, 2014; Bull, Haj-Hariri, Atkins, & Moran,2015; Chery, Mburu, Ward, & Fontecchio, 2015; Dumond et al., 2014; Eisenberg, 2013; Jacobs et al., 2016), providing effective replacement to real (e.g. industrial, medical, laboratory) components/equipment for demonstration and study purposes.

In response to educational needs, leading 3D printer manufacturers have developed specialised machines for such use. Nevertheless, the first step is for both teachers and students to acquire the skills needed for printing, e.g. how to convert a drawing/object into a digital format for printing, and the manipulation (modelling) of such digital formats for novel constructions. In doing so, students are also being introduced to (computer-aided) design principles, material properties and testing and developing skills in spatial awareness and visualisation (Corum & Garofalo, 2015; Huleihil, 2017). However, programme changes may be needed to accommodate the skill base necessary for projects involving

3DP and the library approach mentioned above may provide some technical support here.

Not surprisingly, the STEM disciplines are at the forefront of 3DP use (see Ford & Minshall, 2019). Success within these disciplines often requires a genuine interest in technological advancement, and there is an onus on educators to foster such enthusiasm through engaging and stimulating methods. 3DP provides one such example of stimulating technological engagement, with tangible design outputs. In engineering this has predominantly focused on design projects (Abreu et al., 2014; Bilen, Wheeler, & Bock, 2015; Butkus, Starke, Dacunto, & Quell, 2016; Carpenter, Yakmyshyn, Micher, & Locke, 2016; Reggia, Calabro, & Albrecht, 2015; Serdar, 2016). More generally, engineering concepts can be taught through physical analogues, allowing students to better grasp such knowledge through deeper engagement with the theoretical principles (c.f. problem-based learning, Chiu, Lai, Fan, & Cheng, 2015; Williams & Seepersad, 2012). Indeed, engineering students are often motivated in turning ideas to real-life objects that can be inspected, analysed and used as a springboard for further design improvement.

In the engineering disciplines, the ability to print parts for testing and as visual aids can be highly advantageous for engineering students. The relative ease of production allows rapid prototyping and modelling. Visual aids are powerful in explaining concepts and encouraging problem solving through spotting flaws, to be able to improve the designs to overcome a design flaw. This develops the students' skills in research and development in product design, but also, more fundamentally, serves as an introduction to the critical area of digital manufacturing, i.e. the use of an integrated, computer-based system comprising 3D visualisation and collaboration tools to create a product and manufacturing process (Go & Hart, 2016).

3DP brings new opportunities for a new style of learning. Studies show that students do not all respond to the same style of teaching, but rather, based on their educational needs, respond positively to several different styles of learning (Fernandes & Simoes, 2016; Minetola, Iuliano, Bassoli, & Gatto, 2015). 3DP can give rise to new and more interactive approaches to learning where it includes developmental learning, allowing students to draw their own conclusions and lessons learned, rather than theoretically teaching the concepts. This is already evident in teaching methods at university level where engineering students must carry out lab experiments and write reports on their findings. It is through designing and carrying out their own experiments that students really grasp theories and make leaps in their understanding (Loy, 2014). The use of a 3D printer can take experiments a step further where students print their own parts and carry out tests to elucidate theories and engineering laws. Furthermore, students can develop creative presentational skills through physical visualisation methods. In a related way, 3D technology can be extensively used in artistic ways (Chiu et al., 2015; de Sampaio et al., 2013), through the creation of unique and engaging pieces as a possible means of, for example, public engagement (and outreach) in STEM through an artistic (and visual) expression of underlying scientific and engineering principles.

3DP is extensively used in industry for rapid development of parts and tools. Predominant use is made in the car (and general transport) industry for rapid prototyping of mechanical and other functional components (Cunningham, 2019). Personal communication with manufacturing experts in BMW (UK) has made it apparent that 3DP technology has been revolutionary for their predevelopment models, helping to readily modify old parts for performance enhancement, and offering greater flexibility in manufacturing options. For example, one of the main issues with parts is the angles that allow a part to be made and fitted onto the vehicles and 3DP has solved this issue altogether. 3DP has also overcome tooling requirements, i.e. the tools required to fix specific parts onto vehicles can be directly printed for that specific application, opening a wide spectrum of new manufacturing possibilities. In addition, in precise-layer-by layer 3DP, the amount of waste in product manufacturing is reduced. The nature of such industrial use is of much relevance to general engineering education, related to, for example, material science, digital modelling, 3D visualisation and the "conceive, design, implement and operate" (CDIO) teaching and learning ethos that dominates in the mechanical/structural engineering disciplines (see CDIO, 2019), but much less so in the chemical and biological engineering fields.

