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# Variable Seriality: Surfaces and Additive Manufacturing as Design Research

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## Abstract

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This paper investigates the role of variable seriality in the design of modular surfaces produced through additive manufacturing, interpreting the surface as a project-based system rather than a finishing element. The aim is to explore how modular repetition, combined with controlled variation of morphological and production parameters, can generate surface configurations capable of producing differentiated spatial and perceptual effects. The study adopts a design research methodology, integrating parametric digital design, additive manufacturing, and critical observation of prototypes. The experimentation resulted in a repertoire of modular surfaces developed through systematic variations in geometry, depth, and density. The results show how additive manufacturing enables strong continuity between digital models and physical artifacts, transforming seriality into an open design strategy. The paper proposes modular surfaces as flexible systems for the built environment, contributing to the debate on architecture and technology by reinforcing design as a knowledge-producing practice.

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## 1. Introduction

### 1.1 Surfaces beyond finishing systems

Within contemporary design culture, the surface has progressively moved beyond its traditional role as a finishing layer or decorative component, becoming an active system capable of mediating relationships between material, perception, technology and spatial experience. Recent studies in design research and material innovation increasingly interpret surfaces as performative interfaces capable of influencing behavioural, sensory and environmental dynamics rather than merely defining aesthetic qualities (Strappini et al., 2024). This shift reflects a broader transformation in contemporary design disciplines, where the project is no longer understood exclusively as a formal or functional operation, but as the construction of relational and multisensory experiences capable of generating interaction between users, environments and material systems.

In this context, the growing integration of computational design tools and additive manufacturing technologies has significantly expanded the possibilities of surface experimentation. Parametric modelling and digital fabrication allow designers to generate highly differentiated morphologies through controlled variations of geometry, density and depth, enabling the development of adaptive and non-standardised systems. As highlighted by Kandikjan et al. (2022), digital fabrication processes are redefining the relationship between seriality and customisation, introducing production models that integrate variability within coherent generative frameworks.

Recent research in architecture and design has also underlined how surfaces increasingly operate as responsive and communicative systems. Shao et al. (2025) describe contemporary responsive materials as interfaces capable of generating dynamic interactions through material intelligence, emphasising the growing importance of sensory and behavioural dimensions in design processes. Similarly, studies focusing on multisensory environments demonstrate how texture, light interaction and material articulation contribute to the construction of immersive spatial experiences and perceptual atmospheres (Cila et al., 2020).

This transformation has important implications for the understanding of modularity and repetition within contemporary production systems. Traditional industrial seriality was largely based on the exact repetition of identical components, aiming at optimisation and standardisation. Conversely, current computational approaches enable forms of variable seriality in which differentiation becomes an intrinsic part of the generative logic itself. As argued by Liu et al. (2026), advanced digital manufacturing technologies allow the production of adaptive systems characterised by controlled differentiation rather than static repetition.

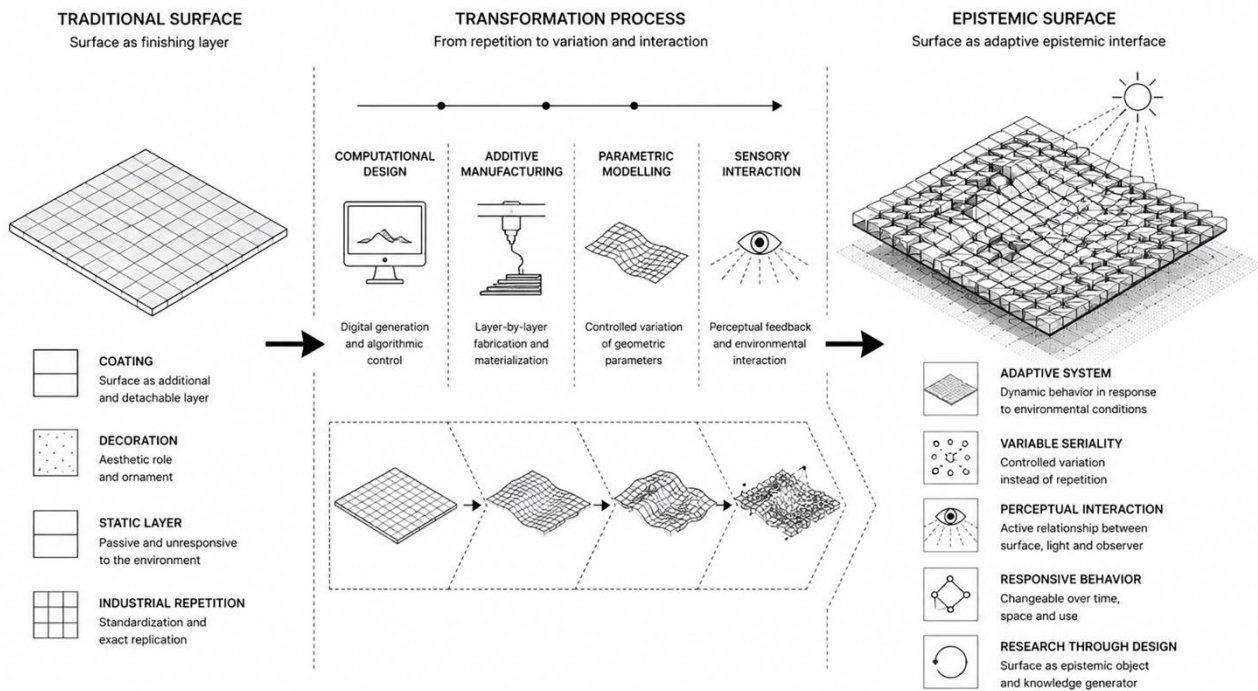
The growing relevance of additive manufacturing within design disciplines is particularly connected to this transition. Recent studies demonstrate that 3D printing technologies are increasingly employed not only for fabrication but also as exploratory tools that support iterative and experimental design processes (Srivastava & Rathee, 2022). In this sense, fabrication becomes part of the research methodology itself, transforming material production into an investigative and knowledge-generating process.

Despite the rapid evolution of additive manufacturing applications in architecture and design, current literature remains predominantly focused on technical optimisation, material performance and production efficiency. Less attention has been dedicated to the epistemological role of surfaces and to the potential of variable seriality as a methodological framework for design research. This gap becomes particularly evident in studies investigating the relationship between perceptual behaviour, modular variation and material experimentation through additive processes.

### 1.1.1 Surface as epistemic interface

Recent debates within design research increasingly interpret design practice as a knowledge-producing activity capable of generating situated forms of understanding through material experimentation and iterative processes. Within this framework, artefacts are not considered merely final outputs, but epistemic devices capable of embodying and communicating knowledge through their material existence (Beltagui et al., 2023).

The concept of research through design has significantly redefined the relationship between design practice and scientific inquiry. Contemporary studies emphasise how prototypes, simulations and material experiments can operate as cognitive tools through which designers explore emerging phenomena and construct new interpretative frameworks (Redström, 2021). In this perspective, surfaces can be understood as epistemic interfaces that make visible the interactions among geometry, fabrication, and perception (Figure 1).



**Figure 1.** Surface design workflow integrating computational modelling, additive manufacturing and perceptual experimentation.

