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Engineering Science in Additive Manufacturing

REVIEW ARTICLE

Additive manufacturing: A design-led innovation approach for tertiary education and research training

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Abstract

Identified as a core technology in the Fourth Industrial Revolution, additive manufacturing (AM or 3D printing) has seen considerable industry growth, which has created a significant need for a skilled workforce. Furthermore, AM education and professional training are also crucial in the dissemination and widespread adoption of this technology beyond conventional manufacturing barriers. To address this demand, various educational institutions have undertaken different initiatives to incorporate AM components into their interdisciplinary engineering curricula. AM is not just about instrumentation and materials, but also involves design, programming, and validation skills. While most AM training courses focus on general knowledge and hands-on laboratory training, there is a lack of innovation frameworks led by digital design, which is arguably one of the core elements of AM technology. In this review, the authors examine global representative AM training and education programs. Additionally, institutional efforts to address this demand are presented through undergraduate and graduate courses employing problem- and project-based pedagogies to equip students with hands-on AM experiences and digital design-led innovation skills.

Keywords: 3D printing; Design optimisation; Design-led innovation; Project-based pedagogies; Digital design

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1. Introduction

Additive manufacturing (AM), or 3D printing, is a leading Industry 4.0 technology that builds products layer by layer from 3D CAD models, in contrast to traditional subtractive methods. This underscores AM's advantage in producing customised, complex geometries at lower cost, shorter lead times and reduced weight—benefits that often elude conventional manufacturing processes.[1-4] Early AM technologies were used primarily as tools for rapid prototyping. The printed objects were mainly made from plastic in various forms, such as filament, powder, and liquid. The materials are added layer by layer using different techniques, including thermal deposition (FDM)[5], laser sintering and melting (SLS, SLM)[6], binder jetting, and photopolymerisation using stereolithography (SLA). In addition to plastic, 3D printing technologies allow for the construction of printed objects made from metal, ceramic, or bioink. The increase in the number of 3D printing techniques and materials, in combination with the advance of other technologies, has made this interdisciplinary technology not only useful as a prototyping tool but also as a direct manufacturing process to construct end-use parts or products for distinct applications.[7,8]

Applications of AM technology in the field of automotive manufacturing are very diverse, ranging from pre-production testing to customised tooling equipment or end-use parts for small- and medium-scale production, such as bellows, ducting, brackets, and engine components.[9] Metal AM is particularly well-suited for aerospace applications that require small quantities of parts with complex shapes[10,11] and lightweight, highly efficient designs that reduce fuel costs, such as brackets, compressor blades, turbine blades, inducers and impellers, fuel nozzles, and metamaterials.[7,10,12-14] The use of AM technology for biomedical applications has developed over the last 30 years. AM has been widely used to fabricate customised products like external aids, surgical implants, surgical guides, and prosthetics in orthopedics and dentistry.[15] For individual patients, 3D-reconstructed virtual models are generated by capturing model data obtained through magnetic resonance imaging (MRI), computerised tomography (CT)[16,17], or other scanning technologies, and are then quickly constructed using AM. Recently, bioprinting technology using AM principles has shown the potential to directly produce 3D human-engineered tissues or organs from biomaterials.[18,19] The potential application of AM in drug delivery has been investigated because of the benefits of controlling dosage forms with varying doses and release profiles.[20] In addition, AM also plays an important role in many other manufacturing fields, such as construction, civil engineering, and even the fashion industry.[21,22]

As a key technology in Industry 4.0, 3D printing market has developed significantly and tends to continuously boost in the near future. Figure 1a shows the 3D-printing market doubling in key application areas from 2019 to 2027.[23] The number of 3D-printing and AM devices is forecasted to grow to over 2.7 million by 2030, an increase of over two million since 2020.[24] According to the Additive Manufacturing Market (2026–2033) report from Grand View Research, the market size of AM in 2025 has reached $30.6 billion.[25] With an estimated compound annual growth rate (CAGR) of 23.9%, the projected market size in 2033 will reach $168.9 billion.[25]

The rapid growth and potential of AM techniques require human resources with an adequate combination of knowledge, capabilities, and skills. 3D printing could also bring millions of manufacturing jobs to the US and create 3–5 million new skilled jobs, as shown in Figure 1b. The demand for human resources in the 3D-printing field is very large, but the education sector has not kept pace with the strong, rapid development of this labour market.

The lack of human resources creates certain barriers to the development of 3D printing technology. According to the state of 3D printing report from Sculpteo company[8], Figure 2 presents the most time-consuming areas for 3D printing users, with CAD design, test prototypes, and research as the top three areas in which the users spend their time. While design for AM is becoming one of the keys to solving fundamental problems of 3D printing and unlocking opportunities for business, it is still limited by low levels of education in various 3D printing application fields. The survey results, as shown, present the barriers to the development and use of 3D printing technology at the respondents' companies, which include various barriers related to training/education and human resources (*e.g.*, lack of training or recruitment).[8] Therefore, different levels of AM education can play an important role in plugging the current skills gap that has been one of the obstacles to the wider adoption of AM.

While several universities currently provide AM courses, most are included in the undergraduate and graduate curricula. The courses may not be accessible to everyone in the general public who is interested in 3D printing or who requires AM knowledge in the workplace. In an effort to maximise the impact of AM in the industry, the European Commission has outlined the challenges affecting the full deployment of AM technology.[26] Among the seven primary gap drivers, the main obstacle lies in the lack of knowledge and training available at different levels. In this regard, there is a need for AM courses to be offered to a broader community, from those in secondary education to working professionals.

This review provides an updated review of the current tertiary educational and training programs in AM. These programs are designed and delivered in academic and professional contexts. **Section 2** provides an overview of these programs and the current challenges. **Section 3** discusses a new approach (*i.e.*, the design-led innovation approach) to 3D printing. **Section 4** discusses a case study based on a course delivered at RMIT University, Melbourne, Australia, highlighting the benefits and challenges of this approach.

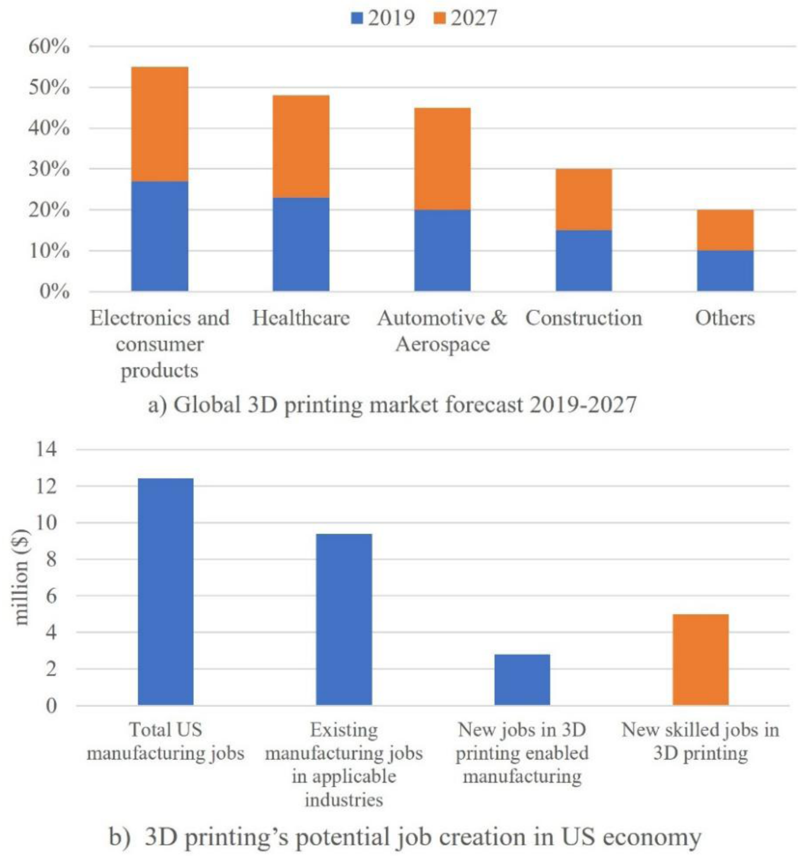

Figure 1. The development of 3D printing market and job creation (based on results from global 3D printing market report 2019–2027[23])