Methodology

3DP in engineering education is a relatively new area that requires further research to explore its broad and potential uses. In this work, the research design focused on student, work placement and recent graduate attitudes towards 3DP in education (taken together as two main participant groups: students, and work placement students and recent graduates). For participants in employment, the study was conducted at BMW Group Plant (Oxford, UK), i.e. the current work-placement location of the student research partner in this study. Although the industrial location is automobile manufacturing-focused, the participants had broad disciplinary backgrounds (see below), and the study thus allowed reflection upon university education and employment preparation in the context of a sector where 3DP is being used extensively.

For university participants, the study was conducted in the Department of Chemical and Process Engineering at the University of Surrey. Similar to other chemical engineering departments, 3DP does not feature within the undergraduate curriculum, although it is anticipated that most students will have some basic awareness of the technology. The study thus allowed investigation of student attitudes on the potential use and benefits of 3DP in an engineering discipline not conventionally associated with the technology.

With reference to Table 7.1, a questionnaire was designed to explore the level of awareness and experience of 3DP (Q2–Q6) and perceptions of the value of 3DP in disciplinary knowledge and skills support (Q8–Q10). As indicated in the table, several questions employed a 4-point Likert scale to gauge perceived benefit. A qualitative response for one question (Q8) provided the main student input on potential learning value of 3DP. The questionnaire was administered electronically using SurveyMonkey. A general email with the survey link was sent to all students (FHEQ levels 4–7) across the undergraduate programmes in Chemical Engineering, i.e. an approximate cohort size of 350 students. Direct emails were also sent to relevant industry-based participants, i.e. approximately 40 individuals. The placement students are all in their penultimate year of study and thus fairly knowledgeable about their discipline.

Table 7.1 Summary of the 3DP Awareness and Benefits Questionnaire

Question	Response options
1. Choose your university degree from the options below. If it's not on the option list, please state your degree in the comment box.	
2. What's the extent of your knowledge of how 3D printing works?	4-point scale: {I know the technical details as well as applications; I do not know how it works but know the applications; I have a rough idea of how it works and general applications; I have no idea}
3. Which of the following 3D printing types do you know?	Multiple selection: {fused deposition modelling; stereo-lithograph; digital light processing; selective laser sintering; selective laser melting; laminated object manufacturing; digital beam melting; none of the above}
4. In which of these sectors do you think 3D printing is used?	Multiple selection: {automotive; medical; infrastructure and architecture; chemical; education; art; film and entertainment}
5. Have you used 3D printers at University?	{yes; no}
6. Have you used 3D printers on work placement (where relevant)?	{yes; no; not relevant}
7. Have you used computer aided design (CAD) software in your degree or elsewhere?	{yes; no}
8. Would you like to be trained on the uses of 3D printing as part of the degree curriculum? If so, please explain how 3D printing could be used to help your learning.	{yes; no; comment box}
9. How do you think the use of 3D printers might benefit the following aspects of your degree? {lecture-based modules; laboratory work; design work; computing and simulation}	4-point scale: {not beneficial; could be beneficial; beneficial; very beneficial}
10. How do you think the use of 3D printers might benefit the following skills? {team work; problem solving; analysis; creativity; technical skills; leadership}	4-point scale: {not beneficial; could be beneficial; beneficial; very beneficial}

Results and Discussion

80 participants completed the survey, 48 based at the University of Surrey and 32 at BMW. 15% of the participants were from a mechanical engineering background, 60% from chemical engineering (all university-based) and the remainder distributed across a broad range of disciplines including electrical engineering, aerospace and aeronautical engineering, industrial engineering, computer science, mathematics and sport science, product design engineering, economics, international business management and international events management. Discipline and university/employment cohort variations in response were tested for questions 4, 8, 9 and 10 in the questionnaire; however, no significant differences were noted, suggesting general positive acceptance of the value and relevance of 3DP.