This condition is particularly relevant in additive manufacturing processes, where the continuity between digital modelling and physical production enables direct observation of the effects of parametric variation. Unlike conventional subtractive production systems, additive manufacturing enables rapid, iterative experimentation and the fabrication of differentiated configurations while maintaining strong coherence within a single generative system (Thompson et al., 2016). Consequently, each prototype becomes both a material artefact and a research instrument through which relationships between form, light and sensory behaviour can be critically observed.

Recent investigations on sociomaterial approaches in design further reinforce this interpretation by highlighting how artefacts actively participate in the construction of knowledge rather than simply representing pre-defined concepts (Beltagui et al., 2023). Surfaces generated through variable seriality can therefore be interpreted as dynamic systems in which morphology, production traces and environmental interaction contribute to the emergence of situated and experiential forms of understanding.

Within this context, light assumes a central role as an active design variable rather than a neutral condition of visibility. Research on responsive and perceptual materials demonstrates that illumination significantly affects the readability of geometry, the perception of depth, and the atmospheric qualities of spatial systems (Shao et al., 2025). Surface behaviour consequently emerges from the interaction between material configuration, environmental conditions and user perception. The growing integration of computational design, material experimentation and sensory interaction also aligns with broader discussions surrounding Industry 5.0. Recent studies emphasise how contemporary innovation frameworks

increasingly prioritise human-centered, sustainable and interdisciplinary approaches, integrating technological advancement with environmental and social concerns (Maddikunta et al., 2022). In this scenario, university laboratories and experimental design environments play a strategic role as infrastructures for knowledge production, technological experimentation and interdisciplinary collaboration.

## 1.2 Research gap and objectives

Although additive manufacturing has become a widely investigated topic in architecture and design research, the existing literature primarily focuses on technical performance, fabrication optimisation, and material innovation. Current studies largely explore issues related to efficiency, sustainability, structural behaviour and production customisation. At the same time, comparatively limited attention has been devoted to additive manufacturing as an epistemological and methodological framework for design research.

Similarly, recent discussions on responsive materials and multisensory environments frequently investigate the perceptual effects of surfaces yet rarely analyse how controlled morphological variation can operate as a systematic research strategy through variable seriality. Consequently, there remains a methodological gap in developing replicable frameworks that integrate parametric modelling, additive manufacturing, perceptual observation, and iterative experimentation within a unified research process.

Another unresolved issue concerns the interpretation of surfaces within contemporary design culture. While surfaces are increasingly recognised as performative and communicative systems, they are still often treated as final formal outcomes rather than as open and adaptive infrastructures capable of generating knowledge through material experimentation. This limitation reduces the possibility of understanding how variation, fabrication and environmental interaction contribute to the construction of perceptual and cognitive behaviours.

Starting from these considerations, the present study investigates the role of variable seriality in the design of modular surfaces produced through additive manufacturing, interpreting the surface as a project-based research system rather than as a finishing element. The research aims to explore how controlled variations of morphological parameters can generate differentiated perceptual and spatial effects through iterative experimentation and comparative observation.

More specifically, the paper addresses three main research questions. The first investigates how additive manufacturing can transform surfaces into open systems for design research and material experimentation. The second explores how variable seriality influences perceptual behaviour through controlled modifications of geometry, density and depth. The third examines whether prototyping can operate as an epistemic method capable of generating situated knowledge through iterative material processes.

The study contributes to contemporary debates on design research by proposing additive manufacturing not only as a fabrication technology but also as a methodological environment for knowledge production through material experimentation. In this perspective, variable seriality is interpreted as a research strategy capable of connecting computational design, sensory interaction and critical observation within a coherent experimental framework.

The paper also contributes to current discussions on Industry 5.0 by emphasising the strategic role of university laboratories as infrastructures for interdisciplinary experimentation and innovation. Through the integration of parametric modelling, additive manufacturing and perceptual analysis, the research proposes a methodological framework that reinforces the role of design as a critical and knowledge-producing discipline capable of operating across technological, material and sensory dimensions.

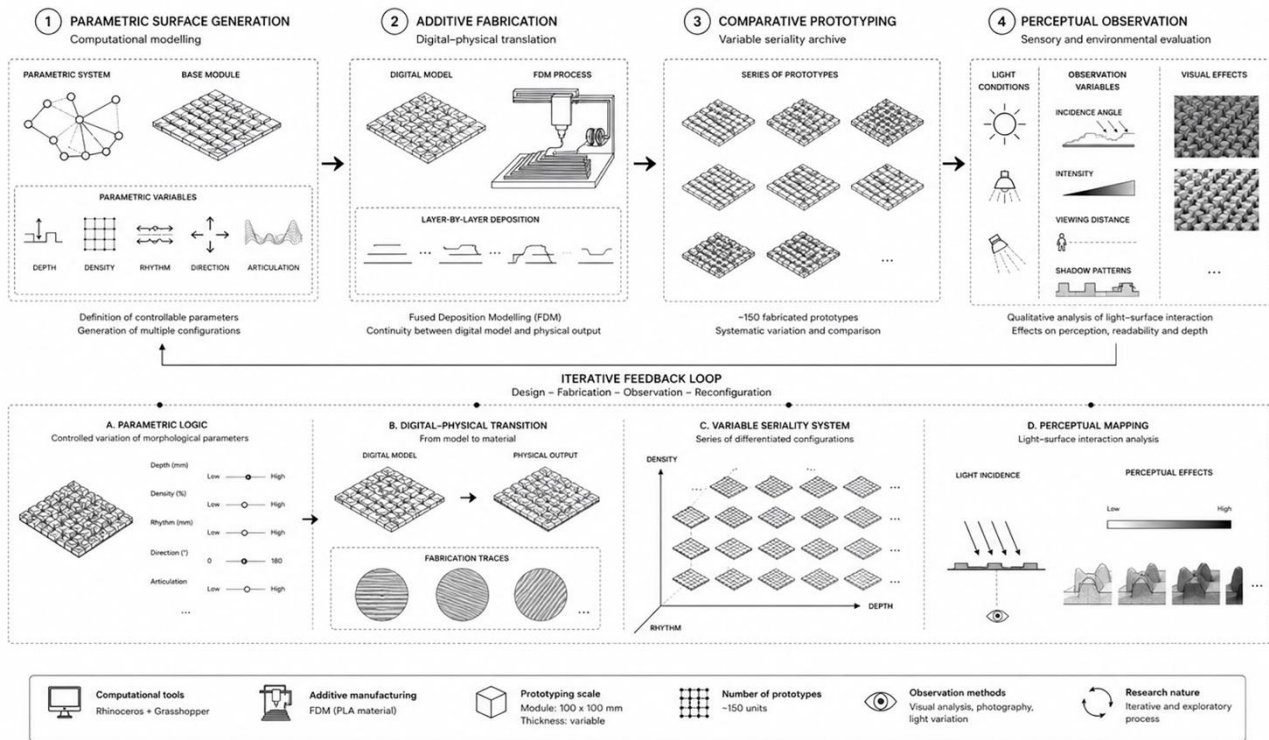
## 2. Materials and Methods

The research adopts a research-through-design approach, in which design practice serves as a methodological framework for knowledge production through iterative experimentation, material investigation, and critical observation. Within this perspective, the project is not interpreted as the application of predefined solutions, but as an exploratory process capable of generating situated forms of understanding through the interaction between computational modelling, additive manufacturing and perceptual analysis (Redström, 2021).

