RT E JOURNAL

An iterative approach to individualized additive manufacturing for defence applications

Siddhartha Biswas[a], Julius Cronau[b], Florian Engstler[b], Alexander Koch[a]

[a] Institute for Technical Product Development – Universität der Bundeswehr München
Werner-Heisenberg-Weg 39, 85577 Neubiberg

[b] Institute of Design and Production Technology – Universität der Bundeswehr München
Werner-Heisenberg-Weg 39, 85577 Neubiberg

Abstract Additive Manufacturing (AM) enables geometric variability and user-specific adaptation; however, established Design for Additive Manufacturing (DfAM) methodologies predominantly address component optimisation under predefined boundary conditions and offer limited explicit formalisation on how anthropometric variability, manufacturing constraints, and performance verification can be systematically consolidated within a single development architecture. This study demonstrates an iterative DfAM implementation that integrates user-derived anthropometric data, additive design strategy selection, constraint management, and requirement-driven evaluation within a defence-relevant subsystem. Using an individualised combat-helmet liner as demonstrator, three structured development iterations progressively verified geometric conformity, manufacturability, and mechanical behaviour under defined operational conditions. The results illustrate how requirement-oriented iteration, supported by explicit linkage between prioritised requirements and validation activities, enables staged reduction of geometric, manufacturing, and functional uncertainty while preserving subsystem level compliance with regulatory and system level constraints. The presented approach provides a structured implementation logic for developing individualised AM products in performance-critical defence applications.

Keywords: Additive Manufacturing, Design for Additive Manufacturing, Individualisation, Defence applications, Iterative development

Introduction

Over the past two decades, AM has evolved from a prototyping tool into a production-ready technology, enabling direct fabrication from digital models and supporting highly complex geometries [1,2]. Industries such as aerospace, medical, and defence have strategically adopted AM for lightweighting, customization, and rapid iteration [3]. To fully leverage these capabilities, design methods must move beyond conventional geometry definition toward approaches that explicitly account for AM-specific constraints and opportunities. DfAM has emerged to address this need by aligning design intent with AM constraints and opportunities. While DfAM has expanded through topology optimization and computational design [4,5], it still emphasizes generic component optimization. This leaves untapped potential for individualization where user-specific data (e.g., 3D scans) inform design directly [6].

Unlike personalisation, which primarily reflects user preference, individualisation is grounded in measurable morphology and functional demand [7]. Individualised AM solutions have been successfully applied in biomedical, sports, and ergonomic contexts where fit and comfort are critical [8–10]. Defence-related systems present a particularly demanding application context. Military protective equipment is commonly produced in standardised size ranges to ensure interoperability, certification robustness, and logistical efficiency. While such standardisation simplifies deployment and compliance, it constrains adaptability to individual users and may limit ergonomic optimisation under operational load [11]. AM enables controlled geometric variability within established system architectures, particularly at user-equipment interfaces [1]. Yet embedding anthropometric variability into defence subsystems requires coordinated integration of user data, additive design reasoning, manufacturing constraints, and performance verification within defined regulatory and operational boundary conditions.

The introduction of user-specific variability and evolving boundary conditions challenges strictly sequential development models. In additive manufacturing contexts, iterative development has been recognised as a mechanism for progressively reducing uncertainty through staged validation and feedback integration [12,13]. Similarly, Agile Hardware Development (AHD) emphasises incremental learning and requirement-oriented validation for physical product development [14,15]. These perspectives suggest that structured iteration can support the management of geometric, manufacturing, and functional uncertainty when boundary conditions are not fully stabilised at project outset.

To examine the current state of integration across these domains, a Scopus-based bibliometric screening was conducted (subject area: Engineering; 2015–2025). Publications addressing DfAM, defence applications, and iterative hardware development are individually well represented. However, when the search was refined to include “individualisation” (or “individualization”) in combination with these domains, no indexed publications were identified within this combined search space. This result does not imply an absence of relevant technologies or isolated applications; rather, it indicates that the explicit consolidation of anthropometric individualisation, additive design strategy, constraint management, and iterative validation within defence contexts has not been formally documented in the examined literature.

Accordingly, the research question guiding this study is:

How can iterative DfAM principles be operationalised to support the development of individualised products within defence-relevant boundary conditions?

