GENERATIVE DESIGN AND ADDITIVE MANUFACTURING IN ASSISTIVE DEVICES: EDUCATIONAL STRATEGIES FOR HUMAN-CENTRED SOLUTIONS

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ABSTRACT
This paper explores how Generative Design (GD), Additive Manufacturing (AM), and multi-stakeholder design approaches can inform engineering education for assistive technology innovation. Drawing on two research projects DIGICLAP and PREMIER, it analyses how these methods support the development of adaptive, personalised, and user-centred devices. The study identifies critical gaps in current curricula, particularly in co-design practice, Product–Service System (PSS) thinking, and the application of feedback-driven design. Based on these insights, it proposes targeted educational strategies that integrate GD, AM, and stakeholder collaboration into project-based and interdisciplinary learning environments. These findings contribute to ongoing efforts to align engineering education with the complex, evolving demands of human-centred assistive device design.

Keywords: Generative design, additive manufacturing, Human-Centred Design, assistive devices, engineering education

1 INTRODUCTION
Assistive devices play a critical role in enhancing mobility and quality of life for individuals with physical impairments. However, traditional design and manufacturing methods often result in solutions that are expensive, slow to develop, and poorly adapted to users' evolving needs [1]. These limitations can lead to reduced usability, emotional disengagement, and abandonment of the device.

Generative Design (GD) and Additive Manufacturing (AM) offer promising alternatives by enabling the development of highly customised, lightweight, and efficient assistive technologies. Together, they allow for greater adaptability and more inclusive, user-centred design solutions.

While GD and AM can improve the design of assistive devices, current engineering curricula often lack sufficient exposure to these technologies, along with training in multi-stakeholder collaboration, leaving graduates underprepared for this emerging field [2].

This paper explores the intersection of GD, AM, and engineering education by analysing two case studies, PREMIER [3] and DIGICLAP [4] that demonstrate the potential of these technologies in assistive device development. These projects serve not only as technical exemplars but also as pedagogical tools to evaluate current gaps in design education. By examining how real time feedback, emotional engagement, and user participation are integrated into these devices, the paper highlights the need to modernise engineering curricula. In doing so, it advocates for interdisciplinary, practice based educational strategies that better equip future engineers to create adaptive, human-centred technologies.

2 BACKGROUNDS
As assistive device design shifts toward greater personalisation and emotional relevance, emerging engineering tools must evolve in tandem. GD and AM are increasingly vital in enabling this transformation, particularly for bespoke prosthetics and smart wearables.

2.1 Assistive Devices and Human-Centred Design
Traditional assistive devices, including prosthetics and orthoses, often fall short in addressing the diverse and evolving needs of users. Their static, one-size-fits-all nature can result in poor ergonomics, discomfort, or stigma-related rejection [1].

The integration of the Internet of Medical Things (IoMT) into biomedical design offers a shift toward dynamic, user-responsive devices [5]. For example, IoMT-enabled orthotic braces driven by AI-generated parametric designs can adjust in real-time via cloud-based sensor data, enhancing fit and function.

At the heart of this innovation is human-centred design, which prioritises emotional acceptance, social integration, and co-creation. Participatory design approaches, where users, caregivers, and clinicians co-develop the device, have been shown to improve therapeutic compliance and reduce stigma [1][5]. Real-time feedback loops play a crucial role in aligning technical performance with user experience. Sensor-embedded wearables allow for continuous adjustment of pressure, alignment, or stiffness, based on live biomechanical data [6]. This shift calls for engineers to engage with psychosocial and ergonomic considerations alongside mechanical ones, a skillset still largely missing from current educational models.

2.2 Generative Design and Additive Manufacturing

GD and AM have redefined what is technically and creatively possible in assistive technology. GD uses AI algorithms to generate and optimise designs based on functional constraints such as weight, material use, and stress distribution, enabling customised geometries that enhance performance and aesthetics [1][5]. AM, or 3D printing, complements this by producing these geometries in layers, enabling fast iteration, on-demand manufacturing, and low volume custom production.

However, manufacturability challenges remain, AM demands careful material selection, orientation, and post-processing, particularly with high-strength or medical grade materials. Design for Additive Manufacturing (DfAM) principles, minimising unsupported spans, optimising print orientation, and accommodating shrinkage must be understood alongside GD techniques. Yet these principles are rarely addressed in undergraduate curricula. Despite GD and AM's growing role in biomedical design, students often lack access to tools like topology optimisation or simulation led workflows. The gap between industry capabilities and academic practice is widening, especially regarding performance-based design integrated with emotional and ergonomic sensitivity [2].