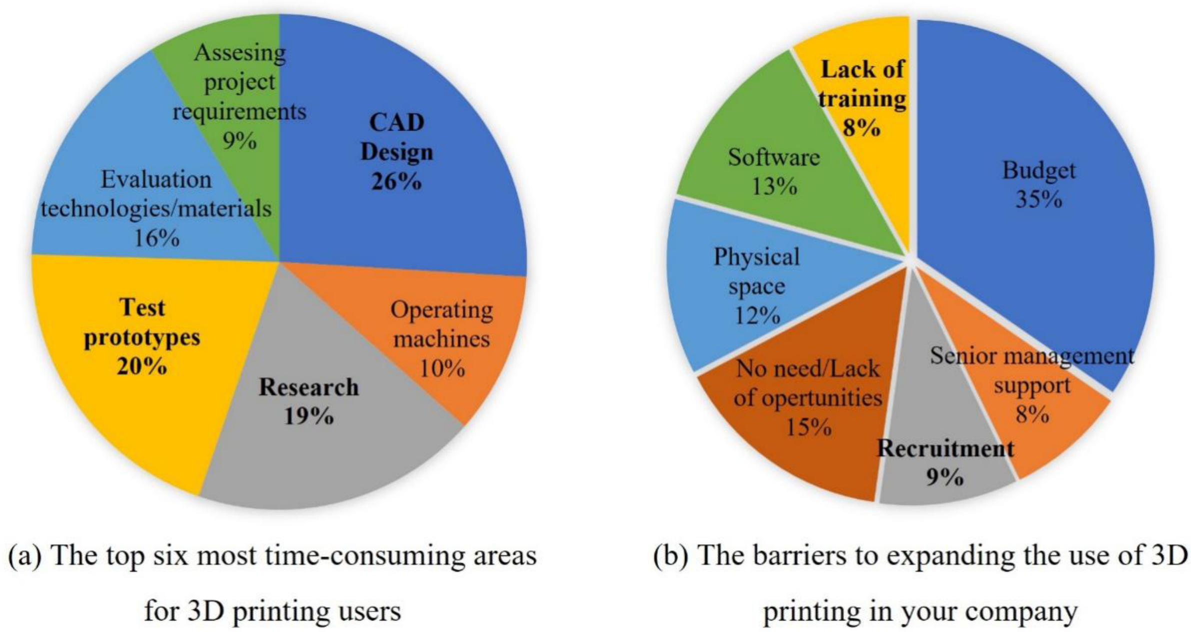

Figure 2. Survey results on the difficulty in using 3D printing (based on results from the state of 3D printing report[8])

2. Review of the current tertiary courses on additive manufacturing

2.1. Development of AM education/training

To meet the requirements of rapid additive manufacturing (AM) development, several AM centres in the United States, Europe, and Singapore with high investments have been established for research, innovation, and educational purposes. For AM courses, teaching materials and methodologies are discussed according to demands of different users (students, industrial partners, and researchers). Due to the insufficient formal AM courses that have conducted survey and shared relevant data, discussions in this review may have limited support from survey-based quantitative analysis.

Various courses focused on AM technologies are integrated into the training curricula, showing a tendency to involve AM in innovative education.[27] At MIT, a 14-week AM course for graduate and advanced undergraduate students, which includes lectures, laboratory sessions, and hands-on projects, is conducted to teach fundamentals and applications of AM, where the end-of-semester feedback from approximate 30 enrolled students reflect preference on design assignments.[27] Especially, some students expressed concern that the term projects were too time-consuming and open-ended for a course setting, while another student further suggested that initial team formation should be more structured to group participants by skillset rather than interest area. Lin *et al.*[28] showed the important effects that innovative education on AM has had on engineering and technological sectors in China, looking at more than 100 universities and colleges that offer specialised or AM-related courses and finding that AM education can improve the overall quality of multidisciplinary subjects. With respect to the contents of current AM-related courses in China, they proposed the following: (1) innovative education should encompass not only coursework but also hands-on experimentation and training opportunities; (2) AM technology can be utilized as effective educational tools by integrating mathematics, physics, chemistry, and computer engineering; (3) increased emphasis should be placed on the development of AM laboratory facilities; and (4) international exchange and collaboration are essential.[28]

Alabi *et al.*[29] proposed a framework to investigate the promotion of both engineering and science sectors through current AM education and research activities at South Africa's universities. In their study, five primary factors that can provide impacts on AM education and research activities, which include AM technology, technology transfer, educational curriculum, in-house facilities, and research and development, have been proposed based on literature review. Subsequently, they designed questionnaires with both closed- and open-ended questions covering the five proposed primary factors and distributed them to 200 participants, accounting for gender, age, degree level, field of study, and AM experience. The survey yielded 130 valid responses, which were used to further evaluate the impact of these factors on AM education. Minetola *et al.*[30] investigated twelve aspects that may positively influence graduate-level learning in computer-aided production (CAP) courses through access to AM devices, designing a survey distributed to over 200 students enrolled in CAP courses at top-tier Italian universities over the previous three years (receiving 82 valid responses). They designed a survey by asking them to respond "yes" or "no" to twelve closed-ended questions and found that all twelve questions received over 60% "yes" answers, where potential to generate new design ideas receive lowest rate of "yes." These questions evaluated the effectiveness of AM prototyping in CAP learning across the following dimensions: (1) increased motivation, (2) better understanding of CAP topics, (3) increased interest in CAP topics, (4) improved teamwork skills, (5) stimulation to learn additional content, (6) enhanced imagination of geometric features, (7) enhanced understanding of assembly processes, (8) better understanding of product functionalities, (9) better understanding of the AM fabrication process, (10) improvement in achieving personal educational objectives, (11) recommendation to use AM tools in other manufacturing-related courses, and (12) potential to generate new design ideas. Feedback from similar questionnaires in other institutions also indicated that AM is a prototyping tool with significant educational benefits in multidisciplinary engineering fields, as well as in improving students' hands-on skills, motivation, creativity, and innovation.[7,31,32]

In summary, AM courses have attracted significant interest among various institutions across different regions not only in engineering education but also across multidisciplinary subjects, where their utilization has shifted from serving as simple prototyping tools to functioning as critical enablers of innovation. However, most research on AM courses, particularly survey-based quantitative analyses, has focused primarily on outcomes from undergraduate or graduate students. Nevertheless, the future development and updating of AM courses should not be driven solely by student demands; other primary users such as researchers and professionals across various engineering fields, whose work heavily depends on AM education and who may contribute to advancing AM techniques, also need to be considered. Under these circumstances, one of the primary objectives of this review, which is providing guidance for and promoting the development of AM courses, requires careful consideration from the perspectives of all primary users. Accordingly, this entails addressing three key questions: what learners want to learn; what content is suitable given their educational backgrounds and the effort they can invest in the learning process; and what content will enable them to benefit most and ultimately equip them to drive future advances in AM techniques and applications within their respective fields, sectors, and roles. Therefore, this review selects and examines typical AM education/training courses in detail across three levels: undergraduate/graduate for students (**section 2.2** and **section 3**), professional for industry partners (**section 2.3**), and cutting-edge for researchers (**section 3**). Course content serves as the analytical core, and teaching methodologies are analyzed in light of the three key questions, with particular attention to the demands of potential users.

2.2. Review of AM courses in undergraduate and graduate programs

At the undergraduate and graduate level, 3D printing technology is mostly accessible through specialised AM courses or AM-supported projects. Based on the information provided in **section 2.1**, practical utilization of AM tools, instead of only virtually introducing AM-related concepts, has become the main trend in the design of AM courses, indicating that the development of innovative AM courses requires at least practical access to AM tools. Therefore, reviews of existing AM courses in this work are limited to those that have concrete AM-based content (*i.e.*, hands-on activities). Table 1 lists courses and projects offered by various universities that incorporate 3D printing technologies into their curricula and feature hands-on activities at the undergraduate and graduate levels. These AM-related courses or projects are divided into two categories: active and passive. The active AM courses are specialised courses that purely focus on AM knowledge and skills, usually lasting for one semester.[27,33-36] The passive courses (*e.g.*, CAP courses, technical drawing courses, and CAD courses) do not directly regard AM as an educational target but mainly utilize AM as a tool for mechanical engineering students conducting their projects.[30,37,38] Such passive courses also spread to fluid mechanics laboratories and mechanics of materials courses that go beyond the CAD-based trainings.[39] In addition, passive courses are also extended to multidisciplinary courses such as digital fashion design[40], arts, biology, and other engineering courses.[41]

In the active courses, teaching activities mostly include class meetings and laboratory sessions. Generally, class meetings are conducted by lecturers, while the specialised lectures are given by industry or academic experts. The transfer of AM technology between academia and industry is facilitated through topic lectures or final projects, which are critical in creating a bridge between training and employment, enhancing the education on engineering content, and helping students benefit from AM training with practical production.[27,34,35] For lab activities, students in most active courses can operate the 3D printer by themselves to prototype their as-designed models. As one of the most typical active courses, Sharma *et al.*[42] designed teaching activities based on the concept of Learners, Users, Manufacturers, Innovators, Operators, and Serviceman (LUMINOS), in which students disassemble existing 3D printers and learn relevant mechanisms first, then suggest improvements, develop and assemble new 3D printers. By calibrating, operating, and modifying processes on their 3D printers, students can achieve high-quality prototypes.[42]

Unlike active courses, passive courses mainly include projects that focus on designs of specific products starting from conceptualization, where 3D printing techniques are commonly adopted as effective tools for prototyping.[27,35,36] In passive courses, models are mainly fabricated with the assistance of laboratory staff, exhibiting insufficient hands-on practice and education in hands-on operational experience.