The methodological structure of the study was developed to investigate how variable seriality can operate as a design research strategy through the controlled variation of surface morphologies. The research process integrates parametric modelling, additive manufacturing, and perceptual evaluation within a continuous workflow intended to establish direct relationships among digital generation, physical fabrication, and sensory observation. Rather than aiming to optimise a single formal outcome, the study focuses on developing an open experimental system capable of producing differentiated configurations through iterative variation.

The experimental activity was conducted within the ‘Laboratorio Modelli per il Design’ (LMD - Design Modelling Laboratory) at the University of Florence. The laboratory environment played a central role in the research process, functioning not only as a technical production facility but also as a cognitive infrastructure supporting experimentation, prototyping and interdisciplinary interaction. The availability of additive manufacturing technologies and computational design tools enabled rapid iterative development and continuous comparison between digital models and physical artefacts.

The research methodology was organised into four interconnected phases: parametric surface generation, additive fabrication, comparative prototyping and perceptual observation (Figure 2). Each phase contributed to the progressive construction of a variable seriality framework intended to investigate relationships between geometry, light interaction and sensory behaviour.



**Figure 2.** Methodological framework describing the iterative relationship between computational generation, additive fabrication and perceptual observation.

The first phase focused on developing parametric surface systems using computational modelling tools. The modelling process was structured around the definition of controllable geometric parameters capable of generating multiple differentiated configurations within a coherent generative logic. Parameters included surface depth, geometric density, rhythm variation, directional continuity and morphological articulation. By selectively modifying these variables, the research generated a series of modular surfaces characterised by distinct spatial and perceptual behaviours.

The computational workflow was intentionally conceived as an open generative system rather than a deterministic modelling process. Instead of producing fixed geometries, parametric modelling enabled the continuous transformation of surface conditions through controlled variation. This approach aligns with recent investigations that emphasise the potential of computational design to support adaptive, non-standardised production systems in architecture and design (Kandikjan et al., 2022).

Following the digital modelling phase, the generated surfaces were physically fabricated using additive manufacturing technologies. The study employed Fused Deposition Modelling (FDM) processes due to their accessibility, rapid prototyping capabilities and compatibility with iterative experimentation. Additive manufacturing enabled direct continuity between the digital generation and physical production, allowing rapid verification of the perceptual effects of geometric variation.

Approximately 150 surface prototypes were produced during the experimental phase. Rather than representing isolated artefacts, the prototypes constituted a comparative research archive through which the effects of controlled variation could be progressively observed and analysed. Each prototype corresponded to a specific configuration generated by selective modifications of morphological parameters, enabling a comparative evaluation of differentiated surface conditions.

The fabrication process itself became an active component of the research methodology. Layer deposition, production traces, and material imperfections generated during printing were not considered technical inaccuracies to be eliminated, but rather informative aspects capable of revealing interactions among geometry, fabrication, and perception. Recent studies on additive manufacturing in design research highlight how material traces and fabrication behaviours contribute to the emergence of situated knowledge within experimental design processes (Gebler et al., 2021).

Perceptual evaluation constituted the final methodological phase of the research. The prototypes were analysed under different environmental and lighting conditions to investigate how variations in geometry influenced sensory and spatial behaviour. Observation sessions were conducted using both natural and artificial lighting configurations, with varying incidence angles, intensities, and viewing distances, to identify changes in readability, shadow generation, and depth perception.

Light was interpreted as an active design variable rather than as a neutral condition of visibility. The interaction between illumination and surface articulation produced dynamic perceptual effects that continuously transformed the prototypes' visual behaviour. Surfaces characterised by deeper morphologies produced strong chiaroscuro and highly variable shadow patterns, whereas flatter configurations generated more diffuse, continuous visual effects. These observations confirm recent findings concerning the role of responsive and multisensory materials in shaping spatial experience and perceptual atmospheres (Strappini et al., 2024).

The evaluation process was conducted through comparative visual observation and photographic documentation. Rather than using quantitative performance metrics, the research prioritised qualitative analysis focused on the relationships among material behaviour, environmental interaction, and sensory response. This approach aligns with recent

methodological perspectives within design research that emphasise the importance of situated observation and material experimentation in the construction of knowledge (Beltagui et al., 2023).

The iterative nature of the workflow allowed continuous feedback between design generation, fabrication and perceptual evaluation. Results emerging from the observation phase informed subsequent modifications of the parametric systems, reinforcing the adaptive and open-ended structure of the research process. In this sense, the methodology did not follow a linear sequence. However, it operated as a recursive experimental framework in which knowledge progressively emerged through iterative cycles of making, observing and reconfiguring.

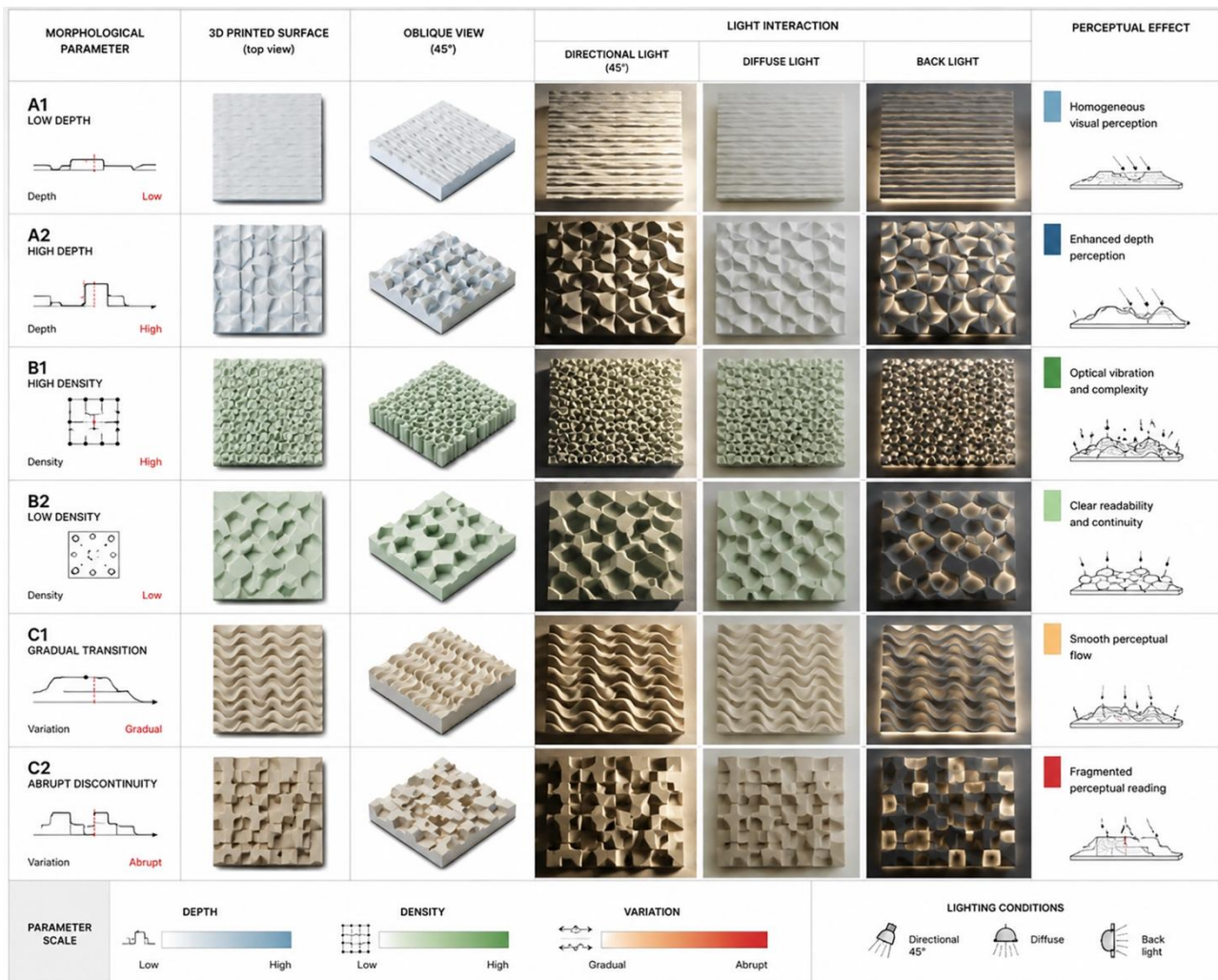
The methodological approach developed through this study therefore proposes a framework in which additive manufacturing operates simultaneously as a fabrication process, an observational device and an epistemic environment for design research. By integrating computational modelling, variable seriality and sensory evaluation, the research establishes a process-oriented methodology capable of connecting material experimentation with broader discussions concerning design knowledge, adaptive systems and Industry 5.0 innovation frameworks.