2.3 Challenges in Engineering Education

The adoption of GD and AM in assistive device design exposes a critical lag in educational preparation. Current programmes remain heavily reliant on traditional CAD, manual modelling, and fabrication skills, with insufficient exposure to generative workflows, design automation, or simulation led design thinking [6][7]. As a result, graduates are ill-prepared to design adaptive, user-centred devices that meet the complex physical and emotional needs of patients.

A further gap lies in the neglect of human-centred methodologies in engineering pedagogy. While students may learn how to optimise structures, few are taught to co-design with users or integrate feedback from stakeholders. The absence of cross disciplinary engagement, such as with physiotherapists, occupational therapists, and prosthetists, limits students' ability to create usable, accepted devices [8]. Moreover, DfAM principles are rarely taught in depth, leaving future engineers unaware of critical constraints such as print orientation, stress gradients, or build failures [9].

3 METHODOLOGIES

This paper draws on two research projects PREMIER and DIGICLAP that demonstrate how GD, AM and a co-design approach support the development of assistive devices. Both projects, conducted at the University of Malta (2021–2024), involved interdisciplinary collaboration across engineering, healthcare, and design. While differing in user group and application, they share a focus on personalisation, emotional engagement, and adaptive design. Used here as pedagogical models, the cases highlight educational gaps through stakeholder informed prototyping and observational evaluation.

3.1 Case 1: Designing of a Smart Wearable

DIGICLAP by SMARTCLAP is a wearable assistive device designed for children aged 6–10 living with upper limb motor impairments such as cerebral palsy. The project employed a multi-stakeholder co-design process involving three occupational therapists, six parents, and six children who contributed insights throughout the development.

GD algorithms were used to generate lightweight Voronoi structures optimised for ergonomics and aesthetic appeal, while AM facilitated custom fit and iterative functional testing. Emotional acceptance was a core design goal, addressed through visual customisation and tactile comfort [4]. Observations from therapists and parents underscored the value of user-centred design in meeting both technical and psychosocial needs [4] [10]. As a case study, DIGICLAP demonstrates how GD and AM can elevate assistive device engineering and serves as a pedagogical model for integrating empathy, interdisciplinary collaboration, and advanced design tools into engineering education [10].

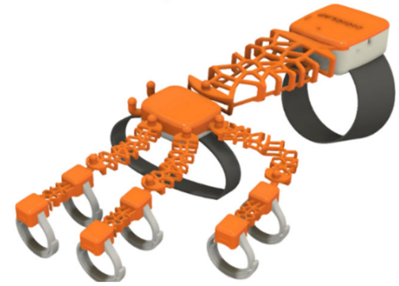
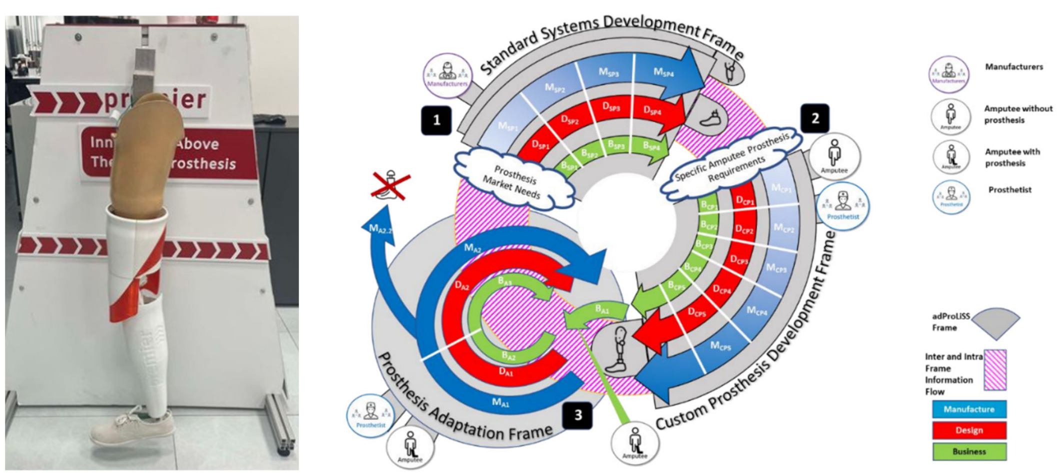