When focusing on the teaching process, strategies can be classified as problem-based learning (PBL), project-based learning (PjBL)[33], additive experiential learning[35], and multidisciplinary learning[34,37], where PjBL is the most utilised one.[27,30,36,40] In PjBL, students can work in groups to identify or design the products, print parts, assemble them into the product, test them to evaluate performance, and, finally, to re-design, re-print, test, and determine the final products.[27,34] The course-end survey shows the students' satisfaction with the learning process and learning environment when AM is integrated into the curriculum as specialised courses or projects.[34,36]

Currently, universities have widely integrated AM into their programs. AM is, however, not systematically taught yet and few specialised AM courses have been designed. Although access to AM tools has been facilitated in most active AM courses, opportunities for students in passive AM courses to gain hands-on operational experience on AM machines remain very limited. Passive AM courses, which often encompass broader engineering and multidisciplinary subjects, should incorporate greater practical potential to significantly enhance both learning performance and adaptation to current industrial technological transformations. As a prevailing trend in current AM instruction, PjBL has been widely adopted to help students not only master AM-related skills but also grasp their practical applications in engineering

Table 1. Examples of courses and projects integrating AM technologies in training curriculum

No.	Types	Hands-on design	Education techniques	Student number	Duration weeks	Education level	Course	AM method	Hands-on experiences	Sources
1	Active	(1) The bottle opener objects; (2) The door opener for people with Parkinson's disease; (3) The personal connector bracket device	(1) Interdisciplinary PBL learning activities; (2) Student-centred and community-based learning environments	30	14	Students at Afeka Academic College of Engineering (Israel)	Additive Manufacturing	FDM	Design and print, quality testing, re-design, re-print	Stern *et al.*[34]
2	Active	(1) Benchmarking part (resolution, accuracy, or surface finish) (2) Selection parts from interested mechanical consumer product	(1) Problem-based learning (Benchmarking part) (2) Problem-based learning (dissection/selection)			Undergraduate/graduate course at University of Texas at Austin and Virginia Tech		SLS, FDM, PolyJet	(1) Design, build and evaluate; (2) Select product, fabricate models, select the most suitable AM and reproduce	Williams *et al.*[33]
3	Active	Captain's wheel Camshaft Bottle opener and phone stand	Project-based learning	22	A semester	Students at Mercer University School of Engineering	3D Modelling and Rapid Prototyping	FDM	Printing, machining, casting parts to compare methods, reverse engineering, rapid prototyping process from designing, making, marketing, selling	Radharamanan[43]
4	Active	(1) A small bridge having maximum specific strength; (2) Multi-mode AM equipment	Project-based learning	30	15	Graduate and advanced undergraduate level in Mechanical Engineering at MIT	Additive Manufacturing	FDM, SLA	Individual design, print, assemble parts, and construct a specific model, final project for conceptualize, justify, design, and prototype	Go *et al.*[27]
5	Active	Self-designed model	Additive experiential learning model	13-19	11	Bachelor and Master	Digital Fabrication Technologies and Processes	FDM, SLS, SLA	Reflective observation, abstract conceptualization, active experimentation, iterative design, present product as an exhibition	Kempton *et al.*[35]

(*Cont'd...*)

Table 1. (*Continued*)

No.	Types	Hands-on design	Education techniques	Student number	Duration weeks	Education level	Course	AM method	Hands-on experiences	Sources
6	Active	Build open-source 3D printer for improvement	(1) Learners, Users, Manufacturers, Innovators, Operators, and Serviceman (LUMINOS) ecosystem; (2) Action-based learning; (3) Innovative AM Education Methodology			Undergraduate students in Mechanical Engineering, Computer Science, Electronics and Material Science	Construction Project	Open-source FDM	Disassemble an existing 3D printer, suggest improvements, develop new version, build, assemble new 3D printer, operate, calibrate, and modify the 3D printer for fine printing	Sharma *et al.*[42]
7	Passive	Various types of ring, button, pendant, cup, vase and clock	Project-based learning	17	16	Students at the Institutions located in Seoul, South Korea	Digital Fashion Design		Design object using Rhino, render model, creative design, fabricate the objects, final presentation	Kwon *et al.*[40]
8	Passive	1/10 scale model of a downhill bike	Project-based learning			Master at Politecnico di Torino	Computer Aided Production	FDM	Design, build, redesign, and assemble model	Minetola *et al.*[30]
9	Passive	Design balloon powered model car (two model cars)	Empirical study methods	473	12	First year student ETH Zurich	Technical Drawing and CAD course		Design model, assemble printed parts, revise the design based on physical prototype, and test the final fabricated design	Chen *et al.*[38]
10	Passive	Video eye-tracking devices for computer interaction	Multi-disciplinary including (1) Inter-disciplinary PBL learning activities (2) Cooperative learning	50–55	A semester	Master of Science Degree in Mechanical Engineering at the Department of Engineering in Modena (Italy)	Computer-Aided Production (CAP)	SLS	Design, run AM machine to build model, test and assemble devices, evaluate performance, functional test	Gatto *et al.*[37]
11	Passive	Hurdle robot that can jump over an obstacle	Project-based learning of engineering systems	24	4	Students at RMIT university	Project		Functional design and system verification; detail design and component testing	Mo and Tang[36]
12	Passive	Diverse models	CDIO approach		A semester	Different levels of education from undergraduate to graduate students	Advanced Issues in Teaching Design and Manufacturing		Design, assembly, analysis, graphics and render, print objects	Verner and Merksamer[44]

Abbreviations: AM: Additive manufacturing; FDM: Fused deposition modelling; SLA: Stereolithography; SLS: Selective laser sintering.

sectors. However, most existing PjBL courses treat AM techniques merely as the endpoint of projects (*i.e.*, physical prototyping), with insufficient consideration given to the relationship between AM and product design. This concern is reflected in the survey by Minetola *et al.*,[30] where nearly 40% of students believed that integrating AM tools does not provide the potential to generate new design ideas.

2.3. Review of AM training courses for professionals

Several universities and organisations have also organised short- or long-term AM training courses. For technicians, entrepreneurs, and officials, development of AM courses may induce more impacts from industries. Therefore, two typical training courses from MIT (academic) and ASTM International (industrial) for professionals are selected for review in this section. The AM-IDP course is suitable for researchers and professionals pursuing AM careers.[45] The 12-week on-demand course content was released weekly, allowing working professionals to access the learning platform at their convenience. The AM-GPC course is a four-week course with eight modules.[46] A detailed summary of these two courses is shown in Table 2.

The course content of both AM-IDP and AM-GPC is compared in Figure 3. AM-IDP aims at offering a practical AM workflow experience to the participants with a focus on design for AM (DfAM) and its applications. AM-GPC provides practical information for different experience levels. AM-GPC is more theoretically focused, with more advanced post-processing and AM simulation education. In the authors' opinion, AM-IDP is more relevant to working professionals, whereas AM-GPC is more suitable for researchers and academicians. Apart from students getting to know how AM is employed in their respective industries, these classes also generate new ideas. However, the lack of understanding of the AM-enabled design process remains one of the main challenges for further AM uptake by industries. With comparison between AM-IDP and AM-GPC, current professional AM courses lack integration of design, simulation, post-processing, and application.

3. Design-led innovation approach to teaching 3D printing

The concept of the *design-led innovation approach*, which can be regarded as comprehensive teaching framework for 3D printing at research level, refers to the process that starts with conceptualization, followed by a design-driven optimization process, extending all the way to manufacturing and mechanical/structural validation. For students, professionals, and researchers, educational courses must cultivate both core technical competencies, which include modelling, numerical simulation, coding, and design of experiments, as well as advanced knowledge of 3D printing applications relevant to future research. The *design-led innovation approach*, particularly its design-driven optimization process, fulfills these requirements across multiple sectors with extension from mechanical engineering to aerospace, biomedical, and materials science, all of which are profoundly shaped by 3D printing advancements. Through a learning pathway that progresses

Table 2. Summary of AM-IDP and AM-GPC courses

Outline	AM-IDP	AM-GPC
Organiser	MIT, USA	ASTM International, USA
Course duration	12 weeks	4 weeks
Targeted audiences	Working professionals; Researchers	Working professionals; Researchers; Undergraduate students
Prerequisite	Any level of AM experience; Pre-college math and physics preferred; Use of engineering design tools	Any level of AM experience
Course delivery	Virtual on-demand	Real-time webinars; On-demand recorded webinars
Course interactivity	Online forum	Question and answer during real-time webinars
Assessment	Assessments (33%) Assignments (42%) Case studies (25%)	Online exam (100 multiple choice questions)
Passing requirement	60%	70%

Abbreviations: AM-GPC: AM General Personnel Certificate; AM-IDP: AM Innovative Design and Production.

