Towards the effective development of Design for Additive Manufacturing (DFAM) curricula: an exploration of strategies and solutions in education

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Abstract. This study investigated the affordances (hindrances and opportunities) of developing a comprehensive Design for Additive Manufacturing (DfAM) curricular product in the South African higher education sector. The methodology consisted of an initial literature review illustrating the use of DfAM in higher education and the existence of formal DfAM curricula. Through the literature, the researchers sought these hindrances and opportunities to guide the development of a curriculum sample product. In addition, appropriate theoretical frameworks were investigated and then combined with pedagogical aids in the form of Embedded Tactile and Sensory Technology (ETaST). The overall theoretical findings indicate that a formally structured DfAM curricular product will benefit not just AM-related subjects, but education fields beyond STEM. This research indicates that a DfAM curricular product may lead to an expansion of AM utilisation beyond mere production initiatives for industry but also as a pedagogical aid product for higher education. Furthermore, the use of such DfAM curricular products can infiltrate broader sectors which will increase the time and uptake of AM. The study recommends the implementation of the DfAM curricular product in the undergraduate sector of various subjects to corroborate the findings.

1 Introduction

Additive Manufacturing (AM) has revolutionised the manufacturing industry by enabling the production of highly customised and intricate products [1]. However, traditional engineering and technology curricula often overlook the specific design and manufacturing skills required for this advanced process [2, 3]. Other fields beyond STEM-based subjects completely ignore AM inclusion. Consequently, this study aims to investigate how to develop a comprehensive and easily accessible Design for Additive Manufacturing (DfAM) curriculum through a co-creative process. By engaging in generative processes, students actively participate in creating alternative forms of knowledge, facilitated by teaching and learning aids known as

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Embedded Tactile and Sensory Technology (ETaSTs) [4]. This investigation serves as the foundation for future lectures, hands-on projects, and case studies once the curriculum is developed. The curriculum product is expected to cover essential concepts such as design topology optimization, generative design, material properties, and process parameters [5]. It will utilise the ETaSTs to enhance the teaching and learning experience (pedagogical practice). The structure of the curriculum product should allow for customisation to align with the specific requirements of different academic subject-matter programmes. The specific modules will address topics including AM material properties and process parameters, ensuring a comprehensive understanding for students.

1.1 Aims

This study aims to provide a comprehensive understanding of the hindrances and opportunities in the development of a DfAM curriculum within an inclusive framework of integrating technology-oriented principles into higher education subject matter. Additionally, this research aims to identify strategies that can enhance the design and implementation of DfAM programmes. By exploring the existing literature, this study seeks to fill gaps and address issues related to DfAM curricula [1–5].

1.2 Objectives

To achieve these aims, several steps will be undertaken. Firstly, a thorough review of the existing literature on DfAM curricula and training components was conducted to identify shortcomings in the current state of development within educational technology (EdTech). This review will serve as the foundation for the subsequent research. Secondly, standardised guidelines will be used to assist in the design and implementation of effective DfAM curricular products in educational programmes. The guidelines will explore hindrances and affordances to develop and include DfAM curricular products. Thereafter create an appropriate framework for educators to ensure that the curricula are comprehensive and aligned with desired learning outcomes.

1.3 Research question

1.3.1 Primary Research Question :

What are the strategies for developing the design and implementation of a DfAM pedagogical curricular product in higher education?

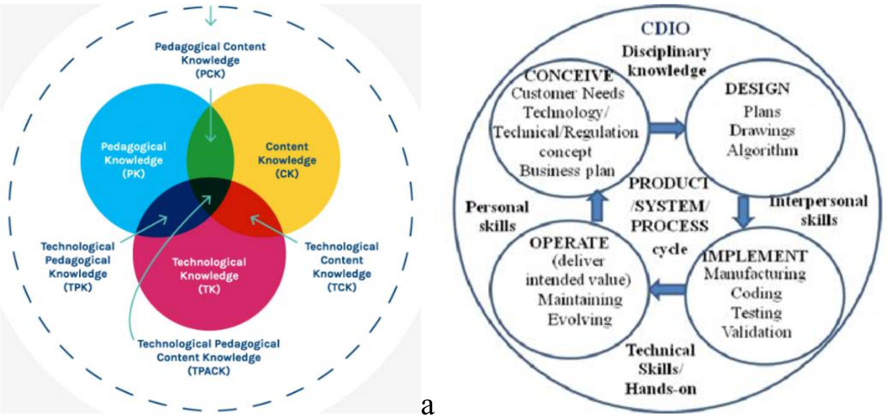
1.3.2 Sub-research Questions :

1) What are the key gaps and issues in the current state of DfAM curricula development in higher education? 2) How can standardised guidelines be utilised to support the design and implementation of effective DfAM curricula? 3) What criteria and metrics can emerge from this investigation to evaluate the effectiveness of DfAM curricula in technological education? 4) Post-investigation: How can access to DfAM technology and equipment be improved to enhance students' hands-on experience, and what are the best practices for doing so?