80% of respondents had some awareness of 3D printers, with half reporting a "rough idea of how 3D printing works". Technical knowledge dominated amongst the mechanical engineering cohort of participants. 64% of the respondents did not recognise any specific type of 3DP. Where knowledge existed, fused deposition modelling (29%) and selective laser sintering (16%) dominated. Interestingly, sintering is a topic that most engineering students encounter in modules related to materials science/engineering, often in the early years of the degree programme. The topic could therefore act as a first (and natural) bridge to 3DP technology. Similarly, module theory could also be extended to materials analysis and stress testing on printed components. There was recognition of wide use of 3DP across different sectors (Q4), with 47% selecting all the listed sectors. The selection ranking of specific sectors (highest to lowest) was recorded as: medical (55.4%), automotive (selected by 54.2% of respondents), art (49.4%), infrastructure and architecture (49.4%), chemical (25.3%), education (32.5%) and film and entertainment (30.1%), indicating a broad appreciation of the potential use of 3DP.

81% of respondents had no university experience of 3DP; only 10% experienced 3DP in their work environment, i.e. 25% of the industry-based participants. Nevertheless, 53.6% of the respondents had experienced CAD in some form, either in their degree programme or other (e.g. school, extracurricular) use. Encouragingly, approximately 78% of the respondents reported a desire for training in 3DP as part of their degree programme, demonstrating widespread interest in the technology and its applications. Not surprisingly, particular benefit to the degree programme was reported for design and computing and simulation work (Q9). However, benefit was also reported for all teaching aspects, with mean responses (on a 4-point scale) of 2.3 for lecture-based modules (81.1% favourable response), 2.7 for laboratory work (83.3% favourable response), 2.9 for computing and simulation work (84.6% favourable response) and 3.2 for design work (94.7% favourable response).

For skills development, low 3DP benefits were reported for teamwork and leadership—an expected trend. Positive benefits were reported for (in decreasing order): creativity (3.4 mean score and 94.6% favourable response), technical skills (3.0; 97.4%), analysis (2.95; 94.8%) and problem solving (2.7; 87.2%). The widespread recognition of 3DP to promote creativity skills is encouraging, especially in (chemical engineering) curricula where creativity tasks may often be confined to paper exercises or 2D simulation software outputs, suggesting that the findings of, e.g. Horowitz and Schultz (2014) are indeed transferable to other disciplines.

A thematic analysis of the respondent comments on question 8 of the survey led to the following general categories of perceived benefits and uses of 3DP in education:

1. Prototyping of equipment in design projects/work (c.f. Bøhn, 1997; Stamper & Dekker, 2000);
2. Material selection and testing for a given application (c.f. Corum & Garofalo, 2015);
3. Physical samples for demonstrations and presentations, e.g. analogues of complex structures, equipment and chemical components, including functional items (c.f. Williams & Seepersad, 2012);
4. Demonstration of industrial additive manufacturing principles (c.f. Go & Hart, 2016; Williams & Seepersad, 2012);
5. A support tool for CAD learning through the printing and analysis of CAD models;
6. Scaled print of a chemical plant, including 3D layout.

Interestingly, with the exception of theme 4, all the themes have generic relevance to the chemical engineering discipline. Comments by students within the chemical engineering department indicated relative ease in transferring 3DP principles to their educational needs, with application examples to process equipment, overall chemical plant design and speciality materials such as column packings and catalysts being readily recognised.

Demonstration and presentation related uses of 3DP received broad mention by the respondents, i.e. alternative tactile teaching resources to complement digital and virtual content. This may be particularly beneficial for the appreciation of scale and magnitude in design components, as well as the visualisation of complex and intricate structures, including the 3D layout of equipment which is often avoided in chemical plant design, but yet can be critical to the operational optimisation and indeed feasibility of the plant (e.g. sea-based oil platforms and mobile plants on ships). Comments also included the production of functional (i.e. operational) components using 3DP that are otherwise often represented as simple schematic diagrams within lectures, or accepted with little critique or analysis within laboratory settings. Indeed, such equipment analogues, once produced, could then be scanned into an immersive virtual reality environment for widespread viewing. Whilst basic (and affordable) 3DP is currently constrained to polymer prints, material science aspects often concern material shape and thickness considerations, such as pressure vessel selection and design in the chemical industry. As indicated by some of the comments, prints of components would provide opportunities for direct, experiment-based application of such material science principles.