Figure 1. DIGICLAP Smart Wearable

3.2 Case 2: Prosthesis Design and Development

The PREMIER project implemented the adProLiSS framework, an Adaptive and Prescriptive Prosthesis Life Service System (figure 2), as a model for designing and evolving smart prosthetic devices. This model offers a Product–Service System (PSS) approach structured into three interconnected frames: the Standard Systems Development Frame, the Custom Prosthesis Development Frame, and the Prosthesis Adaptation Frame [3]. Each frame coordinates different stakeholders to support prosthesis design across its lifecycle. PREMIER operationalised the Prosthesis Adaptation Frame, which centres on collecting real-time biomechanical and sensor data and processing this information through a digital twin. This enables continuous monitoring and configuration of the prosthesis, ensuring that it adapts to evolving user needs. The digital twin serves as a shared interface where different stakeholders can collaboratively analyse performance data and initiate design changes. From an educational standpoint, the PREMIER project demonstrates the value of teaching engineers to work within stakeholder driven, feedback-informed service ecosystems.

The adProLiSS framework exposes key educational needs, the ability to interpret multi-source input data, to model adaptive design solutions using generative design tools and to understand how real-world service systems evolve through continuous user interaction [3] [11].



(a) *(b)*

Figure 2. PREMIER prosthetic (a) and the adProLiss Framework (b) [3]

3.3 Comparative Insights

DIGICLAP and PREMIER embody complementary paradigms in assistive technology. The former emphasises a multi-stakeholder approach and emotional engagement, while the latter focuses on lifecycle adaptability through embedded intelligence. Together, they illuminate overlooked dimensions in engineering education, particularly the challenge of designing for sustained use, adaptation, and psychosocial relevance.

DIGICLAP demonstrates how generative design, and additive manufacturing can yield emotionally and ergonomically attuned solutions through stakeholder involvement. In contrast, PREMIER showcases how data-driven service ecosystems support the ongoing evolution of prosthetic devices. These cases affirm that successful assistive design is not merely technical or clinical; it is a dynamic, user-sensitive process shaped by lived experiences and contextual constraints.

4 FINDINGS AND DISCUSSION

The DIGICLAP and PREMIER projects offer valuable case-based insights into how engineering education can evolve to meet the demands of human-centred assistive device development. This section discusses the educational challenges identified through the projects, proposes targeted strategies for curriculum reform, and explores how concepts such as continuous adaptation and Product–Service Systems (PSS) thinking can inform the future of engineering design education

4.1 Educational Challenges and Skills Gap

The development processes observed in the DIGICLAP and PREMIER projects reveal significant educational shortcomings in how future engineers are prepared to work on adaptive assistive technologies. Despite the increasing relevance of GD, AM, and PSS, many engineering programmes continue to prioritise traditional CAD modelling and static product-based methodologies.

This has left students underprepared to engage with emerging design processes that rely on topology optimisation, parameter-driven modelling, and iterative prototyping [12].

One major gap involves the integration of real-time feedback mechanisms into the design process. In the PREMIER project, for instance, the adProLiSS framework relies on embedded sensors that track pressure distribution and gait dynamics over time. This data is used to inform continuous prosthesis adaptation through a digital twin. However, such data driven design cycles require engineers to interpret feedback from clinical settings and translate it into generative constraints. The challenge is not just technical but also communicative, engineers must coordinate with prosthetists and other health professionals to evaluate, prioritise, and act upon user data [13].

Additionally, both case studies highlight the absence of training in co-design methodologies. DIGICLAP, for example, demonstrated the critical role of the user and therapist's input in shaping the wearable’s form and function. Yet, few programmes equip students with frameworks for engaging non-technical stakeholders in meaningful design dialogue. This leads to misalignments between clinical needs and engineering solutions, limiting device acceptance and effectiveness.

Finally, interdisciplinary integration remains a persistent challenge. Developing adaptive assistive devices demands expertise that spans biomechanics, materials engineering, user experience, and data processing.

However, students are rarely exposed to this kind of collaborative environment, nor are they trained to navigate the tensions between clinical expectations, technical feasibility, and user emotion.