2 Methodology

The study used a literary investigation to lead to a comprehensive understanding of the opportunities and hindrances in the development of DfAM curricular pedagogical products in the technology-inclusive educational sector. The findings of the literature review were then used to identify strategies for improving the design and implementation of these programmes [6]. This literature also lends an understanding of the present trends seen in DfAM development. To structure the development of the DfAM curricular product, the researchers had to look at an experimental framework to build the content.

The theoretical framework is underpinned by the Technological Pedagogical Content Knowledge (TPACK) and implemented through the Community of Inquiry (COI) models, which promote the development of a DfAM curriculum [7]. When superimposed and combined with ETaSTs' a more accurate design process can emerge to develop such a DfAM curricular product [16-19]. TPACK focuses on the integration of technology into teaching effectively by combining technological knowledge, pedagogical knowledge, and content knowledge (Figure 1a). Integrating ETaST pedagogical aids can create interactive and engaging learning experiences due to the convergence of all the sectors of TPACK. The COI focuses on creating a community of inquiry that fosters deep learning and critical thinking. ETaST enhances this experiential learning experience by providing opportunities for collaborative learning and active engagement (Figure 1b). The combination of TPACK, COI, and ETaSTs, therefore, creates a learning environment that promotes the integration of technology and critical thinking. This allows students to develop the necessary skills and knowledge to succeed in a rapidly evolving technological landscape through the co-creation of their own learning experience.



a b

Fig 1 a) TPACK illustrating the convergence of technology, content and pedagogy in the development of a DfAM curriculum structure.†; b) CDIO model illustrating the experiential learning cyclical procedure to investigate DfAM principles‡.

† Image copied from adopted model in TPACK.org from: https://www.powerschool.com/blog/the-tpack-framework-explained-with-classroom-examples/

Therefore, the TPACK model is the foundation from which all sectors are drawn to converge into a symbiotic state to investigate technology inclusion and curricular development. The CDIO model is then superimposed as an experiential learning process to synthesize pedagogy for DfAM curricular product design experimentation.

This CDIO process is cyclical due to the co-creative nature of the investigation (Figure 1b). Firstly, an idea is "*Conceived*" through the content of the subject, the technology used, and the pedagogy implemented. Secondly, it leads to a *"Design"* stage to create educational technology intervention through DfAM principles. Thirdly, these design principles are tested through an "*implementation"* stage to validate their usefulness. Fourthly, an "*operate"* stage is initialized to maintain the successful delivery of the DfAM process.

2.1 Procedures used during the overall investigation.

The primary literary investigation provided evidence to establish the current state of DfAM in higher education as well as possible ways to create a viable foundation through theoretical frameworks that are superimposed with sensibly constructed pedagogical aids. In this section, we will discuss an overview of the steps used to collect data after the literary investigation (Figure 2), [7], [12-15].

- Procedure one consisted of a literature review to identify hindrances and opportunities (yellow in Figure 2).
- Procedure two investigated relevant frameworks and pedagogical aids that support the development of a DfAM curricular product (orange in Figure 2).
- Procedure three consisted of the construction of a DfAM curriculum product sample to be tested during an investigation (grey and black area in Figure 2).
- Procedure four presents a conclusion of the literary review outcome and suggests appropriate areas of scrutiny in the follow-up study.
- Procedure five will introduce workshops, surveys, iterative redesigning, focus group interviews and final data analysis (during and after post-investigation).
- Procedure six presents preliminary data (during and post-investigation).
- Procedure seven will then construct a final DfAM curriculum document for implementation. (Post this investigation).