Although CAD education in engineering is generally viewed as favourable in supporting design and digital skills development, it is uncommon in chemical engineering curricula. This may be related to the specific output needs for such CAD models, where structural and mechanical design is less important than the identification of, for example, input streams, heat transfer areas and operating conditions. However, the advent of affordable and easily accessible 3DP would provide a relatively easy method of extending process engineering concepts to mechanical principles, fostering in turn engineers with a wider knowledge and skills base and potentially greater role pliability (see also the discussions of Alpay, 2013). The responses from the chemical engineering students in this survey indicate that 3DP would be a favoured approach in bridging (to some extent) such historic differences between engineering disciplines.

In the current job market and the increasing pressures of gaining graduate employability skills, it is important to meet the expectations of employers and industry. 3DP can enhance students' learning journeys and it can also boost valuable employability skills, including practical applications and presentation skills. Skills developed from working with 3DP to create and innovate solutions to problems through design and technology have a place in industry and engineering roles. These roles are associated with methodical and rational processes, but enhanced creativity and imagination add alternative answers and solutions, and this gives more flexibility to the field chosen by engineering graduates.

The study confirms both student and institutional desires to adopt 3DP technology, but has also confirmed relatively slow adoption outside the mechanical and civil engineering disciplines. This in part reflects discipline disparities in the knowledge and skills of 3DP, which is a greater barrier for educational applications outside mechanical and civil engineering. However, with the advent of affordable and simple-to-operate devices, the centralisation of such services within institutions seems a natural progression, e.g. the use of printers within library services as reported by Hoy (2013). Future developments in tools for the easy and intuitive translation of sketches, artefacts and even photographs to printable (and scalable) formats would further open teaching and learning possibilities. In this sense, 3DP technology may provide a readily accessible means of visualising digital lecture/design content, especially where testing is required and so virtual reality-based visualisation does not suffice.

Conclusions

The study has indicated great receptivity towards 3DP in education by students and recent graduates in areas both within and outside engineering disciplines normally associated with 3DP technology. In particular, students in chemical engineering were able to recognise a broad range of 3DP uses to support learning and creative design, supporting literature reports in this area. The inclusion of 3DP itself in teaching would open learning content in areas of CAD, real plant layout and magnitude (scale) appreciation in calculations and design. In doing so, an important bridging between mechanical and non-mechanical based engineering disciplines could be achieved, broadening the knowledge and skills base of the graduates. In a similar way, as engineering curricula evolve in digital literacy and content requirements, the study suggests that 3DP technology provides a practical, visual and engaging medium for consolidating learning across areas such as CAD and rapid prototyping.

Reflective Vignette

Student Perspective (Atefeh Eslahi)

The staff–student partnership on this project has been a great experience and there has been significant learning from this collaboration. As the first experience in this way of working it has been a truly beneficial one; the close partnership has provided much closer supervision and has been engaging in taking ownership and having the freedom to produce original work with guidance and help from the staff. The freedom of developing my own ideas and making suggestions in how to carry out the studies has stimulated creativity and has implemented better understanding on how to articulate a scientific topic in clear and concise manner. The staff experience in writing papers has been crucial for this and there has been substantial guidance and learning. Communication has been vital to the development of this project and the importance of student and staff working together has been highlighted in the gains in mutual understanding and contribution to my professional development. Overall this has been a valuable project and has given *me a significant boost in confidence to work alongside experienced academics in the future.*

Staff Perspective

The concept of staff–student partnerships in education is not new: undergraduate projects supporting academic research are a well-established example. However, such partnerships are less common on matters concerning pedagogy or educational development, especially in the science and engineering disciplines. An advantage here is the direct involvement of the recipients (i.e. students) of the intended learning and teaching initiative, providing continuous feedback into its development from the onset. The partnership also allows early and first-hand gauging of the student interest for an initiative, as well as a closer link to the student body for research evaluation purposes. The experience of this project has reinforced the value of such united educational research within discipline contexts. Perhaps an important extension of the approach however, would be to place projects within existing research project modules, thus potentially widening the scope of the research work and ultimate quality of research-informed educational development.

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