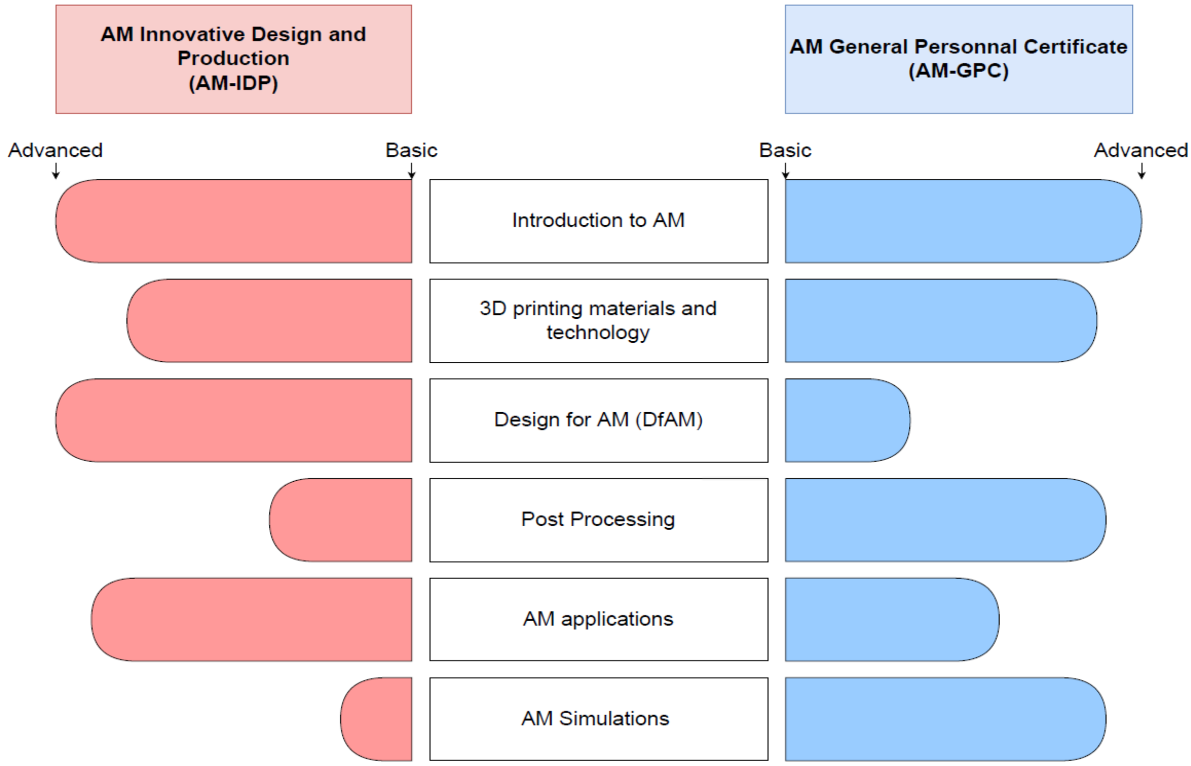

Figure 3. Course content of AM Innovative Design and Production (AM-IDP) and AM General Personnel Certificate (AM-GPC)
Abbreviation: AM: Additive manufacturing

from conceptualization (integrating both knowledge and applications) to design-driven optimization and finally to fabrication and experimental testing, researchers can achieve full proficiency in coding, modelling, simulation, and testing. Consequently, this review concentrates on the educational components of design optimisation, with a detailed focus on problem setup, pre-processing, optimization, post-processing, fabrication, and testing.

In this section, we review various educational codes for design optimisation based on the following metrics: *dependency*, *difficulty*, *flexibility*, and *feasibility*. The *dependency* of these codes is the requirement of access to programming integrated development environments (IDEs) or commercial software. The *difficulty*, which relates to the problem-setting step, is the effort needed for students and researchers to understand and utilise these codes. The *flexibility*, which relates to all the steps except the validation steps (manufacturing and testing), is the ability of these codes to fit different problems. The *feasibility*, which relates to the optimisation and post-process steps, is the capability of these codes to support reasonable design quality and manufacturability.

3.1. Classification of the design optimisation techniques

Design optimisation is often classified by topology, size, and shape optimisation.[47] Among these, topology optimisation[48-52], which can effectively utilise AM's potential for engineering applications, is the main discussion point in this section. The details of theories, techniques, and mathematical backgrounds have been thoroughly documented in many review papers.[53-56] Topology optimisation approaches can be classified as: (1) density-based methods[57-59], (2) level-set methods[60,61], (3) ground structure methods[62,63], and (4) geometric component methods.[64-66] Currently, most educational codes in topology optimisation are based on the classical solid isotropic material with penalisation (SIMP) model (*i.e.*, SIMP to minimize linear compliance).[67-74] There are extensions of SIMP codes to other problems, such as multi-scale design of materials[75] and multi-scale structures[76,77], multi-material structures[51,78,79] with minimal compliance[80], optimised buckling load factor[81], stress-based optimisation[82,83], structural design considering nonlinearity[84,85], and dynamic problems.[86] Educational codes are summarised in Table 3.

Table 3. Summary of educational topology optimisation codes for 3D printing courses

Name	Techniques	Dependency	Difficulty	Flexibility	Feasibility	Dimension
Top99[67]	SIMP	MATLAB	Easy	Low	Low	2D
Top88[68]	SIMP	MATLAB	Easy	Low	Low	2D
PolyTop[69]	SIMP	MATLAB	Hard	Medium	Low	2D
Top3D[70]	SIMP	MATLAB	Easy	Medium	Medium	3D
TOCP[71]	SIMP	SAP2000 (C#)	Medium	Medium	Medium	3D
Top99neo and Top3D125[72]	SIMP	MATLAB	Easy	Medium	High	2D/3D
TopOpt_in_ PETSc[73]	SIMP	PETSc (C++)	Hard	Medium	High	3D
TopADD[74]	SIMP	PETSc (C++)	Hard	High	High	2D/3D
TopX[75] Multi-scale	SIMP Energy-based homogenisation	MATLAB	Easy	Low	Low	2D
ConTop2D and ConTop3D[76] Multi-scale	SIMP Energy-based homogenisation	MATLAB	Medium	Medium	Medium	2D/3D
PolyMat[80] Multi-material	SIMP (multi-material) DMO multi-material interpolation	MATLAB	Hard	Medium	Low	2D
TopBuck250[81] Buckling	SIMP KS aggregation	MATLAB	Medium	Low	Low	2D
PolyStress[82] Stress	SIMP Augmented Lagrangian method	MATLAB	Hard	Medium	Low	2D
To AC[83] Stress	SIMP P-norm stress aggregation	MATLAB	Easy	Medium	Medium	2D/3D
TOGN213[84] Nonlinearity	SIMP Additive hyperelasticity technique	MATLAB ANSYS	Medium	Low	Low	2D
89-line code[85] Nonlinearity	SIMP Stored-energy interpolation	FreeFEM++	Hard	Medium	Low	2D
PolyDyna[86] Dynamics	SIMP HHT-α method	MATLAB	Hard	Medium	Low	2D
DVTOPCRA[87]	SIMP Canonical relaxation algorithm Sequential integer programming	MATLAB	Medium	Low	Low	2D
Tobs101[88]	SIMP Integer linear programming	MATLAB	Medium	Low	Low	2D
BESO[89] Nonlinearity	BESO update Average historical sensitivities	Python ABAQUS	Easy	High	High	3D
SERA[90]	Virtual material SERA algorithm	MATLAB	Easy	Low	Low	2D
DER-BESO[91]	BESO update Dynamic evolution rate strategy Average historical sensitivities	ANSYS	Hard	High	High	2D/3D
TOP_Geo_Non[92] Nonlinearity	BESO update Average historical sensitivities	MATLAB	Easy	Low	Low	2D
Top_level-set[93]	Discrete level-set Hamilton–Jacobi equation Shape sensitivity and topological sensitivity	MATLAB	Hard	Low	Low	2D

(*Cont'd...*)

Table 3. (*Continued*)

Name	Techniques	Dependency	Difficulty	Flexibility	Feasibility	Dimension
FEniCS[94]	Level-set Hamilton–Jacobi equation Distributed shape derivative	FEniCS (Python)	Hard	Low	Low	2D
OpenMDAO[95]	Density-based: SIMP Level-set: Hamilton–Jacobi equation	OpenMDAO	Medium	Low	Low	2D
TOPRBF[96]	Parameterized level-set method Radial basis functions (RBFs)	MATLAB	Easy	Low	Low	2D
Level-set[88,97]	Reaction-diffusion equation Topological sensitivity	MATLAB	Medium	Low	Low	2D
Filter based level-set[98]	Filtered level-set function	MATLAB	Easy	Low	Low	2D
RDE[99]	Filtering function Reaction-diffusion equation SIMP	FreeFEM++	Hard	Low	Low	2D
UNVARTOP[100]	Laplacian regularization filter No material interpolation	MATLAB	Medium	Low	Low	2D
Pareto Optimal Tracing[101]	Topological sensitivity field filter No material interpolation	MATLAB	Medium	Low	Low	2D
GPTO[102]	Regularized Heaviside projection SIMP 3D cylindrical bars	MATLAB	Medium	Medium	High	2D/3D

Abbreviations: BESO: Bi-directional evolutionary structural optimisation; DMO: Discrete material optimisation; KS: Kreisselmeier–Steinhauser; SERA: Sequential element rejection and admission; SIMP: Solid isotropic material with penalisation.

3.2. Evaluation of the education codes for design-led innovation 3D printing course

The process of design optimisation is shown in Figure 4. The first step is the problem setting, where the user needs to set up *optimisation targets*, *design variables*, and *design space*. As Figure 5 shows, the *optimisation target* refers to the design objectives (*e.g.*, minimal structural compliance or specific materials' modulus). The *design variable* relates to geometric features that the users are planning to optimise (*e.g.*, wall thickness, truss diameters, and geometric boundaries of structures). The *design space* is the region where the optimisation happens, which can be a regular shape (*e.g.*, a rectangle) or an arbitrary shape shown in the left part of Figure 5.