### 3. Results

#### 3.1 Morphological variability and perceptual differentiation

The experimental investigation demonstrated how controlled parametric variation significantly affects the perceptual and spatial behaviour of modular surfaces produced through additive manufacturing. Variations in depth, density, rhythm and geometric continuity generated differentiated sensory conditions, confirming that even minimal morphological modifications can substantially alter the visual readability and atmospheric qualities of a surface system.

The comparative analysis of the prototypes revealed that surfaces characterised by greater tridimensional articulation produced stronger perceptual depth and more complex shadow interactions (Figure 3). These configurations amplified the spatial legibility of the texture and intensified the dynamic relationship between geometry and illumination. Conversely, flatter, less articulated morphologies produced more homogeneous visual fields, reducing contrast effects and favouring continuous perceptual transitions.



**Figure 3.** Comparative analysis of parametrically generated surface morphologies showing variations in depth, density and perceptual interaction under controlled lighting conditions.

Geometric density also emerged as a decisive factor in the construction of sensory behaviour. High-density configurations generated optical vibration, fragmented reflections and perceptual instability, especially under directional lighting conditions. Lower-density surfaces instead produced clearer visual organisation and more stable spatial perception, emphasising continuity between modules and reducing visual fragmentation.

The results further demonstrated that perception is not exclusively determined by geometry itself, but emerges from the interaction among morphology, viewing distance, and environmental conditions. Several prototypes exhibited changing perceptual behaviours depending on the observer's position. Certain textures were highly legible at close range but progressively lost definition at greater distances, while other configurations revealed broader compositional patterns only at a distance.

These findings confirm that variable seriality can operate as a dynamic design strategy, generating adaptive perceptual systems rather than static formal compositions. The surfaces produced through iterative variation continuously redefined their visual behaviour according to changing environmental and observational conditions, reinforcing the relational nature of the experimental framework (Table 1.).

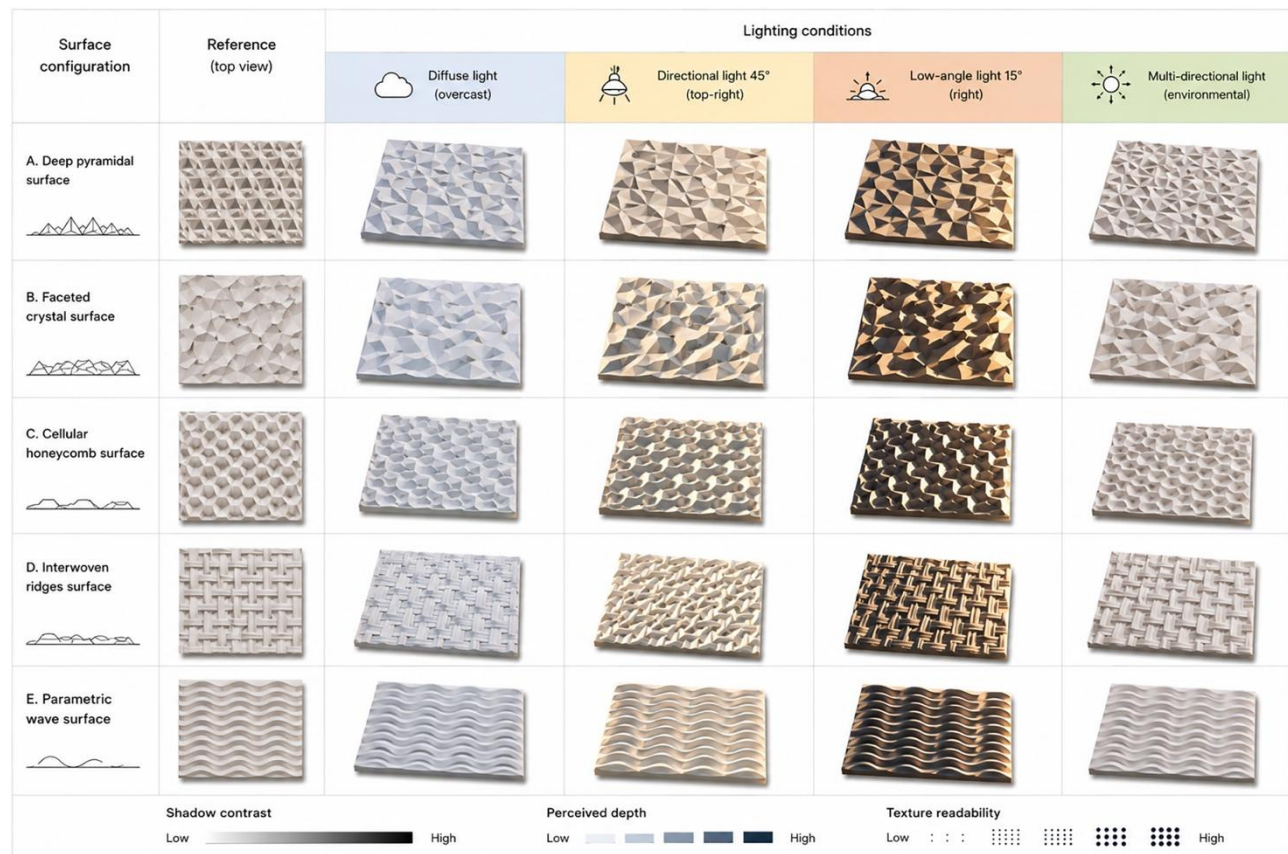
**Table 1:** Relationship between morphological parameters and perceptual behaviour observed during experimental prototyping.