The State of the Art

Design under AM constraints

AM expands geometric freedom while simultaneously introducing process-specific constraints related to build orientation, support generation, feature resolution, and material behaviour [2,16]. DfAM methodologies address these constraints by aligning geometry generation with manufacturing feasibility and performance objectives [4]. Restrictive approaches focus on ensuring manufacturability, while opportunistic approaches exploit AM's design freedoms through topology optimisation, lattice structuring, and function integration [17,18]. Although these methods enable highly optimised components, they are typically applied under predefined and relatively stable boundary conditions. In many cases, user variability and regulatory constraints are incorporated as external parameters rather than as actively evolving design drivers. Consequently, while DfAM provides mature tools for geometry optimisation and process-aware design, it offers limited guidance on how dynamically varying inputs such as anthropometric data should be managed throughout staged development.

Individualisation in AM

Individualisation in engineering contexts refers to the integration of measurable anthropometric or biomechanical data into geometry generation and functional design. In biomedical and ergonomic applications, 3D scanning and parametric modelling are routinely used to produce user-conformal artefacts with improved fit and load distribution [8,9]. In parallel, lattice and architected material strategies allow mechanical behaviour to be tuned to application-specific requirements [10,19]. Despite these advances, individualisation is often implemented as a case-specific design adaptation rather than embedded within a transferable development logic. The focus frequently remains on achieving geometric conformity or local performance optimisation, while the broader coordination of anthropometric acquisition, additive strategy selection, manufacturability verification, and mechanical validation is less systematically described. As a result, individualisation tends to appear as a design outcome rather than as an explicitly structured development process.

Development under evolving boundary conditions

Physical product development rarely proceeds under fully stable assumptions, particularly when new materials, manufacturing technologies, or user-specific inputs are involved. In AM contexts, the absence of dedicated tooling facilitates rapid transitions between digital models and physical artefacts, enabling iterative validation and feedback integration [13,20–22]. AHD extends iterative principles to physical systems, emphasising incremental learning, prioritised requirement handling, and staged verification [14]. While such approaches enhance development responsiveness, they are commonly applied at the project-management or prototyping level. Less attention has been given to how iterative validation can be explicitly coordinated with additive design reasoning and anthropometric variability in performance-critical environments. In contexts where regulatory compliance and subsystem compatibility must be preserved, iteration must function not only as a means of accelerating development but also as a structured mechanism for reducing geometric, manufacturing, and functional uncertainty.

Consolidation challenge in defence relevant applications

The reviewed literature reveals three complementary but largely parallel perspectives:

- DfAM methodologies addressing manufacturability and structural optimisation,
- Individualisation research focusing on user-conformal geometry and biomechanical adaptation,
- Iterative development approaches supporting staged validation and uncertainty reduction.