As shown in Figure 6, the design space needs to be pre-processed so that the finite element analysis (FEA) can be conducted to obtain design objectives. In the left part of Figure 6, design spaces can be meshed with a structured or unstructured mesh. Most education codes, *e.g.*, the SIMP education codes[67-74], have embedded meshing functions, supporting a grid-like mesh. In the middle of the left part of Figure 6, the meshing flaws resulting from cutting between passive void regions and the grids are shown in the magnification of the red-dashed box, with the red circles showing the breaking of the mesh. One way to overcome such flaws is to apply conformal meshing techniques that can fit arbitrary boundaries. In the work proposed by Talischi *et al.*[69], the polygon mesh is utilised to provide conformal meshing. Another method is to incorporate commercial software with scripts to obtain a conformal mesh; examples of this include SIMP with ANSYS[84], bi-directional evolutionary structural optimisation (BESO) with ABAQUS[89], and BESO with ANSYS.[91]

For the classical minimal compliance problems, it is sufficient to use SIMP codes. These codes are short, clear, and free of complex mathematical background and are, therefore, easy to learn. The relevant resources on SIMP are plentiful and informative due to its popularity. All these features lead to low difficulty. Other codes that support conformal meshing are stronger, but the complexity, readability, and required knowledge also increase, leading to higher difficulty.

The third step is to conduct the optimisation, where the algorithm can update the design at each iteration to minimise the objective without violating constraints. Figure 7 illustrates the minimum-compliance cantilever optimisation with volume constraints. From top to bottom, examples are generated from classical educational codes

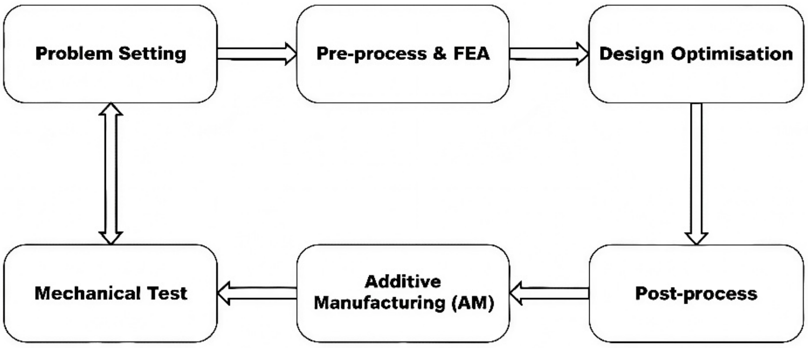

Figure 4. The process of design-led innovation in additive manufacturing
Abbreviation: FEA: Finite element analysis

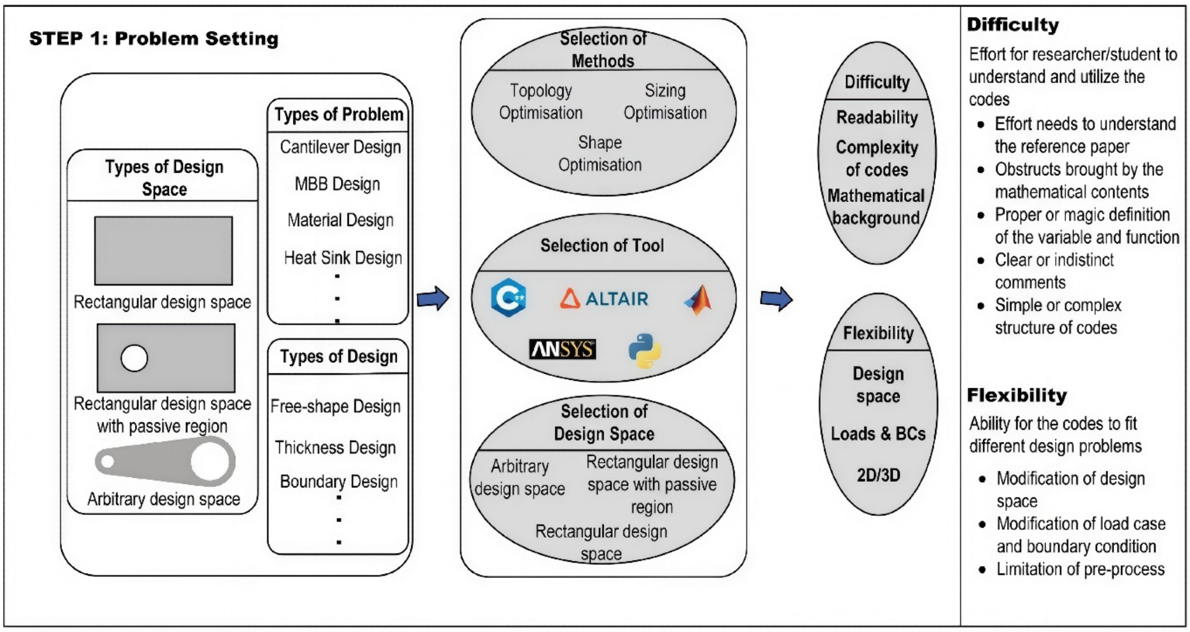

Figure 5. Evaluation of design-led innovation educational optimisation codes in the problem setting
Abbreviation: BC: Boundary conditions

including 2D designs[68], low-resolution 3D designs[70], and high-resolution 3D designs.[72] The setup and the evolution of the design during optimisation are illustrated from left to right.

As the bottom of Figure 7 shows, the high-resolution voxelisation can lead to high-quality mesh, contributing to the capability of fitting arbitrary spaces.[74] As the top part of Figure 7 shows, the 2D codes have significant limitations in flexibility because most real-world problems are in 3D. In the middle part of Figure 7, when the algorithm is extended to 3D with insufficient resolution, the flexibility increases but is still limited for solving large-scale problems. As Figure 8 shows, the optimisation results, which is from post-processing codes[103], are often represented as a density matrix. However, the 3D printer needs G-code as input for manufacturing. In the top part of Figure 8, from left to right, the density matrix commonly needs to be transformed into an .STL file, further smoothed, and sliced into G-code (*i.e.*, post-processing).[103]

The last two steps are fabrication and mechanical tests.[104,105] Figure 9 illustrates the relevant process regarding bracket optimization as examples.[105] The top-right part of Figure 9 shows the manufactured parts via powder bed fusion. Mechanical tests and finite element modelling-based numerical simulations are applied to further validate the structural performance. After evaluating the results,

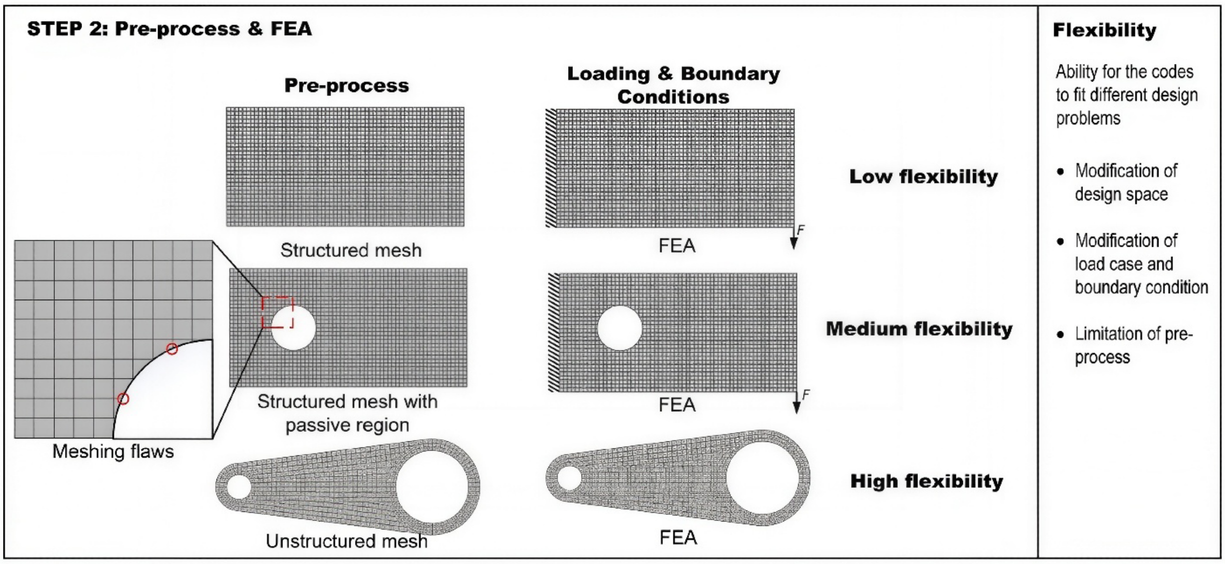

Figure 6. Evaluation of design-led innovation educational optimisation codes in the pre-process
Abbreviation: FEA: Finite element analysis