Without structured exposure to real-world complexity, graduates often struggle to translate their skills into socially responsive innovation [13].

4.2 Proposed Education Strategies

To prepare future engineers for the complexity of assistive technology design, engineering curricula must undergo a structural shift from traditional, discipline bound instruction to approaches that prioritise adaptability, user experience, and advanced digital tooling. While many programmes introduce CAD and prototyping fundamentals, few offer sustained exposure to design processes that incorporate real-time data, collaborative iteration, or the emotional dimensions of use. Addressing these gaps requires embedding educational strategies that mirror the complexity of real-world contexts.

One emerging initiative that exemplifies this shift is the EDUWEAR project [14], which develops an e-learning platform paired with hands-on modules for designing customisable rehabilitation wearables.

EDUWEAR emphasises systems thinking, simulation-based feedback, and integration between engineering and healthcare disciplines. Such projects serve as a scaffold for rethinking how generative and additive design tools are introduced, not as niche electives, but as core competencies.

Building on this model, engineering programmes could implement project-based learning modules centred on open-ended, evolving design briefs. Rather than fixed exams, students could engage in tasks where assistive products must adapt over time, such as adjusting material properties, pressure zones, or structural configurations based on changing usage patterns or patient feedback. These tasks would require learners to simulate the interaction between digital twins and physical prototypes, aligning design decisions with long-term device use and lifecycle thinking [15].

In parallel, co-creation simulation environments could be embedded within design studios or final-year projects. Here, students would engage in dialogues with different stakeholders such as professors, design specialists and assistive device users whose feedback would directly inform iterative changes. Emphasis would be placed not on solving a static problem, but on negotiating between competing user needs, therapeutic goals, and technical constraints. This structure would foster a more reflective design process and prepare students to operate across disciplinary boundaries.

Crucially, these innovations must be supported by assessment models that reflect the iterative, collaborative, and adaptive nature of assistive device development. Rather than relying on end of term deliverables alone, assessment could include reflective journals documenting design rationale, feedback integration, and ethical dilemmas encountered. Peer and stakeholder critique sessions could be used to evaluate interpersonal and communicative competencies, while performance in simulations could be assessed through structured rubrics that measure responsiveness to changing constraints.

In addition, faculty development is essential. Educators themselves must be equipped with tools and training to guide students through interdisciplinary design, navigate feedback loops, and supervise projects involving complex user scenarios. Institutions could support this through cross-faculty workshops or co-teaching arrangements with clinicians and rehabilitation specialists [16].

Ultimately, reforming engineering education for the assistive technology context is not simply a matter of inserting new content, it requires a paradigm shift toward learning environments that model complexity, prioritise user experience, and reward responsiveness. By embedding such strategies within the curriculum, engineering graduates will be better prepared to design devices that are not only technically robust, but truly adaptive, inclusive, and emotionally resonant.

4.3 Human-Centred Product-Service System (PSS) and Continuous Adaptation

Both PREMIER and DIGICLAP illustrate the need for real-time user feedback to ensure assistive devices remain adaptive and relevant throughout their lifecycle. Traditional technologies often fail to meet evolving user needs, leading to functional obsolescence or emotional disengagement. In contrast, the PSS approach supports continuous reconfiguration and personalisation through iterative feedback loops [3][10].

Emerging AI-driven design tools expand this potential further. By linking machine learning algorithms with GD procedures and sensor-based biomechanics tracking, assistive devices can be refined dynamically anticipating user needs and suggesting design adjustments to enhance comfort, usability, and durability. These systems shift the paradigm from static, one-off designs to lifelong adaptive solutions. For engineering education, this evolution necessitates a new set of curricular priorities. Students must not only learn how to develop functional products, but also how to design adaptive systems that integrate sensor data, machine learning, and feedback informed iteration.

Embedding such capabilities into educational frameworks through simulation projects, AI-assisted design studios, or digital twin modelling exercises can help prepare graduates for the next generation of intelligent assistive technologies.

5 CONCLUSION AND FUTURE WORK

This paper examined how GD, AM, and multi-stakeholder design can modernise and improve engineering education for human-centred innovation. The case studies demonstrate that combining GD and AM with iterative, stakeholder-informed processes enables the development of adaptive, personalised, and emotionally acceptable assistive devices. These findings highlight the importance of equipping future engineers with the skills and mindsets necessary to design not only functional products, but also responsive systems that evolve over time.