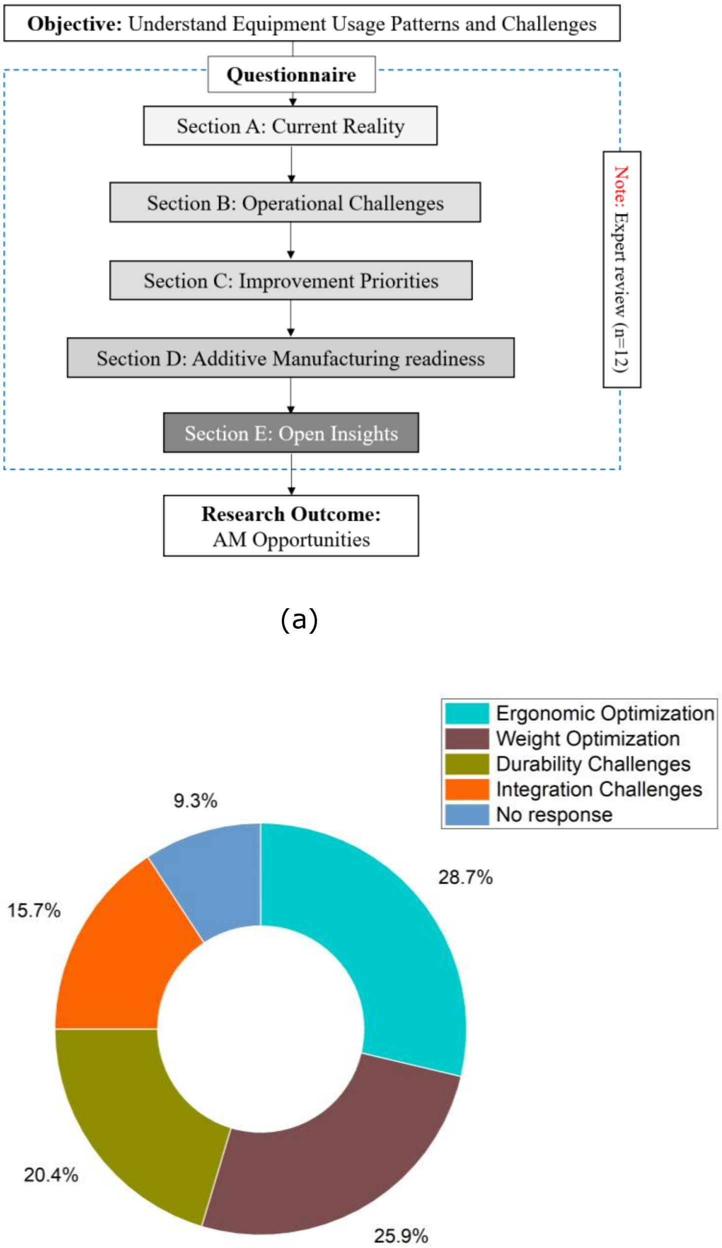
Individually, these perspectives provide mature tools and methods. However, their coordinated implementation under defence-relevant boundary conditions remains sparsely documented. Defence subsystems operate within predefined regulatory frameworks, certification constraints, and system-level interfaces, limiting the freedom to redesign entire assemblies [23,24]. Under such conditions, anthropometric variability cannot be addressed through isolated geometric adaptation alone; it must be integrated in a manner that preserves compliance, manufacturability, and functional robustness. The gap is therefore not conceptual absence of methods or tools, but limited documentation of how anthropometric variability, additive design strategies, and staged requirement-linked verification are coordinated in practice under defence-specific subsystem constraints.

Methodology

This study adopts an implementation-oriented methodology to operationalise iterative DfAM principles for the development of individualised products within defence-relevant boundary conditions.

Requirement identification

To establish an empirically grounded requirement basis, a structured survey was conducted among military trainees enrolled in an engineering programme who regularly use issued personal protective equipment. The purpose of the survey was to identify recurring ergonomic and functional limitations and to prioritise improvement needs relevant to additive redesign. The survey was not intended to produce statistically generalisable results for the broader defence population, but to structure development objectives based on empirically observed user concerns. The questionnaire comprised multiple-choice items, prioritisation tasks, and open-ended questions addressing equipment usage patterns, perceived performance limitations, and improvement priorities. A total of $n = 59$ complete responses were analysed. The survey structure and aggregated prioritisation outcomes are presented in Figure 1.



(a)

(b)

Figure 1: Structure and key outcomes of the survey; (a) Structure of the survey focusing of five key themes, (b) Key responses obtained from the survey highlighting areas where the user anticipated the improvements

Protective headgear was identified as a frequently used equipment category, with fit stability, weight reduction, and impact-related comfort emerging as the most consistently prioritised concerns. Based on these findings, the M92 combat helmet (Schuberth GmbH, Germany) was selected as the demonstrator system for the staged implementation presented in this study. The M92 helmet represents a certified and operationally deployed protective system, providing a realistic boundary condition for controlled subsystem-level adaptation. To preserve certification integrity and subsystem interoperability, geometric adaptation was restricted to the liner subsystem of the protective assembly, while certified structural components and external interfaces remained unchanged.

Iterative development logic

Iterative DfAM principles were operationalised through staged development cycles, each defined by a distinct verification objective linked to prioritised requirements. Rather than addressing all objectives simultaneously, development was sequenced to ensure that verification activities remained focused and that progression between stages was governed by predefined criteria.

The staged verification objectives were defined as follows:

- **Geometry verification stage**: Assessment of user-specific conformity and interface stability based on anthropometric input and predefined fit-related criteria.
- **Manufacturing verification stage**: Evaluation of manufacturability and dimensional fidelity under defined additive manufacturing constraints, including assessment of mass-related targets where applicable.
- **Functional verification stage**: Evaluation of mechanical behaviour under impact-related loading conditions using predefined performance-related criteria.