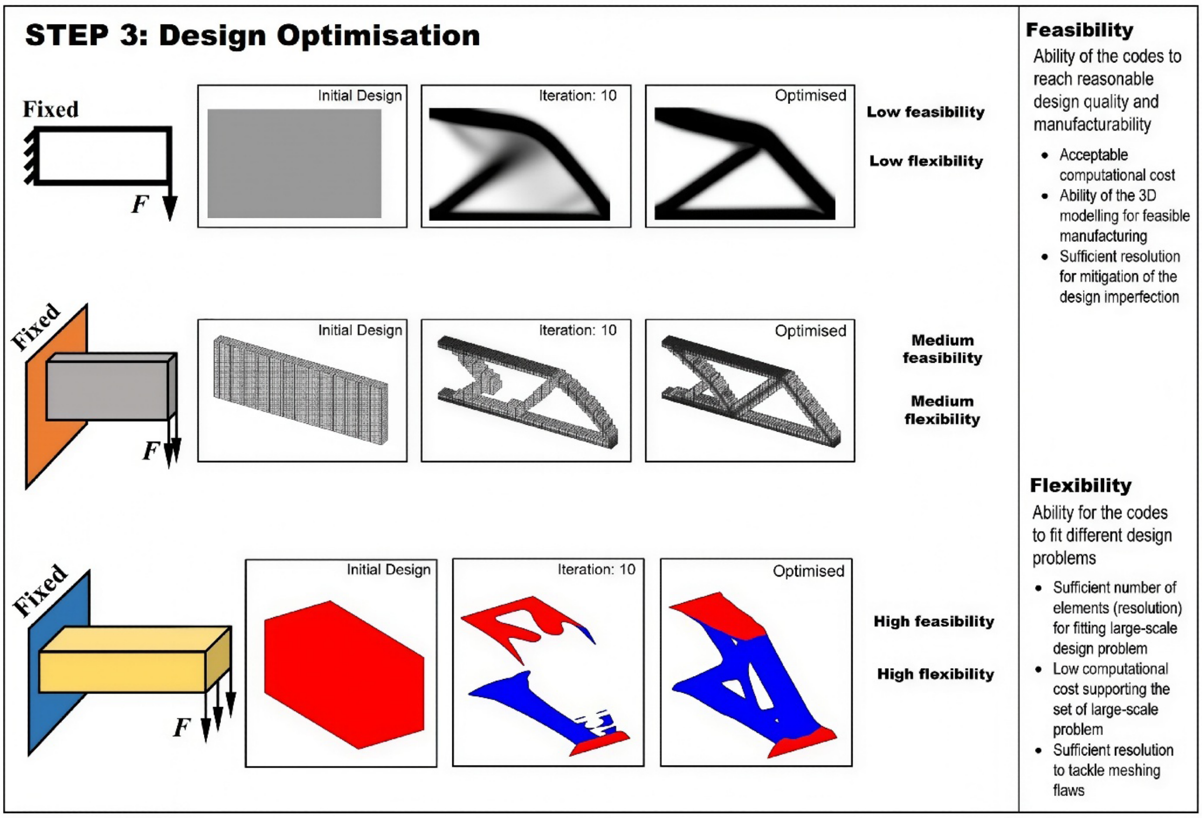

Figure 7. Evaluation of design-led innovation educational codes in design optimisation (results are obtained from design optimization codes[68,70,72])

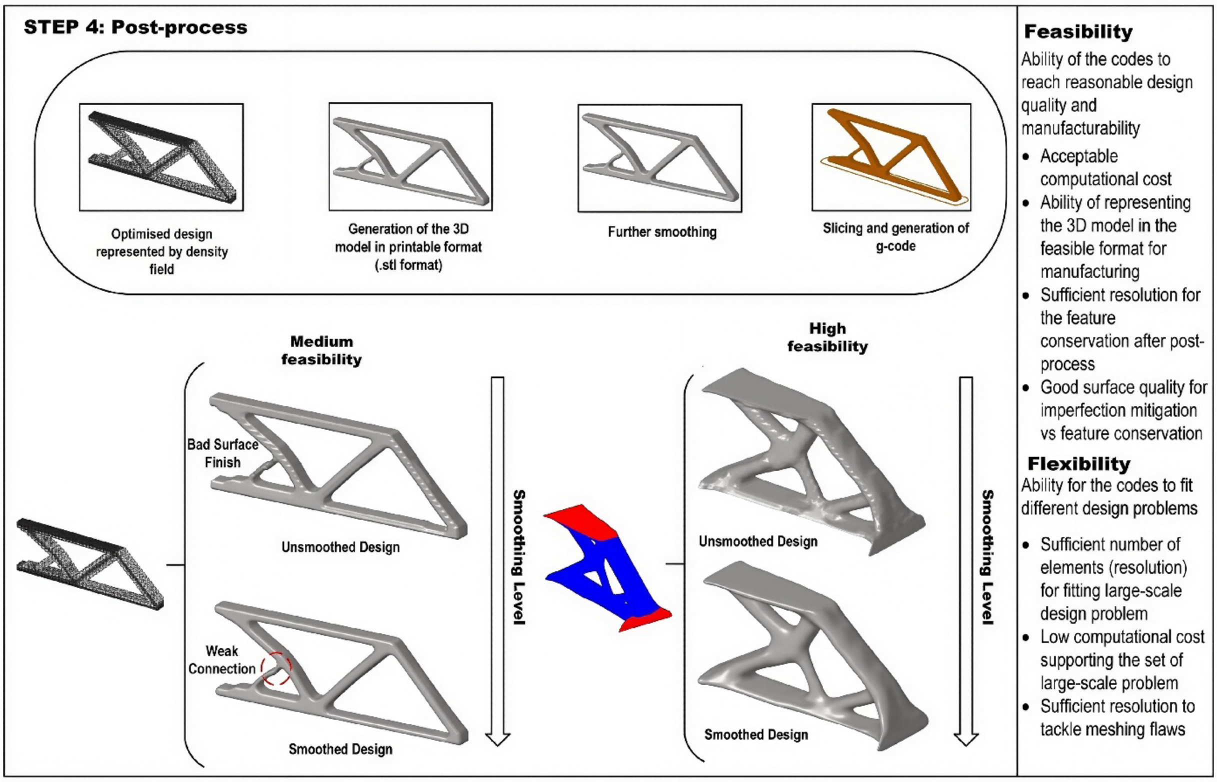

Figure 8. Evaluation of design-led innovation educational optimisation codes in post-process (results are generated from design optimization codes[70,72] and post-processing code[103])

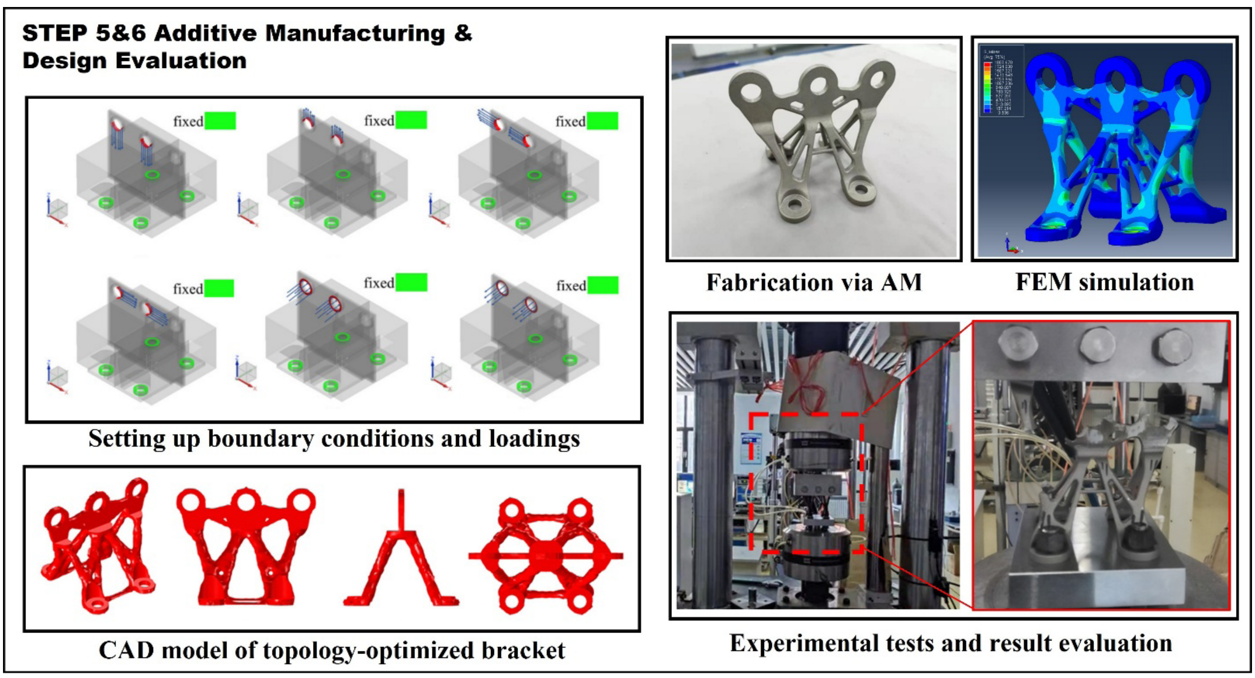

Figure 9. Evaluation of design-led innovation educational optimisation codes on fabrication and mechanical test[105]
Abbreviations: AM: Additive manufacturing; CAD: Computer-aided design; FEM: Finite element method.

modifications can be applied to the problem-setting step according to the feedback. A closed loop, which is shown in Figure 4, can therefore be achieved to obtain the final optimised design that meets all criteria.

The 2D design derived from most of the educational codes cannot directly support a printable format. In the middle part of Figure 7, the insufficient resolution often leads to imperfections such as staircase boundaries. Although adding filters can smooth imperfections, it can lead to weak connections as shown in the red circles at the bottom of Figure 8. When conducting the mechanical tests in Figure 9, the actual performance of parts is much lower than the expectations due to these weak connections, highly limiting the practical application of design-led optimisation approaches. Although plenty of resources have been provided, conflicts between difficulty, flexibility, and feasibility through the design-led optimisation process commonly exist in current educational codes, preventing practical education of design-led optimisation in AM-based programs.