The study identified critical gaps in current curricula, particularly the limited integration of real-time feedback, PSS thinking, and structured co-design practices. Although some progress has been made in teaching AM and DfAM, the systematic application of GD and adaptive design methodologies remains inconsistent across programmes. To address this, the paper proposes targeted educational strategies grounded in the case findings, including project-based learning centred on PSS frameworks and interdisciplinary simulation modules for stakeholder engagement.

Future research should explore scalable implementations of these strategies across institutional contexts, as well as the potential of emerging AI-driven design tools to support the lifelong adaptability of assistive devices. By embedding generative, additive, and human-centred methods into engineering education, curricula can be aligned more closely with the evolving demands of assistive technology design bridging the gap between academic training and real-world innovation.

REFERENCES

[1] Thorsen R., Cugnod D., Ramella M., Converti R. M. and Ferrarin M. From patient to maker - a workflow including people with cerebral palsy in co-creating assistive devices using 3D printing technologies. *Disability and Rehabilitation: Assistive Technology*, pp. 1–11, Mar. 2023

[2] Go J. and Hart A. J. A framework for teaching the fundamentals of additive manufacturing and enabling rapid innovation. *Additive Manufacturing*, vol. 10, pp. 76–87, Apr. 2016.

[3] Bonello M., Buhagiar N., Farrugia P. and Mercieca J. Unveiling the impact of the SMARTCLAP project on habilitation. *Computational and Structural Biotechnology Journal*, vol. 24, pp. 451–463, Jun. 2024.

[4] Patiniott N. *et al.* Towards a Product Service System Framework for Lower Limb Prosthetic Devices. *Proceedings of the Design Society*, vol. 2, pp. 1341–1350, May 2022.

[5] Mouanda G. Comprehensive up-to-date impact of the IoMT in healthcare and patients. *Health Informatics - An International Journal (HIIJ)*, vol. 13, no. 3, 2024.

[6] Gherardini F., Petruccioli A., Dalpadulo E., Bettelli V., Mascia M. T. and Leali F. A Methodological Approach for the Design of Inclusive Assistive Devices by Integrating Co-design and Additive Manufacturing Technologies. *Advances in Intelligent Systems and Computing*, pp. 816–822, 2020.

[7] Coulthard J. and Wang C. Generative Design and Topology Optimisation of Products for Additive Manufacturing. Nov 2022.

[8] Ponsa P. Human Factors and Ergonomics in Engineering Curricula. *Journal of Ergonomics*, vol. 02, no. 02, 2012.

[9] Residual stress in AM can cause major build failures: How to prevent it. *Metal Additive Manufacturing*, Dec. 01, 2018.

[10] Bonello M. and Farrugia P. Towards a multi-perspective based ontology to develop smart wearables for paediatric habilitation. *Um.edu.mt*, 2023.

[11] Patiniott N. *et al.* Elements of a Prescriptive and Adaptive Prosthesis Development Service Framework. *Proceedings of the Design Society*, vol. 3, pp. 1605–1614, Jun. 2023.

[12] Borgianni Y., Pradel P., Berni A., Obi M. and Bibb R. An investigation into the current state of education in Design for Additive Manufacturing. *Journal of Engineering Design*, vol. 33, no. 7, pp. 461–490, Jul. 2022.

[13] Aflatoony L. and Lee S. J. CODEA: A Framework for Co-Designing Assistive Technologies with Occupational Therapists, Industrial Designers and End-Users with Mobility Impairments. *Proceedings of the Design Society: DESIGN Conference*, vol. 1, pp. 1843–1852, May 2020,

[14] EDUWEAR: Engineering Educational Competence Development on Customisable Wearable Rehabilitation Devices. *University of Strathclyde*, 2025. Available: https://pureportal.strath.ac.uk/en/projects/eduwear-engineering-educational-competence-development-on-customi. [Accessed: Mar. 03, 2025]

[15] Transforming Engineering Education: Project-Based Learning and Technology Integration in a Senior-Level Mechanisms Course American Society for Engineering Education. *Asee.org*, 2025.

[16] Omland M. *et al.* Co-creation in higher education: a conceptual systematic review. *Higher Education*, Jan. 2025.