Surface configuration	Morphological variation	Perceptual effect	Light interaction	Spatial behaviour
Low-depth surface	Reduced tridimensional articulation	Homogeneous visual perception	Diffuse reflection and low shadow contrast	Stable and continuous spatial reading
High-depth surface	Increased geometric extrusion	Enhanced depth perception	Strong chiaroscuro and articulated shadows	Dynamic and immersive perception
High-density texture	Compact geometric distribution	Optical vibration and perceptual complexity	Fragmented reflections	Visually unstable behaviour
Low-density texture	Wider spacing between modules	Clearer readability and visual continuity	Uniform light diffusion	More ordered spatial perception
Gradual parametric transition	Progressive geometric variation	Smooth perceptual flow	Continuous shadow gradients	Adaptive and fluid spatial behaviour
Abrupt geometric discontinuity	Sudden morphological change	Fragmented perceptual reading	High local contrast	Discontinuous spatial perception

### 3.2 Surface-light interaction

One of the most relevant outcomes of the research concerns the relationship between surface morphology and light interaction. The experimental observations demonstrated that illumination acts as an active design variable, continuously transforming the perceptual behaviour of the surfaces.

Directional lighting conditions significantly enhanced the readability of tridimensional configurations (Figure 4) Deep morphologies generated strong chiaroscuro effects and articulated shadow systems, amplifying the perception of depth and geometric variation. In these cases, the surfaces behaved as dynamic perceptual fields capable of producing continuously changing atmospheric effects through the interaction between texture and illumination.



**Figure 4.** Variations in shadow generation and perceptual depth produced by different lighting conditions on additive-manufactured surface systems.

Under diffuse lighting conditions, however, the same geometries produced substantially different behaviours. Reducing shadow contrast decreased the visual prominence of tridimensional articulation, yielding flatter, more homogeneous perceptual conditions. In these situations, the sensory qualities of the surfaces depended more strongly on material continuity and texture distribution rather than on volumetric definition.

Several prototypes also demonstrated anisotropic visual behaviour, altering their perceptual readability with the angle and direction of illumination. This condition was particularly evident in configurations characterised by irregular or progressively varying geometries, where small changes in light incidence generated substantial transformations in shadow distribution and visual depth.

The experimental observations confirm recent studies on responsive and multisensory materials, which hold that perception emerges from the continuous interaction among environmental conditions, material systems, and sensory experience (Strappini et al., 2024). Within this framework, the surface cannot be interpreted as a passive material layer, but rather as an adaptive perceptual infrastructure capable of mediating relationships among light, space, and the observer.

### **3.3 Variable seriality and adaptive modularity**

The research demonstrated how variable seriality can redefine the relationship between modularity and differentiation within additive manufacturing processes. Rather than producing repetitive standardised systems, the parametric workflow enabled the generation of coherent families of surfaces characterised by controlled transformation and adaptive variation. The prototypes maintained strong visual continuity while simultaneously incorporating local geometric differences that could modify their overall perceptual behaviour. This condition enabled the development of systems in which repetition and variation coexist within a single generative structure. The resulting modularity therefore operated not through exact replication, but through progressive transformation and controlled differentiation.

Particularly significant results emerged from surfaces characterised by gradual parametric transitions. Configurations developed through progressive variation produced smoother perceptual flows and more immersive spatial effects than those based on abrupt geometric discontinuities. Continuous transformations across different densities and depths produced adaptive visual gradients that reinforced atmospheric continuity and spatial fluidity.

The findings suggest that variable seriality can function as a methodological framework for adaptive design systems. Instead of treating modularity as a process of standardisation, the research proposes a model in which modular systems become open and responsive structures capable of integrating coherence and differentiation simultaneously.

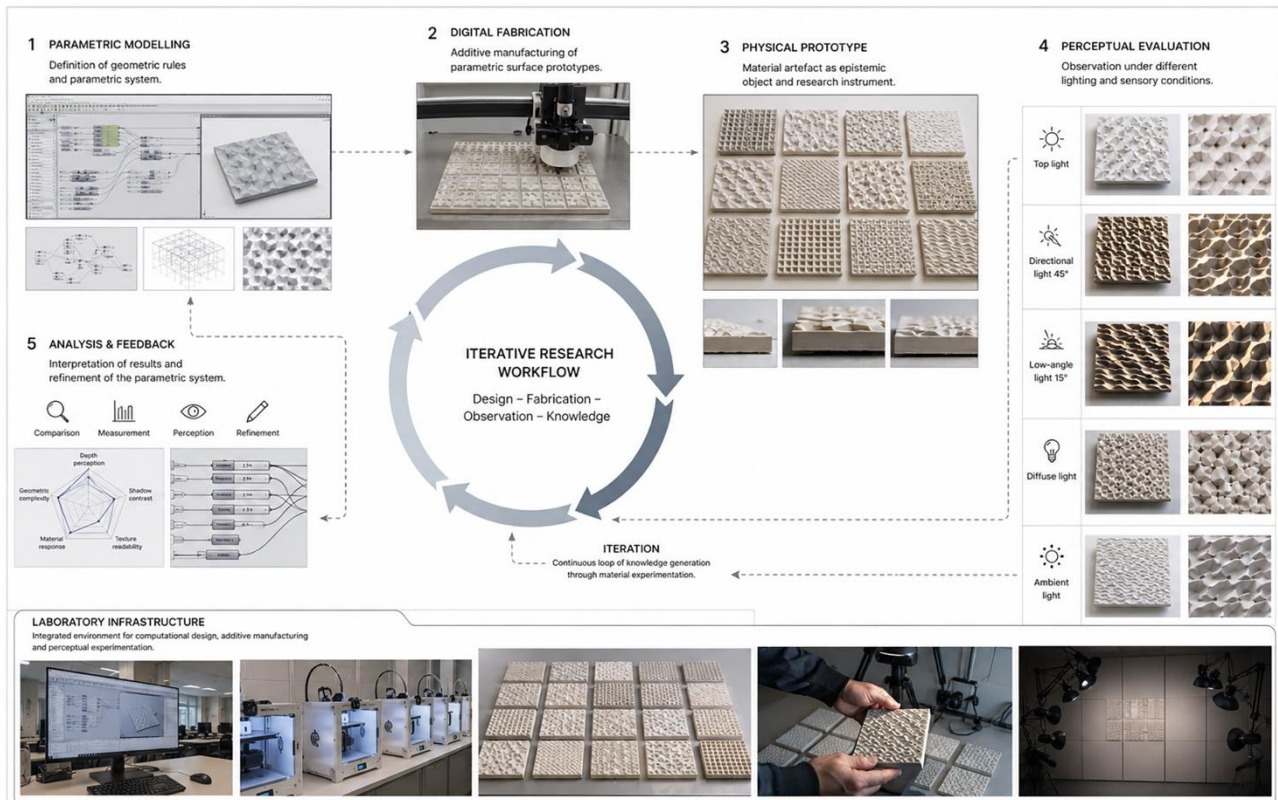
This condition aligns with recent investigations concerning computational fabrication and adaptive design methodologies, which increasingly interpret digital production systems as environments for controlled variability rather than industrial repetition (Kandikjan et al., 2022). Within this perspective, additive manufacturing supports the development of non-standardised systems capable of responding dynamically to perceptual and environmental conditions.

