

Using Iteration to Support Design Reasoning in Individualised Additive Manufacturing

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Abstract: Individualised additive manufacturing requires designers to operate under user-specific variability that cannot be fully resolved at the outset of development. In engineering design literature, iteration is often treated as a cost to be reduced rather than as a mechanism to structure uncertainty. This paper examines iteration as a component of design reasoning in the context of individualised additive manufacturing. Using the development of a combat helmet liner as an empirical basis, successive iterations are analysed with respect to geometry definition, manufacturability assessment, and energy-absorption characterisation. The findings indicate that iteration does not merely refine solutions but enables the progressive clarification of requirements under variable boundary conditions. The paper contributes an empirical account of how iteration functions as a structured response to design uncertainty in individualised additive manufacturing.

Keywords: Additive Manufacturing, Design for Additive Manufacturing, Individualisation, Iteration

1 Introduction

Additive manufacturing (AM) enables the development of individualised products by allowing user-specific data, such as anthropometric measurements or three-dimensional scans, to be embedded directly into design geometry (Simpson et al. 2017; Zamani et al. 2025; Zhou et al. 2016). This capability has been demonstrated across application domains including biomedical devices, ergonomic products, and personal protective equipment (Kusmaul et al. 2019). At the same time, individualisation alters the nature of the design task. When each product instance differs, aspects such as geometry definition, feasibility, and expected behaviour cannot always be fully specified at the beginning of development (Kermavnar et al. 2021; Dean et al. 2005). In practice, designers often respond to this situation through iteration, wherein designs are created, materialised, evaluated, and revised as additional information becomes available.

Within AM, iteration is commonly discussed in relation to rapid prototyping, manufacturability verification, or incremental performance improvement (Joaquin et al. 2019; Reichwein et al. 2020a; J. Montero et al. 2019). A substantial body of work therefore focuses on reducing the number of iterations by increasing process knowledge, deriving design guidelines, or establishing cause-effect relationships within the manufacturing process (Wirths et al. 2021). Such approaches are particularly relevant where robust and repeatable production is the primary objective. In individualised AM contexts, however, iteration may persist even when process knowledge is mature. User-specific geometry, interface conditions, and behavioural expectations often emerge progressively through embodiment and evaluation, making complete upfront specification difficult (Joaquin Montero et al. 2019; Reichwein et al. 2020b). As a result, iteration serves not only as a means of refinement but also as a mechanism for interpreting and reducing uncertainty associated with user-specific variation. Design research has long recognised that design problems are rarely fully defined at the outset of a project, and that understanding develops through successive design actions and interactions with representations such as sketches, models, and prototypes (D.A. Schön 1983; Cross 2001; Donald A. Schön 2017). From this perspective, iteration supports design reasoning and learning rather than merely the refinement of predefined solutions. While this perspective is well established in existing design research literatures (Adams 2002; Wynn and Eckert 2017), its empirical manifestation within individualised AM development remains comparatively under-articulated. Many studies report iterative development as part of the workflow, but the design decisions supported by each iteration and the different types of uncertainty addressed across iterations often remain implicit (Reichwein et al. 2020a). As a result, it remains difficult to understand how designers decide what to focus on next when working with user-specific variation.

This paper addresses this gap by examining iteration from a design perspective. It investigates how iterative development supports design reasoning in individualised AM, rather than treating iteration solely as a technical refinement activity. This research contributes an empirical, episode-based account of how iterations support design reasoning in individualised AM by linking *uncertainty*, *artefacts*, and the *decisions* they enable. Specifically, the study examines how successive iterations address different types of uncertainty, introduce different forms of artefacts, and enable different design decisions over the course of development.

How does iteration support design reasoning when designing individualised products using additive manufacturing?

2 State of the Art

2.1 Individualisation as a design condition in additive manufacturing

AM enables the direct incorporation of user-specific data such as anthropometric measurements or three-dimensional scans into product geometry and has therefore become a central enabler for individualised products (Zadpoor 2017; Simpson et al. 2017). Across biomedical, ergonomic, and protective applications, prior work shows that individual fit and comfort can be improved when geometry is adapted to the user (Kermavnar et al. 2021). In protective equipment such as in helmet-related contexts, research has addressed materials, liner concepts, and design improvements, indicating both the relevance and the complexity of individualised protection artefacts (X. Zhang et al. 2024; Singh and Behera 2023; Prosperi 2021).