Across stages, a consistent procedural logic was applied:

- Parameterised geometry generation informed by anthropometric input.
- Selection of a validation activity appropriate to the targeted requirement (digital assessment and/or physical prototype evaluation).
- Evaluation against predefined qualitative and quantitative criteria derived from the requirement set.
- Conditional progression to the subsequent stage based on fulfilment of the defined criteria.

If criteria were not satisfied, geometric or process parameters were adjusted within the established additive design strategy before re-evaluation. Iteration was therefore implemented as controlled refinement within a predefined subsystem scope, rather than exploratory redesign of the complete system. In defence context, subsystem modification operates within structured quality assurance and configuration-control frameworks, such as those defined in NATO AQAP standards [25]. These frameworks impose requirements on verification, documentation, and system integrity, limiting the freedom for unrestricted redesign. Accordingly, regulatory and system-level constraints were embedded from the outset as fixed boundary conditions guiding each development stage.

Results: Developments across iterations

Requirement definition and prioritization

The user-centred insights obtained from the survey were translated into a set of actionable design requirements that guided the subsequent development activities. Each requirement corresponds to a functional, ergonomic, or process-related objective derived from aggregated user feedback, expert assessment, and technical feasibility considerations. Table 1 summarises the prioritised requirements, which collectively defined the development focus for the iterative DfAM implementation.

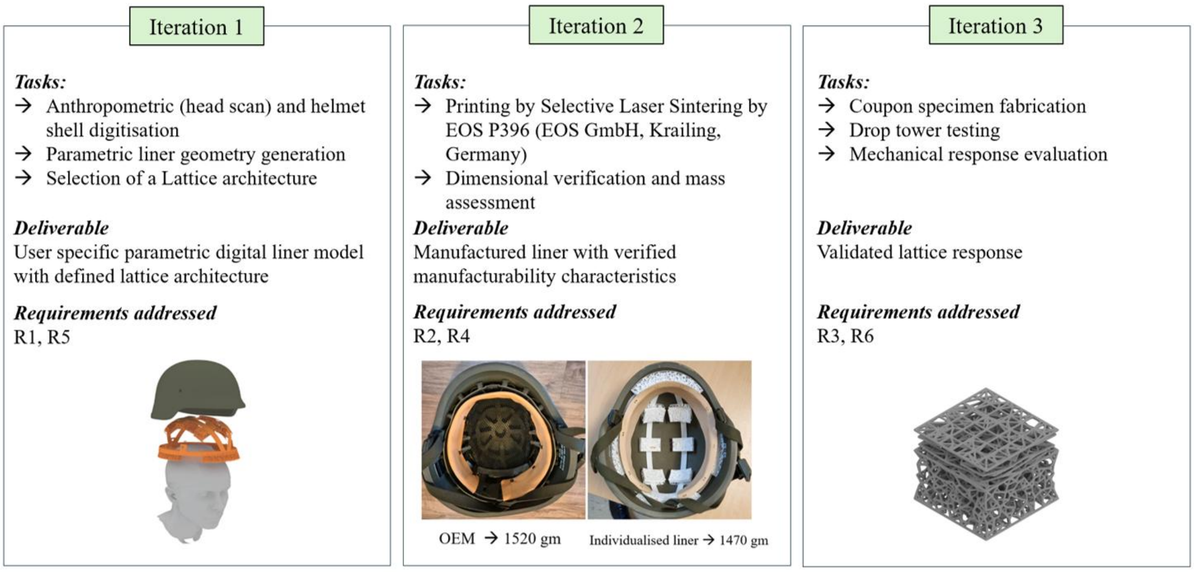
Table 1 User-derived needs from survey translated to a requirement backlog

Req. ID	**Requirement**	**Description**	**Priority**
R1	Fit and clearance	Defines head–helmet interface geometry for stable fit	High
R2	Lightweight design	Achieves weight reduction to minimise fatigue and enhance operational endurance.	High
R3	Impact energy absorption	Ensures mechanical energy dissipation and load distribution to meet protection requirements.	High
R4	Manufacturability under AM constraints	Guarantees repeatability and print fidelity	Medium
R5	Geometric adaptability to user data	Enables the liner geometry to be parametrically adjusted for varying anthropometric inputs.	Medium
R6	Structural calibration from validation data	Updates design parameters based on mechanical-test feedback to enhance predictive accuracy.	Medium
R7	Ventilation and thermal comfort	Improves air circulation and thermal regulation without compromising protection.	Low
…			
Rn	*Context-specific requirement*	*Placeholder for future or application-specific needs.*	