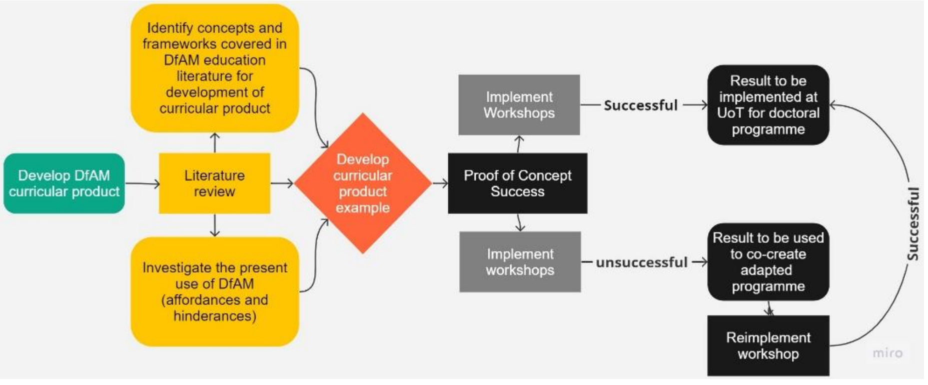


Fig 2 presents the systematic development of a DfAM curriculum product (green, yellow and orange) as well as the suggested practical implementation of it after this investigation (black and grey).

3 Results

The investigation highlights the hindrances and opportunities as it is observed through literary reviews. Subsequently, the investigation then reports an experimental curriculum product to be developed for a DfAM course.

3.1 Hindrances to develop DfAM curriculum pedagogical products

As early as 2017 researchers found that relatively few AM programmes were available as formal curricular and pedagogical products. The main contributing factors appear to indicate systemic lecturing methods and a lack of specialised course development for AM-related programmes such as DfAM [12]. Subsequently, some courses have been developed without academic accreditation leading to restrictions in continued articulation points. Literature and practice indicate that developers choose industry endorsement over qualifying and accreditation for DfAM skills development. [16, 17].

Another hindrance that has been documented, is the use of the correct software to design pedagogical products, such as ETaST aids and is seen as a critical gap to design for specific applications in DfAM curricula [18]. This lack of application becomes even more important when CAD models are constructed for various non-STEM-based subject fields in Higher Education, such as art, law and tourism.

Additionally, some researchers find the development of a DfAM curriculum problematic due to the exorbitant costs of software and hardware. The technology constantly evolves at a rapid pace, making content development complicated for DfAM. Definitions and skillsets required for DfAM from an interdisciplinary perspective have also not been appropriately defined due to the constant developments in AM [19].

Presently, issues with the sustainable practices of AM have been identified across the African continent [20]. The first gap illustrates little to no quantifiable data collection in academic research taking place when DfAM is applied [7]. The second gap identified is that the industry and educational sectors are not yet utilising Smart AM Machinery due to a lack of skills in DfAM. [21]. The third gap points to the lacking use of a formal DfAM curriculum is impairing the remanufacturing and repairing of products, tools and material needs [20, 22].

In South Africa, some research directly links the lack of development of AM-related programmes to influence economic opportunities. In the educational sector, this affects the development of teaching and learning aid products such as ETaSTs [6].

3.2 Opportunities that may advance the development of DfAM curriculum pedagogical products.

Developing DfAM curriculum pedagogical products may offer several advantages that can bridge the gap between higher education and industrial application when considering the inclusion of 4IR (3D printed objects as ETaST) elements into pedagogical practices. These advantages could provide students with practical skills and knowledge that align with the needs of the AM industry [19]. The literature also points to possible academic samples from an ETaST perspective that may support the development of a DfAM curriculum pedagogical product [2, 23].

A DfAM curriculum pedagogical product can provide students with hands-on experience in using AM technologies and tools [24]. By engaging in practical activities, such as designing and printing prototypes, students can develop a deep understanding of the capabilities and limitations of additive manufacturing in real-world applications. This hands-on experience prepares them for the challenges they may face in industrial settings [18].

Additive manufacturing often requires students to think creatively and solve complex design and manufacturing problems. A DfAM curriculum pedagogical product can foster students' problem-solving skills by presenting them with real-world design challenges and encouraging them to develop innovative solutions. Through iterative design processes and feedback loops, students can refine their problem-solving abilities, which are highly valued in industrial contexts [24].

A DfAM curriculum pedagogical product can facilitate collaboration between higher education institutions and the additive manufacturing industry. By incorporating industry guest lectures, case studies, and project partnerships, the curriculum can expose students to the current practices, trends, and challenges faced by professionals in the field. This collaboration enhances the relevance of the curriculum, exposes students to industrial workflows, and enables them to network with potential employers [19].

Additive manufacturing is a multidisciplinary field that requires knowledge in areas such as design, materials science, engineering, and computer-aided design (CAD). A DfAM curriculum pedagogical product can integrate these disciplines, encouraging interdisciplinary learning and collaboration. By working on projects that require expertise from different domains, students can develop a holistic understanding of additive manufacturing and its applications, preparing them for the multidimensional nature of industrial work [22, 25].