However, individualisation changes the design problem beyond geometry generation. Much of the AM individualisation literature frames the task as a parametric mapping exercise: user data are translated into predefined design logics, after which development proceeds as if the problem is already sufficiently specified for subsequent design activities (Y. Zhang and Kwok 2019; Bilalis et al. 2022). This framing underrepresents a recurring practical condition in individualised AM: early requirements and interfaces are often provisional, and feasibility and expected behaviour may remain uncertain until artefacts are embodied and evaluated. As a result, individualisation should not only be treated as a “*shape variation*” problem but also as a *design condition* that produces evolving requirements, interpretation challenges, and decision uncertainty during development (Kusssmaul et al. 2019; Dean et al. 2005). What remains less explicit is how designers decide what to do next when user-data translation, interfaces, and requirements cannot be stabilised upfront.

2.2 Iteration in additive manufacturing design practice

Iteration is commonly described in AM as a cycle of design-build-test, and adjustment used to confirm manufacturability, reduce defects, and improve performance (Mellor et al. 2014). Design for AM (DfAM) contributions also emphasise that process constraints, material process interactions, and production variability can drive repeated design changes, motivating structured strategies for AM-oriented development (Klahn et al. 2015; Thompson et al. 2016). In individualised AM, iteration may persist not because process knowledge is missing, but because design questions emerge sequentially as evidence becomes available.

A substantial stream of work therefore aims to reduce iteration by increasing process knowledge, formalising design rules, and establishing cause-effect relations that improve “first-time-right” outcomes (Wirths et al. 2021). This orientation is particularly appropriate in production settings where repeatability and robustness dominate. Yet the underlying assumption is often that the design problem can be sufficiently defined upfront for prediction and rule-based prevention to be effective. In individualised contexts in AM, where user data and interfaces drive case-by-case variation this assumption becomes weaker, and iteration can persist even when AM process knowledge is mature.

In parallel, recent DfAM research has considered how principles from agile hardware development or iterative development logics may be applied in AM projects, acknowledging that development cycles may be structured around incremental knowledge acquisition rather than linear specification and verification (Thiele et al. 2020; Reichwein et al. 2020a; Joaquin et al. 2019). These contributions indicate an emerging interest in iteration as an organised development mode, but they still leave open how iteration supports *specific design decisions* when individualisation prevents full problem specification.

2.3 Iteration as a component of design reasoning

Design research provides a complementary and well-established view: design problems are rarely fully defined at the outset, and understanding develops through interaction with representations such as sketches, models, and prototypes (Donald A. Schön 2017). From this perspective, iteration is not merely repetition; it is a mechanism through which designers explore assumptions, interpret evidence, and progressively clarify both the problem and solution spaces (Cross 2001). Iteration therefore functions as a reasoning process in which artefacts play an epistemic role, supporting judgement and learning in situations characterised by uncertainty and ambiguity. Building on this perspective, Wynn and Eckert conceptualise iteration in terms of episodes that differ in intent, scope, and outcome (Wynn and Eckert 2017). Rather than treating iteration as a uniform loop, the authors demonstrated that iterations may serve exploratory, corrective, consolidating, or coordinative purposes at different stages of development. This work provides a theoretical vocabulary for understanding iteration as a sequence of distinct reasoning activities rather than continuous refinement.

This conceptualisation is particularly relevant to individualised AM, where designers must translate user-specific data into geometry while simultaneously accounting for manufacturability, interfaces, and behavioural expectations that may only become visible through embodiment and testing (Diegel et al. 2019; Rosen 2007). In such contexts, iteration may be less about optimising an already defined solution and more about determining what the design is, what it must satisfy, and what evidence is sufficient to proceed.

However, while integrative accounts such as Wynn and Eckert's clarify the types of iteration that can occur, they remain largely abstract and cross-domain. In contrast, AM case studies typically report iterative development without explicitly relating iterations to the design questions, evidence, and decisions they support. As a result, the decision-support role of iteration in individualised AM remains largely implicit.

2.4 Positioning of the present study

Although iteration is widely reported in AM development, its role is most often framed as a cost to be minimised through better prediction and guidelines (Wirths et al. 2021). At the same time, design research suggests iteration is an inherent part of reasoning under incomplete specification (Donald A. Schön 2017; Cross 2001). The intersection how iteration supports design reasoning in individualised AM remains under articulated in empirical AM accounts, and even where iterative or agile-inspired development approaches are discussed (Joaquin et al. 2019; Reichwein et al. 2020a).

Accordingly, this paper analyses iterative development in an individualised AM case by treating each iteration as a bounded reasoning episode that addresses a specific type of uncertainty and supports a particular design decision. This positioning shifts the focus from "reducing iteration" to explaining how iteration structures decision-making when user-specific variation prevents full problem specification at the outset.