High-priority requirements (R1-R3) defined the primary development focus, addressing ergonomic conformity (R1), mass reduction (R2), and impact-related performance (R3). Medium-priority requirements (R4-R6) informed manufacturability verification, geometric adaptability, and structural calibration through testing. The lower-priority requirement (R7) was retained for future integration without altering the staged development logic. In addition to user-derived priorities, the requirement configuration incorporated manufacturability constraints imposed by the geometric envelope and interface characteristics of the M92 helmet. The liner geometry was required to remain fully compatible with certified structural components and fixed attachment interfaces. Consequently, permissible adaptation was restricted to the internal liner subsystem, and minimum feature size, material behaviour, and dimensional tolerances were defined as boundary conditions. The development implementation described in the following section directly maps each development phase to the corresponding requirement categories, ensuring explicit linkage between development activities and requirement fulfilment.

Development over the iterations

The development across the iterations derived from the requirement configuration is illustrated in Figure 2. The three iterations were executed sequentially, with each phase building upon the validated outcomes of the preceding stage. Progression between iterations was governed by predefined qualitative and quantitative criteria linked to the prioritised requirement set. Figure 2 summarises the staged implementation described below and visually maps requirement categories to iteration-specific tasks and deliverables.



Iteration 1

Tasks:
- → Anthropometric (head scan) and helmet shell digitisation
- → Parametric liner geometry generation
- → Selection of a Lattice architecture

Deliverable
User specific parametric digital liner model with defined lattice architecture

Requirements addressed
R1, R5

Iteration 2

Tasks:
- → Printing by Selective Laser Sintering by EOS P396 (EOS GmbH, Krailing, Germany)
- → Dimensional verification and mass assessment

Deliverable
Manufactured liner with verified manufacturability characteristics

Requirements addressed
R2, R4

Iteration 3

Tasks:
- → Coupon specimen fabrication
- → Drop tower testing
- → Mechanical response evaluation

Deliverable
Validated lattice response

Requirements addressed
R3, R6

Figure 2: Overview of the three completed iterations, indicating the tasks done, the deliverables received, and which requirements were addressed

Iteration 1 - Digital definition

The first iteration focused on establishing a user-specific digital liner configuration within the certified geometric envelope of the M92 helmet. Anthropometric head-scan data and helmet-shell digitisation were used to define the available design space. A parameterised liner geometry was generated to ensure conformity to individual morphology while maintaining stable head–helmet clearance (R1) and adaptability to varying anthropometric inputs (R5). Within this iteration, a lattice architecture was selected as the AM design strategy. The selection was motivated by its established suitability for lightweight construction and tuneable energy absorption behaviour in polymer-based additive systems [17,19,26]. This design choice aligned the digital design stage with subsequent objectives related to weight reduction (R2) and impact energy absorption (R3), while remaining compatible with subsystem constraints. The outcome of Iteration 1 was a fully defined parametric digital liner model incorporating a lattice-structured internal architecture, constrained by the fixed M92 shell geometry and interface conditions.

Iteration 2 - Additive manufacturing implementation

The second iteration addressed manufacturability and weight-related requirements. The digital liner model developed in Iteration 1 was fabricated using Selective Laser Sintering (SLS) on an EOS P396 system with PA12. Process parameters were defined in accordance with manufacturer specifications and predefined AM constraints. Evaluation in this stage focused on dimensional fidelity relative to the digital model, structural integrity of lattice regions, compliance with minimum feature-size limitations, and mass characteristics relative to the OEM liner configuration. This iteration directly addressed lightweight design objectives (R2) and manufacturability under AM constraints (R4). The manufactured liner demonstrated compatibility with the existing helmet assembly and preserved subsystem interfaces, confirming that geometric adaptation and additive production could be implemented without modification of certified structural elements.