Additive manufacturing enables rapid prototyping and iteration, allowing designers and engineers to quickly test and refine their ideas. A DfAM curriculum pedagogical product can emphasize the importance of rapid prototyping and iteration in the design process. By engaging in iterative design projects, students can learn how to quickly generate prototypes, gather feedback, and make iterative improvements. This agile approach aligns with industrial practices and equips students with skills that are valuable in fast-paced manufacturing environments [6, 26].

Additive manufacturing has opened up new possibilities for entrepreneurial ventures, as it enables cost-effective production of customised products and small production runs. A DfAM curriculum pedagogical product can foster an entrepreneurial mindset by encouraging students to explore the entrepreneurial opportunities offered by additive manufacturing. Students can learn about business models, market analysis, and product development strategies specific to additive manufacturing, empowering them to become future innovators and entrepreneurs in the field [20, 24].

3.3 Developing a sample DfAM curriculum pedagogical product

3.3.1 Module 1: Introduction to DfAM Principles and Additive Manufacturing Technologies:

This module explores the understanding of the fundamentals of DfAM principles, exploring various AM technologies and discussing the advantages and limitations of AM for teaching and learning aid product development.

3.3.2 Module 2: Needs Assessment and Ideation

This module investigates conducting a needs assessment to identify subject-specific challenges and learning objectives. Brainstorming and ideation sessions to generate ideas for AM teaching and learning aids that address identified needs. Evaluating the feasibility and potential impact of proposed ideas using DfAM principles.

3.3.3 Module 3: Design Optimisation for Additive Manufacturing

This module focuses on applying DfAM principles to optimise designs, utilising generative design or topology optimisation for efficient teaching aids, and exploring AM-tailored design software tools.

3.3.4 Module 4: Customisation and Personalisation

This module involves incorporating customisation AM features into teaching aids, using parametric design tools for personalized models that cater to individual student needs and learning styles and designing adaptive AM aids for diverse learning needs.

3.3.5 Module 5: Iterative Design and Prototyping

This module focuses on implementing rapid prototyping and iteration processes with AM, creating prototypes of teaching aids for feedback, and refining designs based on feedback to enhance functionality, effectiveness, and usability.

3.3.6 Module 6: Multi-Sensory and Interactive Learning Aids

This module investigates designing teaching aids with multi-sensory elements for enhanced student engagement and understanding, integrating visual, and tactile elements. It further explores the use of embedded sensory elements, movable parts, or modular components for interactive teaching aids.

3.3.7 Module 7: Collaborative Design and Co-Creation

This module focuses on fostering collaboration and co-creation within AM educational environments. This involves promoting active engagement by involving educators, students, and stakeholders in the design and development of AM teaching aids. Furthermore, the module emphasizes integrating feedback and ideas from diverse perspectives to enhance the effectiveness and engagement levels of the teaching aids.

3.3.8 Module 8: Project Management and Production Planning

Developing project management skills specific to DfAM teaching aids product development. Creating production plans, considering factors such as material selection, cost analysis, and time constraints. Exploring partnerships with local manufacturers, Makerspaces, or 3D printing facilities to aid production. Learn techniques for breaking down a project into manageable tasks and assigning responsibilities to team members.

3.3.9 Module 9: Evaluation and Assessment of Teaching Aid Products

Focus is placed on evaluating teaching and learning aids through user surveys and qualitative feedback to assess impact. It emphasizes an iterative approach, refining aids based on evaluation results for continuous improvement in their educational value.

4 Conclusion

The DfAM curriculum product example developed in this study is vital for equipping students with skills crucial for application-specific design, enhancing competitiveness in modern manufacturing. Its adaptability makes it a valuable resource for diverse education programmes, making it a valuable tool for educators seeking to incorporate DfAM principles. It also reshapes education by integrating DfAM into technological models. Additionally, the literature indicates that this integration fosters deeper generative learning experiences, addressing a current gap in education.

The DfAM curriculum product principles not only bridge gaps in AM education but also enable the creation of subject-specific teaching aids across disciplines like art, law, and tourism. Integrating DfAM principles stimulates hands-on learning, encourages interdisciplinary collaboration, and fosters innovative problem-solving skills in students.

The study suggests piloting the proposed curriculum through workshops and surveys, as depicted in the methodology flowchart (Figure 1). A subsequent investigation should identify effective assessment methods for evaluating DfAM curricula in higher education subjects. These assessments could then enable educators to gauge impact, fostering continuous improvement. Additionally, a follow-up study should explore strategies to improve student access to DfAM technology and integration into existing technological education models, enhancing hands-on DfAM-related education.

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