### **3.4 Prototype as epistemic object**

Another significant result concerns the epistemic role prototypes play within the experimental workflow. The fabricated artefacts did not operate merely as representations of predefined geometries, but as research instruments capable of generating situated knowledge through material experimentation and sensory observation.

The continuity between digital modelling and physical fabrication enabled direct observation of conditions that were not entirely predictable during the computational phase. Layer deposition traces, fabrication anomalies, and micro-imperfections contributed to the emergence of unexpected perceptual behaviours, transforming the production process itself into a source of knowledge.

Rather than being interpreted as technical inaccuracies, these material deviations became informative components capable of revealing hidden relationships between geometry, fabrication and environmental interaction. The prototypes, therefore, functioned simultaneously as design outcomes and epistemic devices through which the research process could be critically observed and continuously reformulated (Figure 5.).



**Figure 5.** Iterative workflow connecting parametric modelling, additive manufacturing, material observation and perceptual evaluation within the laboratory research environment.

The workflow's iterative structure reinforced this condition. Results from perceptual observation informed subsequent modifications to the parametric systems, establishing recursive cycles of modelling, fabrication, and evaluation. Knowledge progressively emerged through repetition, comparison and variation rather than through linear optimisation. These findings support recent discussions on sociomaterial approaches in design research, which hold that artefacts actively participate in the production of knowledge through their material and relational behaviours (Beltagui et al., 2023). Within this framework, prototyping becomes not only a method of verification but a process through which design constructs critical and situated forms of understanding.

### 3.5 Laboratory experimentation and research infrastructure

The research also highlighted the strategic role of the university laboratory as an experimental infrastructure supporting interdisciplinary design investigation. The integration of computational modelling, additive manufacturing and perceptual analysis created an adaptive research environment capable of connecting technological experimentation with broader spatial and sensory questions.

The laboratory functioned not only as a production facility but also as a cognitive ecosystem supporting iterative exploration and material observation. The availability of digital fabrication technologies enabled rapid cycles of prototyping and comparative evaluation, facilitating the continuous transformation of the experimental systems throughout the research process.

The possibility of fabricating multiple differentiated configurations within short timeframes significantly reinforced the methodological structure of the investigation. Rapid prototyping enabled systematic comparison between variable conditions while maintaining coherence within the same generative framework. This capability proved fundamental for observing how controlled morphological variation affects perceptual and environmental behaviour.

The findings further reinforce current discussions surrounding Industry 5.0, which increasingly emphasise the importance of human-centred, interdisciplinary and research-oriented innovation systems (Maddikunta et al., 2022). Within this perspective, the university laboratory emerges as a strategic environment for integrating technological experimentation, material research and sensory investigation through adaptive and collaborative workflows.

The experimental framework developed in this study, therefore, demonstrates how additive manufacturing environments can support not only fabrication processes but also broader epistemological and methodological transformations within contemporary design research.

## 4. Discussion

### 4.1 Variable seriality as a design research strategy

The results demonstrate that seriality can be interpreted not only as a formal or production-oriented approach, but also as a methodological strategy capable of generating knowledge through controlled differentiation. The experimental framework developed through the research transformed parametric variation into an investigative process through which relationships between geometry, perception and environmental interaction could be progressively observed and critically analysed.

Traditional industrial seriality has historically been associated with standardisation and exact repetition, aiming to optimise production efficiency and minimise variation. Conversely, the present study shows how additive manufacturing and computational modelling enable the development of adaptive systems in which differentiation becomes an intrinsic component of the generative logic itself. Within this framework, modularity no longer operates through static replication but through controlled transformation and progressive variation.

This condition significantly redefines the role of computational design within contemporary design culture. Parametric systems are often associated with formal complexity and geometric control; however, the findings suggest that their most relevant contribution may reside in their capacity to support iterative experimentation and perceptual investigation. Variable seriality, therefore, becomes a research methodology through which design can explore how minor morphological changes influence sensory and spatial behaviour (Figure 6.).

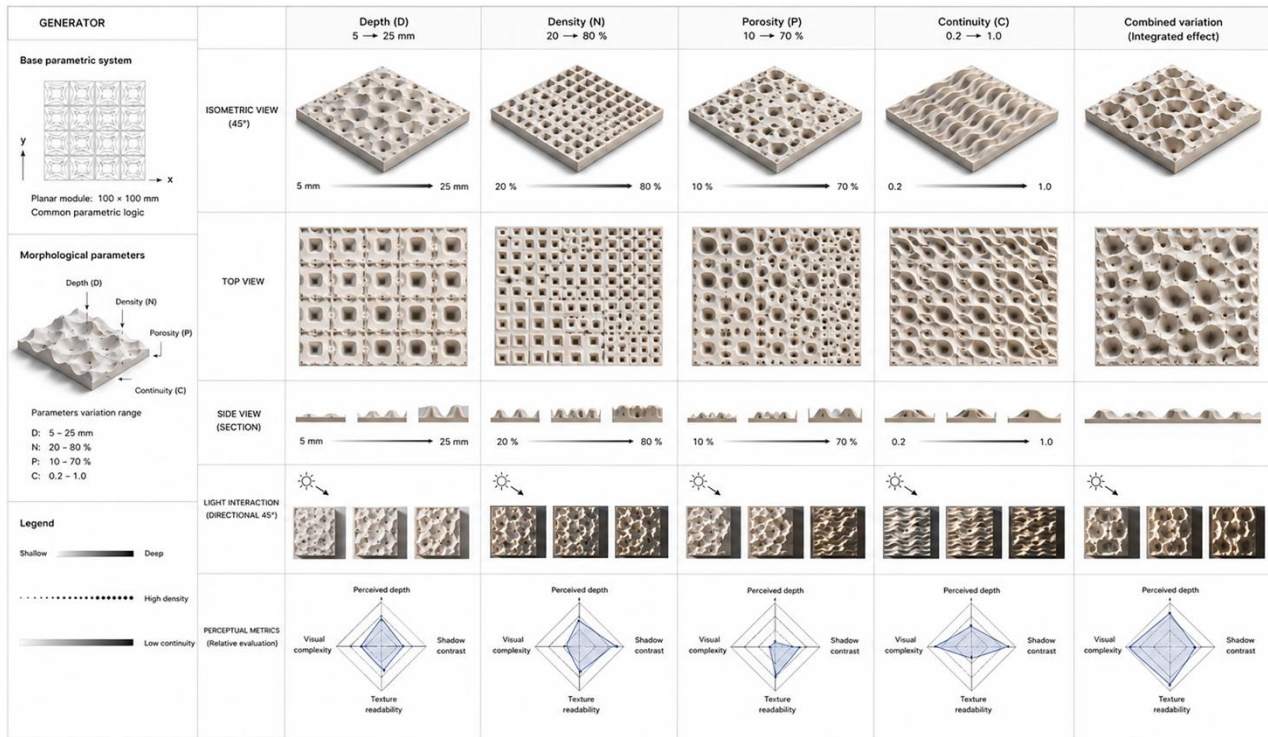


Figure 6. Comparative matrix of parametrically generated additive-manufactured surface variations.