Iteration 3 - Mechanical validation

The third iteration focused on functional verification of the selected lattice architecture. To isolate and evaluate structural behaviour, representative coupon specimens derived from the liner’s lattice configuration were manufactured and subjected to drop-tower testing. Testing conditions were aligned with operationally relevant performance criteria to ensure functional comparability with impact-related requirements of protective headgear systems. The objective of coupon-based testing was to characterise the mechanical response of the lattice configuration independently of full-system variability, thereby enabling controlled evaluation of impact energy absorption behaviour (R3). The measured response satisfied predefined performance criteria and provided calibration input for structural parameter adjustment (R6). Mechanical validation was conducted without altering subsystem interfaces or modifying certified shell components, ensuring that functional verification remained embedded within defence-relevant boundary

Further iterations

While the three iterations described above address primary geometric, manufacturability, and lattice-level functional requirements, further validation at subsystem-representative scales is ongoing. Current work includes impact testing of larger, round-shaped specimens derived from the liner geometry to evaluate curvature-dependent structural behaviour and to further assess compliance with relevant operational and OEM performance criteria. These extended validation stages aim to complement the coupon-based mechanical evaluation presented in Iteration 3 and to support calibration of the lattice configuration at geometrically representative scales. Detailed analysis of these results will inform subsequent refinement stages within the established staged development logic.

Conclusion and Outlook

This study demonstrated how iterative DfAM principles can be implemented in practice for the development of individualised defence-relevant subsystems. By structuring development around a prioritised requirement configuration and embedding manufacturability and regulatory constraints from the outset, staged progression was demonstrated without modifying certified structural components. The three completed iterations addressed distinct but interrelated requirement categories. The first iteration established a user-specific parametric digital liner model within the geometric envelope of the M92 helmet and defined a lattice architecture aligned with lightweight and impact-related objectives. The second iteration verified manufacturability and dimensional fidelity through additive fabrication under defined process constraints. The third iteration evaluated the mechanical response of representative lattice specimens under impact-related loading conditions, providing calibration input while preserving subsystem compatibility.

Rather than proposing a new framework or additive design methodology, this work illustrates how existing DfAM tools, anthropometric modelling, and staged verification can be coordinated within defence-relevant boundary conditions. The contribution lies in demonstrating a requirement-linked implementation logic that enables individualisation while maintaining interoperability, manufacturability, and compliance constraints. The current implementation remains limited to staged validation steps and representative mechanical specimens. Extended validation of geometrically representative assemblies and further performance testing are ongoing. Future work will focus on subsystem-scale impact evaluation, durability assessment under repeated loading, and application of the staged development logic to additional defence-relevant components.

Overall, the presented study indicates that iterative DfAM can be operationalised as controlled, requirement-driven refinement within existing certified system architectures, providing a practical pathway toward individualised, high-performance additive manufacturing solutions in defence applications.

Acknowledgment

This research is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr. Dtec.bw is funded by the European Union – NextGenerationEU

Literature

[1] Segonds F. Design By Additive Manufacturing: an application in aeronautics and defence. Virtual and Physical Prototyping. 2018;13(4):237–245.

[2] Thompson MK, Moroni G, Vaneker T, et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. CIRP ANN-MANUF TECHN. 2016;65(2):737–760.

[3] Ngo TD, Kashani A, Imbalzano G, et al. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering. 2018;143:172–196.

[4] Laverne F, Segonds F, Anwer N, et al. Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study. Journal of Mechanical Design [Internet]. 2015 [cited 2025 Oct 13];137(121701).

[5] Wang Z, Yang W, Liu Q, et al. Data-driven modeling of process, structure and property in additive manufacturing: A review and future directions. Journal of Manufacturing Processes. 2022;77:13–31.

[6] Simpson TW, Williams CB, Hripko M. Preparing industry for additive manufacturing and its applications: Summary & recommendations from a National Science Foundation workshop. Additive Manufacturing. 2017;13:166–178.

[7] Turner C, Oyekan J. Personalised Production in the Age of Circular Additive Manufacturing. Applied Sciences. 2023;13(8):4912.

[8] Zadpoor AA. Design for Additive Bio-Manufacturing: From Patient-Specific Medical Devices to Rationally Designed Meta-Biomaterials. International Journal of Molecular Sciences. 2017;18(8):1607.