4. A case study on a 3D printing course using design optimisation approach

In an undergraduate course titled *Structural Optimisation and 3D Printing (SO3DP)* conducted at RMIT, the teaching activities and performance of the students illustrate some of the features, merits, and challenges mentioned in the above sections. The 3D printing work was carried out using various 3D printers in the RMIT Advanced Manufacturing Precinct, Civil Lab, and a virtual printing simulation with Unity using virtual reality (VR).

4.1. Course overview

SO3DP covers all aspects an engineer will experience during their daily work-site surveying to acquire information/requirements about the design, developing a problem statement to inform the project, applying design-led procedures (as presented in **section 3**) to obtain an optimal design, preparing digital files, and fabricating parts via 3D printing. The teaching activities follow the process shown in Figures 5–9. As shown in Figure 10, students are given more flexibility to do their assignments by relaxing constraints on optimisation and 3DP tools. Those arrangements offer students sufficient time to master the "*walking before attempting to run*" approach. Those assessments gradually monitor their skills to prepare their designs for 3D printing, transitioning them from a digital model to a scaled model to be printed using a commercially available 3D printer, and a full-scale model to be built onsite through VR.

4.2. SO3DP course evaluation and assessment

4.2.1. Merits and challenges in teaching 3D printing techniques

The merits and challenges in teaching 3D-printing techniques are discussed together with evidence to indicate the effectiveness and ineffective teaching strategies in the 3D printing course using statistic data from the teaching platform Canvas.

SO3DP was attractive to most of the students enrolled in this course, which is reflected in the following comments from students during consultations:

- Rendering the digital model to the construction site is fascinating, and it provides a vision of what the design looks like after it is constructed.
- It was really good to obtain a souvenir of the scaled model of my design.
- It was hard to feel the real scale of my design until I watched them in the virtual model in VR and the full-sized 3D-printed example.
- I did not remember much of what I learned at RMIT, but I still had a vivid scene in my mind when I walked around our designed model with its 3D-printed featured surface.

Students have also experienced some challenges during the coding of design optimisation as they tried to verify and validate their designed models and prepare them for materialisation. Due to budget and space and device limitations, it may not be possible to construct a model similar to existing buildings in this course. Some examples of these sentiments are listed below:

- I cannot find any similar examples to do the innovation design in my assignments.
- I did not expect that there were so many checks to prepare a model for 3D printing.
- It is hard to change the MATLAB code to fit it into my design requirement, and I barely made it through, even with assistance from my teacher.
- It is petty that we could not construct a bigger model in our lab.

These challenges may be resolved with further 3D printing developments and additional support from the university in the form of a larger printer, more lab space, and increased funds to buy more raw materials. It may be helpful if the students' final designs could be supported or adopted by industries who provide 3D printing services as possible demonstration examples virtually or physically.

Figure 10. Overview of assessments for SO3DP (Assignment 1. Optimising a simple bridge from a sketch and render it on site digitally; Assignment 2. Optimising the reinforcement structure to repair the space station and preparing the 3D printing file for a scaled design; Assignment 3. Replacing an existing structure on Earth with an optimal design to be constructed on Mars using virtual 3D printing; Assignment 4. Future perspectives of potential application of structural optimisation and 3D printing).
Abbreviation: SO3DP: Structural Optimisation and 3D Printing.

4.2.2. Effectiveness and ineffective teaching strategies in the 3DP course using statistic data from the teaching platform Canvas

For five years starting in 2019, several strategies have been employed to promote student engagement, satisfaction, and teaching outcomes. Such indicators can be partially reflected by the time spent on learning materials tracked by Canvas, assignment submissions, final marks, and students' feedback. The employed strategies are summarised in Table 4. The effectiveness of these strategies could be partially reflected by the analytical data from Canvas. Based on comments during consultation sessions with students, whether they are satisfied with the employed strategies is also included in Table 4.

The recorded views of the learning materials on Canvas in Figure 11a show that page views occurred more frequently from 2019 to 2021. In all three years, views peaked 1–2 weeks before the due date of each assignment. When more interesting content was included and linked with real-world examples, students tended to spend more time than during other periods of the semester. For the revision of the assignments, if too many changes were involved (as occurred in 2020), students experienced more difficulties in completing their assignments, as illustrated by the submissions in Figure 11b. This aspect is also reflected by the slight decrease in the students' final marks, as illustrated by the mark distribution in Figure 11c. Some new developed technologies such as VR, digital twins, robotic simulations were used in the course to enrich students' learning experience, students had mixed feelings about the maturity of those new technologies. They were interested in those new technologies. However, they experienced some confusion on how to use them in the real world due to lack of access to existing projects, protypes, and demonstration buildings.

In conclusion, it is essential to link the teaching content and assessments to real-world projects so that students can sense the practical meanings of their designs, feel their designs and see the potential of their learning outcomes, and improve their critical thinking and learning outcomes from the course. Progressive changes to learning content and projects used for assessment are necessary to keep pace with the development of 3D printing technology. It is still challenging to employ 3D printing in fabricating/constructing full-scale structures in the current lab environment. A well-organised group design and a link to industry-funded projects are potential solutions to this challenge.

4.3. Future directions: integrating real-world projects into SO3DP

Based on feedback and demands from students enrolled in SO3DP courses, real-world projects can be integrated into SO3DP courses, which can innovate AM education in the future. Due to the continuous challenges in construction of large buildings, a multi-discipline project can be employed to partly resolve the missing of real-world project in the current course delivery. As illustrated in Figure 12a, design-led optimisation approaches can be integrated with heat transfer theory to enhance fluid cooling efficiency on electronics such as antenna.[106] As illustrated in Figure 12b, design-led optimisation approaches can be integrated with 3D scanning data, which is obtained on-site at real-world clinics, to enable customisation of biomedical devices such as ankle-foot orthoses.[107] As illustrated in Figure 12c,

Table 4. Different teaching strategies used in *Structural Optimisation and 3D Printing* (SO3DP) (2019–2021)

Teaching strategies	Starting-ending years	Advantages	Limitations	Y/N
Design completion	2019–2020	Encourage students to complete their assignment with high level	No clear rubrics; Difficult to evaluate innovations	N
Invited lecture by leading researchers	2019	Increase learning depth	Poor attendance	N
Authentic assessment	2019–2021	Encourage student enthusiasm and engagement	Time consuming on developing assignments	Y
Assessment revision	2020–2021	Prevent contract cheating	Time consuming on developing assignments	Y
Introduction to real world competition by NASA	2020–2021	Encourage engagement and attraction	N/A	Y
Individualization of projects for assignment	2020–2021	Prevent contract cheating	Time consuming on marking	Y
Video presentation of projects	2020–2021	Encourage engagement and mutual understanding		Y
Future career recommendation	2020–2021	Lift student satisfaction and course outcome	Students may come back for referees when applying jobs	Y
Invited lectures by industry related speaker	2021	Encourage engagement and mutual understanding		Y
Virtual visualization using VR	2021	Lift student satisfaction and course outcome	Time consuming in learning virtual reality	Y

Notes: As illustrated in the rightmost column, "Y" indicates that most of students are satisfied with the proposed strategy, whereas "N" indicates no remarkable difference from previous setups of the course.