The iterative production of differentiated prototypes enabled the construction of a comparative research environment in which each configuration contributed to the understanding of broader perceptual dynamics. Instead of pursuing a single optimised solution, the study privileged multiplicity, variation and continuous reformulation. This approach aligns with recent discussions on adaptive and non-standardised fabrication systems, which increasingly interpret computational production as a process-oriented and exploratory practice rather than merely a fabrication technique (Kandikjan et al., 2022).

The findings also reinforce the idea that additive manufacturing can support open-ended design systems characterised by flexibility and adaptability. The surfaces developed through the research continuously redefined their perceptual behaviour according to environmental conditions and observational perspectives, confirming the relational nature of the experimental framework. In this sense, seriality becomes dynamic rather than fixed, generating systems capable of integrating continuity and transformation simultaneously.

#### 4.2 Surface as cognitive and perceptual infrastructure

One of the most significant implications emerging from the research concerns the interpretation of the surface as a cognitive infrastructure capable of mediating relationships between materiality, perception and knowledge production. The experimental surfaces cannot be understood solely as formal artefacts or aesthetic outcomes, but rather as material interfaces through which design processes become observable and critically interpretable.

The interaction between geometry, light and fabrication traces revealed how surfaces actively participate in the construction of perceptual and cognitive experiences. Surface behaviour emerged not as a stable property embedded within geometry itself, but as a dynamic condition continuously produced through environmental interaction. This finding supports recent investigations that emphasise the relational and multisensory nature of material systems in contemporary design research (Strappini et al., 2024).

The research also demonstrates how additive manufacturing contributes to making design processes materially visible. Layer deposition, fabrication traces and production anomalies exposed aspects of the generative process that would otherwise remain hidden within digital simulations or conventional manufacturing systems. The prototypes, therefore, operated as epistemic artefacts capable of embodying information about the relationships among computational generation, material behaviour, and environmental interaction.

This condition is particularly relevant within research through design methodologies, where artefacts are increasingly understood as active components of knowledge production rather than passive representations of predefined ideas

(Beltagui et al., 2023). Through iterative fabrication and perceptual observation, the surfaces became tools for investigating how material systems influence sensory behaviour and spatial experience.

The findings further suggest that surfaces can operate as adaptive perceptual infrastructures capable of producing atmospheric and environmental effects through variable interaction with light. The experimental configurations generated continuously changing sensory conditions in response to illumination, viewing angle, and geometric articulation, reinforcing the idea that contemporary surfaces increasingly function as dynamic environmental interfaces rather than static material boundaries.

### 4.3 Additive manufacturing and situated knowledge production

The study highlights the epistemological potential of additive manufacturing within contemporary design research. Although 3D printing technologies are frequently investigated from technical and industrial perspectives, the experimental results demonstrate that additive fabrication can also operate as a methodological environment for situated knowledge production.

The continuity between digital generation and physical fabrication enabled direct observation of how parametric variation affects perceptual behaviour. Unlike conventional production systems characterised by rigid standardisation, additive manufacturing enables rapid, iterative experimentation and continuous comparison of differentiated configurations. This condition transformed fabrication into a research process rather than a merely productive operation.

A particularly relevant aspect concerns the role of material imperfections and fabrication anomalies. Instead of being interpreted as errors to eliminate, these conditions became informative components capable of revealing hidden relationships between geometry, matter and environmental interaction. Unexpected visual behaviours generated through layer deposition and micro-variations contributed to the emergence of situated forms of understanding that could not have been fully anticipated during the digital modelling phase.

The findings therefore reinforce recent discussions concerning sociomaterial and process-oriented approaches within design research, according to which knowledge emerges through interaction between artefacts, technologies and environmental conditions rather than through abstract theoretical models alone (Beltagui et al., 2023). Additive manufacturing becomes, in this perspective, an epistemic medium capable of supporting iterative observation, critical interpretation and adaptive experimentation.

The workflow's recursive structure further contributed to this condition. Continuous feedback between modelling, fabrication and observation generated a dynamic research process in which knowledge progressively emerged through repetition, variation and comparison. The study, therefore, supports the interpretation of prototyping not as a final verification phase, but as an active process of investigation through which design constructs new forms of understanding.

### 4.4 University Laboratories and Industry 5.0

The research also contributes to broader discussions concerning the role of university laboratories within emerging Industry 5.0 frameworks. Recent studies increasingly emphasise the importance of interdisciplinary, human-centered and research-driven innovation systems capable of integrating technological advancement with social, environmental and cultural dimensions (Maddikunta et al., 2022).

Within this context, the experimental environment developed through the study demonstrates how university laboratories can operate as strategic infrastructures for adaptive and exploratory research processes. The integration of computational modelling, additive manufacturing and perceptual analysis created a flexible ecosystem that connects technological experimentation with broader questions about spatial behaviour, material interaction and sensory experience (Figure 7.).

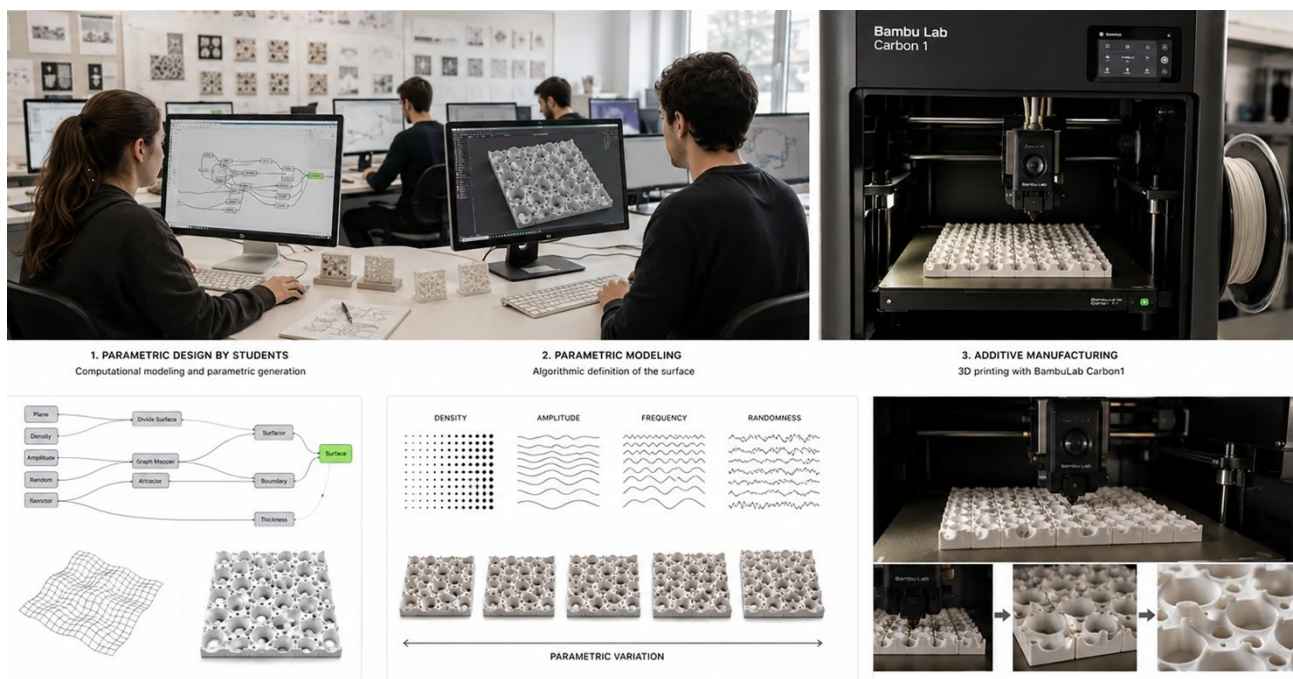


Figure 7. Development of parametric surfaces and prototyping via 3D printing at the Design Models Laboratory.