3 Methodology

3.1 Research approach

This study adopts a design research approach aimed at understanding how design decisions are made when individualisation prevents full problem specification at the outset. In such situations, iteration is not merely a procedural step, but a means through which designers explore, interpret, and progressively clarify both the design problem and potential solutions. This perspective aligns with established design research that conceptualises design as an activity in which understanding emerges through successive design actions and reflections (Donald A. Schön 2017; Cross 2001).

Rather than seeking to optimise a final artefact or to validate technical performance, the objective of this research is to analyse the role of iteration in design reasoning. The focus is therefore on how designers use iterative development to address uncertainty, test assumptions, and decide how a design should progress. This positioning distinguishes the present work from AM studies that treat iteration primarily as an inefficiency to be reduced through improved prediction or design guidelines (Wirths et al., 2021).

To support this objective, an analytical case study was selected as the research strategy. Case based approaches are widely used in design research when the aim is to gain insight into design activities and reasoning processes over time, rather than to establish statistical generalisation (Moreno Nieto and Moreno Sánchez 2021). The case is used here to examine iteration as it unfolds in practice and to make explicit the reasoning embedded in successive design iterations.

3.2 Case selection and scope

The study examines the development of an individualised liner of a combat helmet realised through AM. The case was selected because it exhibits characteristics that are central to the research question: *user-specific* variation, *evolving* requirements, and *limited ability* to define all relevant constraints upfront at the outset. Such conditions are commonly discussed in the existing DfAM literature as challenging for conventional, sequential development approaches (Thompson et al. 2016; Reichwein et al. 2020a).

To maintain analytical focus and ensure traceability of design decisions, the investigation concentrates on a single subsystem rather than a complete product system. Focusing on a subsystem allows the study to examine design decisions and learning across iterations in sufficient detail, while avoiding the complexity associated with full-system optimisation. The case therefore serves as a concrete context for analysing iteration as a design activity, not as a demonstration of a finished product.

3.3 Iteration as the unit of analysis

In this research, individual development iterations constitute the primary unit of analysis. Each iteration is treated as a bounded design "episode" in which a specific design question or uncertainty is addressed through design action and evaluation. This interpretation is consistent with design research that frames iteration as a means of testing assumptions and refining understanding when problems cannot be fully specified in advance (Donald A. Schön 2017).

For each iteration, the analysis considers four aspects:

- the design uncertainty being addressed,
- the design decision taken,

- the form of evaluation used, and
- the insight generated that informed subsequent development.

By structuring the analysis in this way, iteration is examined not as a repetitive design fabrication loop, but as a sequence of reasoning steps through which understanding of both the design problem and potential solutions evolves. This approach contrasts with process-oriented studies that primarily seek to minimise iteration through guideline development or improved process control (Wirths et al. 2021).

3.4 Data sources and analytical perspective

The analysis draws on design artefacts and documentation generated during the development process, including digital models, physical prototypes, evolution artefacts, and records of evaluation activities. These materials provide evidence of how design decisions were made, revised, or confirmed across iterations.

Consistent with prior work on iterative and agile-inspired approaches in DfAM, the analysis adopts a qualitative and interpretive perspective (Joaquin et al. 2019; Reichwein et al. 2020a). Rather than quantitatively comparing performance outcomes, the focus is on identifying how each iteration contributed to clarifying requirements, assessing feasibility, or informing subsequent design decisions. This allows the study to capture forms of design knowledge such as judgement, assumption testing, and learning that are often implicit in outcome-focused reporting.

3.5 Methodological limitations

As a single-case study, the findings of this work are not intended to be statistically generalisable. The contribution instead lies in providing analytical insight into how iteration supports design reasoning in individualised AM contexts. While the case itself is specific, the reasoning patterns observed align with established design theory and are expected to be transferable to other individualised AM design tasks with similar characteristics.

4 Case study and results

This section presents the case study used to analyse how iteration supports design reasoning in an individualised AM context. Rather than documenting the technical development of a product, the case is examined analytically to show how successive iterations supported different design decisions as the design task evolved. In line with the research approach described in Section 3, each iteration is treated as a bounded design “episode” addressing a specific form of uncertainty.

4.1 Case context and scope of analysis

The case study concerns the iterative development of an individualised combat helmet liner realised through AM. The liner was developed as an anthropometrically adapted subsystem intended to improve fit and comfort while preserving the certified helmet structure. The case is used here not as a demonstration of a final solution, but as a concrete context for examining how design reasoning unfolds when user-specific variation prevents full problem specification at the outset.