[9] Kermavnar T, Shannon A, O’Sullivan LW. The application of additive manufacturing / 3D printing in ergonomic aspects of product design: A systematic review. Applied Ergonomics [Internet]. 2021;97.

[10] Decker T, Kedziora S. Optimizing the Thickness of Functionally Graded Lattice Structures for High-Performance Energy Absorption: A Case Study Based on a Bicycle Helmet. Applied Sciences. 2024;14(7):2788.

[11] Torrens G, Campbell I, Tutton W. 7 - Design issues in military footwear and handwear. In: Sparks E, editor. Advances in Military Textiles and Personal Equipment [Internet]. Woodhead Publishing; 2012. p. 139–164. Available from: https://www.sciencedirect.com/science/article/pii/B9781845696993500074.

[12] Mellor S, Hao L, Zhang D. Additive manufacturing: A framework for implementation. International Journal of Production Economics. 2014;149:194–201.

[13] Reichwein J, Vogel S, Schork S, et al. On the Applicability of Agile Development Methods to Design for Additive Manufacturing. Procedia CIRP. 2020;91:653–658.

[14] Atzberger A, Paetzold K. Current Challenges of Agile Hardware Development: What are Still the Pain Points Nowadays? Proceedings of the Design Society: International Conference on Engineering Design. 2019;1(1):2209–2218.

[15] Michalides M, Nicklas S, Weiss S, et al. Agile Entwicklung physischer Produkte 2022 - Eine Studie zum aktuellen Stand in der industriellen Praxis. 2022.

[16] Vaneker T, Bernard A, Moroni G, et al. Design for additive manufacturing: Framework and methodology. CIRP Annals. 2020;69.

[17] Maskery I, Sturm L, Aremu AO, et al. Insights into the mechanical properties of several triply periodic minimal surface lattice structures made by polymer additive manufacturing. Polymer. 2018;152:62–71.

[18] Yang S, Zhao YF. Additive manufacturing-enabled design theory and methodology: a critical review. Int J Adv Manuf Technol. 2015;80(1–4):327–342.

[19] Cronau J, Engstler F. Energy absorption of 3D printed stochastic lattice structures under impact loading – design parameters, manufacturing, and testing. Progress in Additive Manufacturing. 2025;10:3145–3156.

[20] Joaquin M, Alexander A, Matthias B, et al. Enhancing the Additive Manufacturing process for spare parts by applying Agile Hardware Development principles. 2019 IEEE 10th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT) [Internet]. 2019 [cited 2025 May 19]. p. 109–116. Available from: https://ieeexplore.ieee.org/abstract/document/8712045.

[21] Wynn DC, Eckert CM. Perspectives on iteration in design and development. Res Eng Design. 2017;28(2):153–184.

[22] Montero J, Weber S, Bleckmann M, et al. Spare part production in remote locations through Additive Manufacturing enhanced by agile development principles. 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) [Internet]. 2019 [cited 2025 Apr 14]. p. 1–8. Available from: https://ieeexplore.ieee.org/document/8792631/.

[23] Busachi A, Erkoyuncu J, Colegrove P, et al. A review of Additive Manufacturing technology and Cost Estimation techniques for the defence sector. CIRP Journal of Manufacturing Science and Technology. 2017;19:117–128.

[24] Colorado HA, Cardenas CA, Gutierrez-Velazquez EI, et al. Additive manufacturing in armor and military applications: research, materials, processing technologies, perspectives, and challenges. Journal of Materials Research and Technology. 2023;27:3900–3913.

[25] NATO Quality Assurance Requirements for Aviation, Space and Defence Suppliers (AQAP-2310) [Internet]. Edition B Version 2. NATO Standardization Office (NSO); 2022. Available from: https://nso.nato.int/nso/nsdd/main/list-promulg.

[26] Hanks B, Frecker M. Lattice Structure Design for Additive Manufacturing: Unit Cell Topology Optimization. American Society of Mechanical Engineers Digital Collection; 2019 [cited 2025 July 18]. Available from: https://dx.doi.org/10.1115/DETC2019-97863.

Contact details

Siddhartha Biswas
Universität der Bundeswehr München
Institute for Technical Product Development
Werner-Heisenberg Weg 39
85577 Neubiberg, Germany
E-Mail: siddhartha.biswas@unibw.de
WEB: https://www.unibw.de/itpe