The laboratory environment proved particularly significant in supporting iterative and open-ended experimentation. The possibility of rapidly producing multiple differentiated prototypes enabled continuous reformulation of the research process, facilitating adaptive workflows that would be difficult to implement within conventional industrial systems. This flexibility reinforced the methodological structure of the investigation and supported the development of variable seriality as an experimental framework.

The findings also highlight the educational and cultural value of experimental fabrication environments. By integrating digital technologies and material investigation, university laboratories can foster interdisciplinary forms of knowledge production that connect design research with emerging technological and environmental challenges. In this sense, the laboratory operates not only as a production space but as a cognitive infrastructure supporting critical experimentation and collaborative innovation.

The study therefore suggests that additive manufacturing laboratories can play a strategic role in future design research ecosystems, contributing to the development of adaptive methodologies that integrate computational design, sensory experimentation, and material sustainability. This perspective aligns with current Industry 5.0 approaches that increasingly prioritise relational, human-centered and environmentally responsive innovation frameworks.

#### **4.5 Limitations and future research directions**

Despite the relevance of the experimental results, the research presents several limitations, primarily due to its exploratory methodology and the prototypical scale of the investigation. The study focused predominantly on perceptual and morphological behaviour within controlled laboratory conditions, without extending the experimentation to full-scale architectural applications or long-term environmental performance analysis.

Another limitation concerns the range of materials employed during the additive manufacturing process. Although the experimental framework successfully investigated relationships among geometry, light, and perception, future studies could significantly expand the research by integrating bio-based materials, responsive composites, and environmentally adaptive systems that introduce additional sensory and performative dimensions.

Future research could also explore the integration of artificial intelligence and generative computational systems within variable seriality workflows. Machine learning algorithms and adaptive modelling systems may enable the development of surfaces that dynamically respond to environmental conditions or user interaction through real-time morphological transformations.

Further investigations may include quantitative environmental and perceptual evaluation methods, such as user-based sensory testing, atmospheric analysis, and sustainability assessment frameworks. Such developments would strengthen interdisciplinary integration among design research, additive manufacturing, and adaptive environmental systems.

The study nevertheless establishes a methodological foundation for future investigations into the role of surfaces as epistemic and perceptual infrastructures within contemporary design culture. By connecting computational variation, material experimentation and sensory interaction, the research proposes an adaptive framework capable of supporting broader discussions concerning the future relationship between design, technology and knowledge production.

#### **5. Conclusions**

The research investigated the role of variable seriality and additive manufacturing within the design of modular surfaces, interpreting the surface not as a passive finishing layer but as an adaptive and epistemic system capable of generating knowledge through material experimentation. By integrating parametric modelling, additive manufacturing and perceptual observation within a unified research framework, the study explored how controlled morphological variation can influence sensory behaviour, spatial perception and environmental interaction.

The findings demonstrate that variable seriality can operate as a methodological strategy rather than solely as a formal or productive approach. Through iterative transformation and comparative prototyping, the research showed how minimal variations in depth, density and geometric continuity significantly affect the perceptual qualities of surfaces. The resulting configurations generated dynamic, adaptive behaviours that continuously changed in response to lighting conditions, viewing distance, and environmental interactions, confirming the relational nature of contemporary surface systems.

One of the most relevant contributions of the study concerns the reinterpretation of additive manufacturing as an epistemic environment for design research. The continuity between digital generation and physical fabrication enabled direct observation of material and perceptual phenomena that could not be fully predicted through computational modelling alone. Fabrication traces, micro-imperfections and production anomalies became informative components of the research process, transforming prototyping into a method of situated knowledge production rather than a simple verification phase. The research further contributes to contemporary debates surrounding research through design by reinforcing the role of artefacts as active participants in the construction of knowledge. The prototypes developed during the experimental process functioned simultaneously as material outcomes and cognitive devices, revealing relationships between geometry, light, and perception. In this perspective, the project does not merely represent ideas but actively produces interpretative frameworks through iterative interaction with material systems and environmental conditions.

Another important contribution concerns the understanding of modularity within contemporary computational design culture. The study demonstrates how additive manufacturing and parametric modelling can overcome traditional forms of industrial repetition by enabling adaptive and differentiated systems based on controlled variation. Modularity, therefore, shifts from rigid standardisation to dynamic, open-ended configurations capable of integrating continuity and transformation within the same generative framework.

The experimental results also highlight the strategic role of university laboratories as infrastructures for interdisciplinary and exploratory research. The integration of computational tools, digital fabrication technologies and sensory analysis enabled the development of a flexible experimental environment capable of supporting iterative workflows and adaptive

methodologies. Within the context of Industry 5.0, such environments become increasingly important as platforms connecting technological innovation, material experimentation and human-centered design research (Maddikunta et al., 2022).

Although the research focused primarily on prototypical and exploratory experimentation, the methodological framework developed through the study opens significant future perspectives for the investigation of responsive and adaptive surface systems. Future developments may include the integration of bio-based materials, interactive technologies, artificial intelligence and real-time environmental responsiveness within variable seriality workflows. Additional investigations may also expand the research towards full-scale architectural applications and quantitative perceptual evaluation methods. Ultimately, the study proposes a shift in how surfaces are understood within contemporary design culture. Rather than being interpreted as static and decorative boundaries, surfaces emerge as dynamic perceptual infrastructures capable of mediating relationships between materiality, environment, technology and sensory experience. Through the integration of additive manufacturing and iterative experimentation, variable seriality becomes a framework for investigating how design can generate adaptive forms of knowledge through continuous interaction between computational systems, material processes and human perception.

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### **Conflicts of Interest**

The authors report no conflicts of interest.

### **Data Availability Statement**

The data supporting the findings of this study, including digital models, experimental documentation, process data and photographic materials, are available from the corresponding author upon reasonable request. Due to the experimental and ongoing nature of the research, some materials are not publicly available.

### **Institutional Review Board Statement**

Not applicable.

### **CRedit Author Statement**

Alessandro Spennato: Conceptualisation; Methodology; Investigation; Digital Modelling; Additive Manufacturing; Visualisation; Data Curation; Writing – original draft.

Gianpiero Alfarano: Conceptualisation; Supervision; Validation; Theoretical Framework; Writing – review & editing.

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