The selection of the case was informed by an exploratory user questionnaire conducted in a defence training context, which identified fit and comfort as recurring issues in daily equipment use. These findings motivated the selection of the helmet liner as a suitable subsystem for analysis, as it allows individualised geometric adaptation without modifying certified structural components. The survey itself is reported in detail elsewhere and is not analysed further in this paper.

In accordance with the methodology, the analysis focuses on individual development iterations. Each iteration is examined in terms of the uncertainty it addressed, the design question it raised, and the decision it supported. This perspective allows iteration to be analysed as a design reasoning activity rather than as a repetitive design fabrication cycle.

4.2 Iterative development and design reasoning

Each iteration is analysed here as a bounded design reasoning episode, defined by a focal uncertainty, a design question, an artefact-based evaluation, and a resulting decision that enabled progression to the next episode.

4.2.1 Iteration 1: Establishing an individualised design reference

The first iteration addressed uncertainty related to problem definition, specifically the interpretation of user-specific data and its translation into a designable geometry. At this stage, the primary design question was, whether an individualised reference geometry could be defined that meaningfully interfaces with both the user and the surrounding system. Design activities focused on translating anthropometric scan data into a conformal liner geometry while maintaining compatibility with the existing helmet-shell interface. The outcome of this iteration was not a performance improvement, but the establishment of a stable design reference that clarified the scope of the design task and enabled subsequent development. This episode therefore closed with the decision to proceed to physical embodiment using the established reference geometry.

Design reasoning outcome: Iteration supported clarification of the design problem by transforming abstract user data into a concrete design reference, thereby reducing uncertainty related to problem definition rather than solution performance.

4.2.2 Iteration 2: Assessing physical feasibility

The second iteration addressed uncertainty related to physical feasibility. The central design question at this stage was whether the design logic established in the first iteration could be realised as a physical artefact using AM. Evaluation activities focused on fabricating an additively manufactured liner prototype to assess manufacturability, dimensional fidelity, and practical embodiment of the selected design logic. Rather than aiming to optimise the design, this iteration served to test whether the chosen design direction was viable in practice. The outcome confirmed feasibility and revealed practical considerations associated with fabrication and handling.

Design reasoning outcome: Iteration functioned as a feasibility checkpoint, enabling designers to confirm or revise assumptions about physical realisation before progressing toward behaviour-oriented evaluation. This episode closed with the decision to retain the design logic and progress to behavioural evaluation rather than revising the geometric concept.

4.2.3 Iteration 3: Interpreting behavioural assumptions

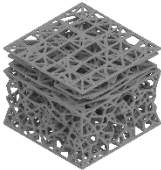
In the third iteration, mechanical behavioural assumptions could no longer be meaningfully assessed using full-scale or system-level artefacts, as geometric complexity and interface effects would obscure interpretation. A reduced stochastic lattice test specimen ("coupon" scaled specimen), derived from the liner design concept established in earlier iterations, was therefore introduced as an evaluation artefact to isolate the behavioural characteristics relevant to the selected design approach. The purpose of this artefact was not performance optimisation or validation, but to support judgement about whether the underlying structural concept exhibited behaviour consistent with its intended functional role. Importantly, this iteration included a deliberate shift in representation, from a system-level prototype to reduced specimen to isolate a specific uncertainty and make a *go* or *no-go* design judgement possible.

Design reasoning outcome: Iteration supported informed decision-making by enabling designers to assess mechanical behavioural assumptions and guide subsequent design progression based on evidence rather than conjecture.

Across the three iterations, design reasoning was supported through interaction with different forms of artefacts, ranging from digital models to physical embodiments and evaluation artefacts. These artefacts did not serve as final results, but as material anchors that enabled designers to interpret user-specific data, assess feasibility, and form judgements about behavioural assumptions. Table 1 illustrates representative artefacts produced across the analysed iterations. The table is included to support the interpretation of how design reasoning unfolded through successive iterations, rather than to document technical performance or development outcomes.

Table 1. Artefacts produced across three iterations

Iteration	Artefact type	Design question addressed	Role in design reasoning
1	Digital reference model (individualised geometry) 	Can user-specific data be translated into a stable design reference?	Enabled interpretation of anthropometric data and clarification of problem definition
2	Physical prototype (additively manufactured liner)  OEM → 1520 gm Individualised liner → 1470 gm	Can the defined design logic be realised physically within AM constraints?	Supported feasibility judgement and confirmation of embodiment assumptions

3	Evaluation artefact (test specimen / setup) 	Does observed behaviour justify continuation of the design approach?	Enabled judgement about behavioural assumptions and informed subsequent design direction
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The primary result of the case analysis is the explicit mapping of artefacts to the design questions they enabled and the decisions they supported across episodes.