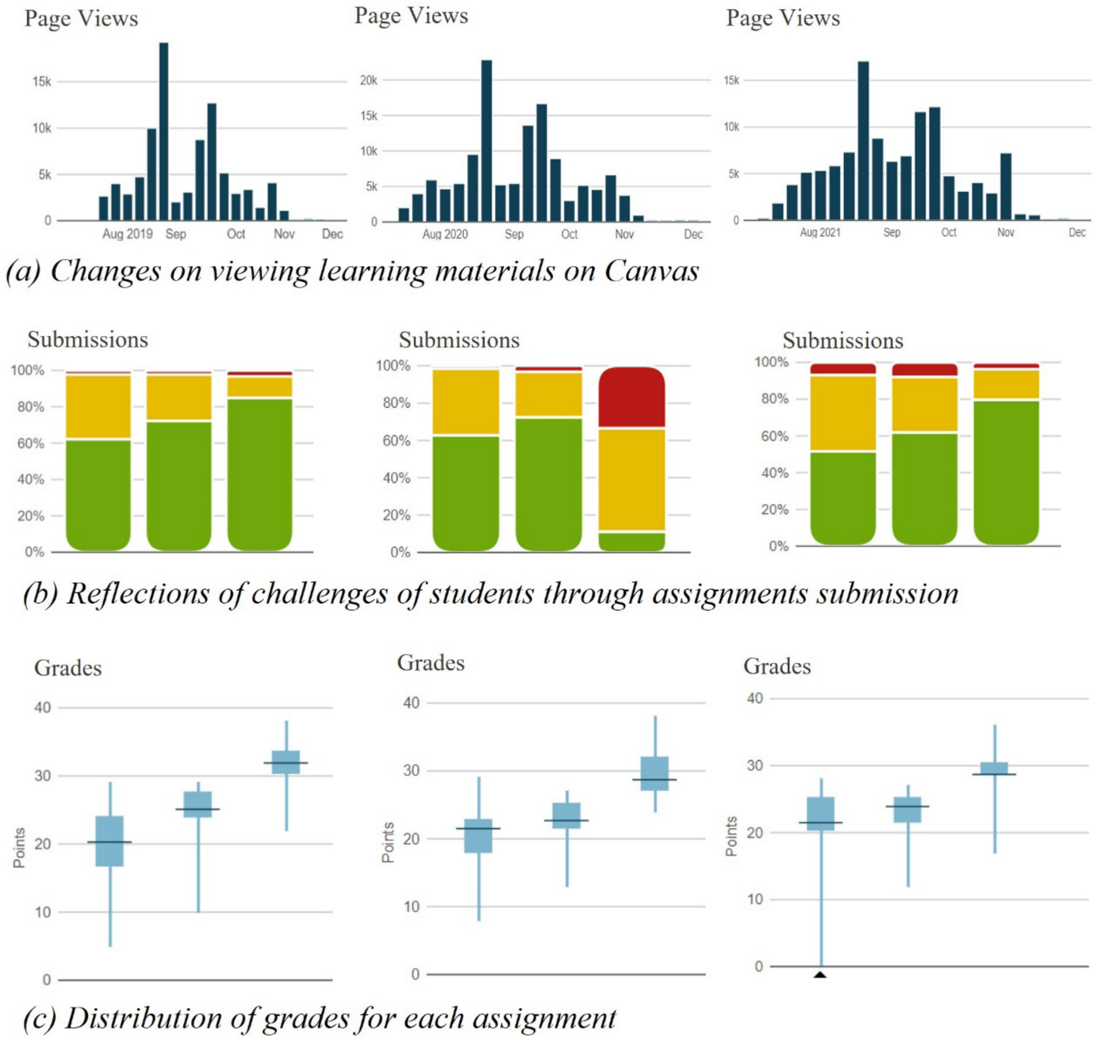

Figure 11. Analytical data from RMIT teaching platform Canvas to reflect the teaching strategies applied in SO3DP in the last three years (2019–2021)
Abbreviations: SO3DP: Structural Optimisation and 3D Printing

design-led optimisation approaches can be integrated with lattice structures to accelerate development of advanced engineering materials.[108] These integrations of real-world applications can inevitably increase creativity, skill levels, and knowledge in AM education across various educational stages, making teaching practices better aligned with the needs of both industry and academia.

For example, integrating design-led optimisation approaches into ankle-foot orthosis applications can contribute not only to a practical understanding of AM's role in the biomedical sector but also to powerful driving forces for innovation. Specifically, as one of the leading medical fields adopting this technology, orthopaedic surgery can be revolutionised by 3D printing in the following ways:

- Patient-specific implants: Traditional implants (*e.g.*, for total hip arthroplasty) come in standard sizes. AM allows surgeons to print custom hip, knee, or cranial implants for complex revision surgeries or severe bone loss. These match the patient's anatomy perfectly.
- Trabecular (porous) structures: AM can print complex, honeycomb-like metal structures (usually titanium) that mimic the porous texture of natural bone. This allows the patient's real bone to grow into the implant (osseointegration), creating a much stronger, longer-lasting bond with better clinical outcomes. Related

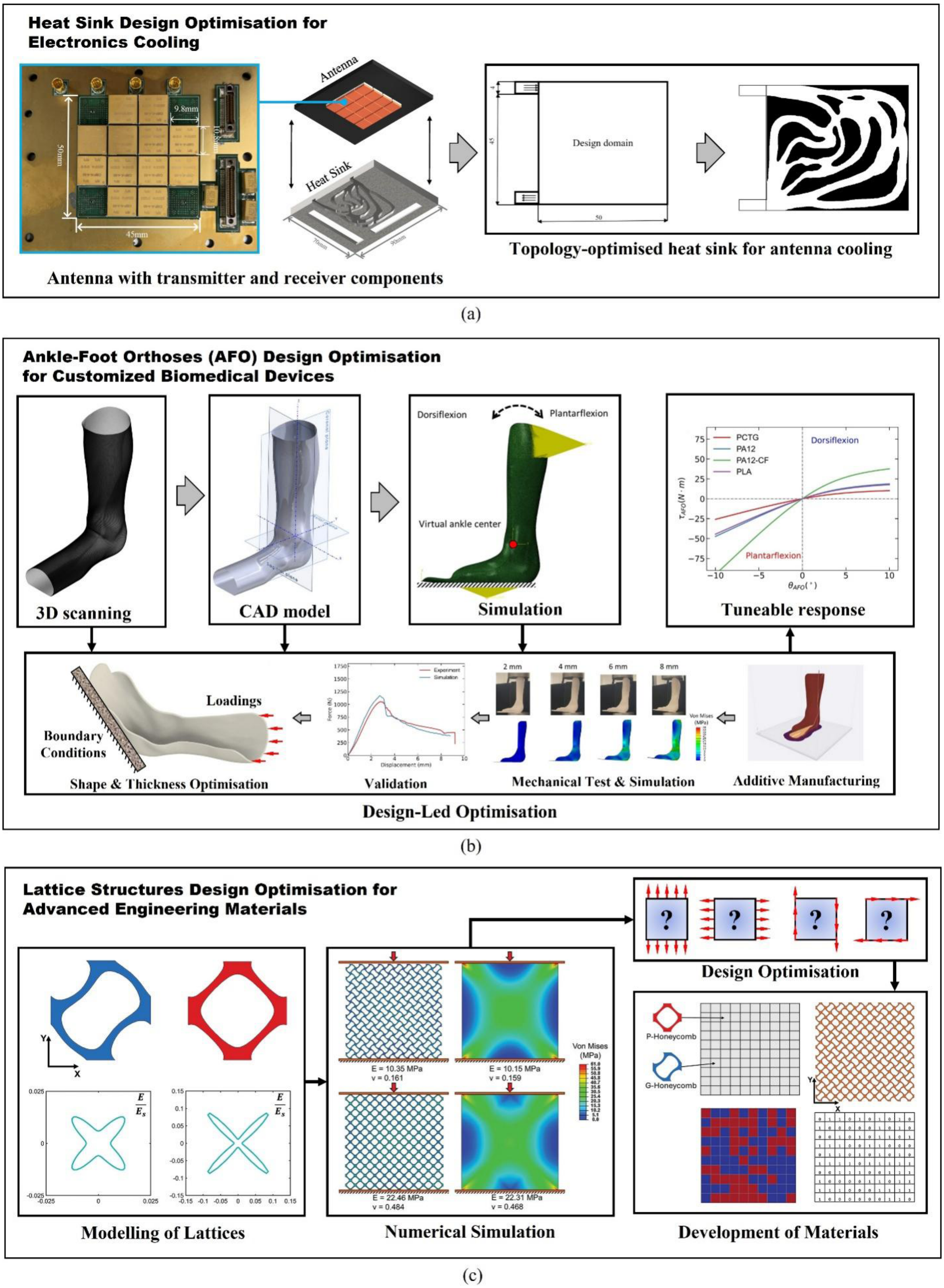

Figure 12. Development of design-led optimisation course by integrating real-world projects: (a) heat sink for electronics cooling[106], (b) ankle-foot orthoses for customized biomedical devices[107], and (c) lattice structures for advanced engineering materials.[108]

healthcare costs could be reduced significantly as well.

- Patient-specific instruments & guides: Before the first incision, surgeons can print custom cutting blocks and drill guides that fit exactly onto the patient's bone. This ensures perfectly accurate alignment during joint replacements and preoperative planning of complex 3D osteotomies/corrections.
- Complex anatomical models: Surgeons print exact 1:1 tactile models of a patient's fractured bone or deformity. They use these to practise the surgery beforehand, significantly reducing anesthesia and operating room time.
- Next-gen prosthetics & orthotics: AM enables the production of highly affordable, lightweight, and custom-ventilated prosthetic limbs and scoliosis braces. This is especially life-changing for growing children who need new prosthetics every few months.
- Point-of-care (PoC) printing: Instead of ordering devices from external manufacturers, hospitals are opening their own in-house 3D printing labs. A surgeon can in house order a custom anatomical model or surgical guide and have it printed on-site within hours.

5. Conclusions

There is a growing number of undergraduate and postgraduate courses offered for AM or 3D printing training to address the shortage of skills and qualified personnel demanded by the industry. Most of the courses introduce fundamental knowledge of AM and 3D printing, focusing mostly on simple CAD design skills and printing techniques. The distinctive benefits of AM/3D printing over the conventional manufacturing approach are not demonstrated effectively. A design-led innovation approach in teaching AM/3D printing was based on the combination of design optimisation programming skills, presented in **section 3**, and the ability to realise the designed/optimised structures. This teaching approach enabled students to develop design-oriented AM frameworks, deepening the understanding of the AM process from initial design concept to validation. However, there are major challenges for teaching 3D printing technology within current education courses:

- Knowledge and skills used in the teaching materials may be out of date in a year or two. Students are usually reluctant to learn information that quickly becomes outdated.
- Education of 3D printing is still costly to print life-sized structures as real practice experience for all students.
- Current educational codes still have conflicts between difficulty, flexibility, and feasibility, preventing practical design-led optimisation in AM-based programs.
- It is still challenging to employ 3D printing for large-scale structures in sectors such as construction and aerospace engineering due to high-cost equipment requiring significant investment and laboratory safety standards.

Future pedagogical strategies to resolve these challenges include grounding curricula in fundamental 3D printing principles to enhance long-term knowledge retention. Furthermore, integrating collaborative fabrication projects linked to real-world industrial applications can significantly elevate student engagement and practical efficacy.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

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