4.3 Cross-iteration synthesis and interpretation

Across the case study, different iterations addressed different types of uncertainty and supported different kinds of design decisions (see table 2). Early iterations primarily supported problem clarification and design definition, while later iterations informed feasibility judgement and behavioural interpretation.

The synthesis shows that iteration did not serve a single, uniform purpose across development. Instead, the role of iteration evolved as the design task matured, shifting from problem definition toward judgement-based decision-making. In this context, iteration supported design reasoning by structuring uncertainty and guiding decisions about how the design should progress. Rather than functioning primarily as a means of performance optimisation, iteration enabled designers to decide what to address next at each stage of development. This directly addresses the research question by showing how iteration supports design reasoning when individualisation prevents full problem specification at the outset.

Table 2. Summary on how each iteration contributed to design reasoning by linking the primary uncertainty addressed, the design question posed, and the decision supported.

Iteration	Primary uncertainty addressed	Design question	Decision supported	Design insight
1	Geometry interpretation	Can a meaningful individualised reference be defined?	Establish reference geometry	Clarified problem definition
2	Physical feasibility	Can the design logic be realised physically?	Continue design direction	Confirmed feasibility assumptions
3	Behavioural expectations	Does observed behaviour justify continuation?	Progress or refine design approach	Informed design trajectory

The three analysed iterations should therefore be interpreted as representative reasoning episodes rather than a complete development lifecycle.

5 Conclusion and Outlook

The contribution is an explicit, *episode-based* account of what different iterations were used for in an individualised AM task. By mapping iterations to design questions, evidence, and decisions, the paper shows how progress is achieved through structured uncertainty reduction rather than through continuous performance optimisation. This research examined how iteration supports design reasoning in individualised AM. Rather than treating iteration as a technical inefficiency to be reduced, the study analysed iteration as an intentional design activity through which designers clarify problems, test assumptions, and decide how a design should progress when individualisation prevents full problem specification at the outset.

Using a case-based analysis, the paper showed that different iterations served different purposes across development. Early iterations supported problem definition and interpretation of user-specific data, while later iterations enabled feasibility judgement and interpretation of behavioural assumptions. This progression aligns with Wynn and Eckert's characterisation of iteration as episodes of differing intent and scope, while extending their account to the specific conditions introduced by user-specific variability in individualised AM (Wynn and Eckert 2017). Across the case, iteration functioned less as a

mechanism for optimisation and more as a means of structuring uncertainty and guiding design decisions. Making this role explicit contributes design knowledge that is largely implicit in existing AM literature.

Implications for design research and DfAM

The findings have implications for both design research and DfAM. For design research, this research reinforces the view of iteration as a *reasoning activity* whose role evolves as design maturity increases. For DfAM, the results suggest that individualisation challenges the assumption that requirements and solution strategies can be fully specified upfront. Iteration therefore remains necessary even when process knowledge and design guidelines are well developed. For practitioners, the findings suggest that iterations should be deliberately scoped around specific uncertainties rather than treated as generic development cycles. In the analysed case, different iterations addressed geometry interpretation, physical feasibility, and behavioural assumptions respectively. Explicitly linking each iteration to a focal design question may support more traceable decision-making and reduce unnecessary trial-and-error development.

This study shows that iteration does not need to be unstructured. When iterations are deliberately scoped to address specific design questions, they can support decision-making without collapsing into trial-and-error development.

Limitations of the study

The study is based on a single case and focuses on a limited number of development iterations. It does not aim to generalise statistically or to validate a final product solution. Instead, it provides analytical insight into how iteration supported design reasoning in this specific context. The findings should therefore be understood as design knowledge rather than prescriptive rules.

Outlook

The analysis also highlights that design reasoning through iteration does not end once initial feasibility and behavioural assumptions are addressed. In the present case, subsequent iterations are planned to address additional design questions, including the evaluation of behaviour at larger scales and the integration of ergonomic and comfort related considerations. These future iterations will introduce new forms of uncertainty and may require reprioritisation of design concerns. From a design-research perspective, this suggests that requirement prioritisation itself becomes an object of reasoning across iterations, rather than a fixed input defined at the outset. Investigating how designers manage shifting priorities as new evidence emerges represents a promising direction for future research on individualised AM.

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