Design for Customization

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Preface

Over recent decades, design has increasingly been confronted with the need to reassess its theoretical foundations and operative frameworks in response to profound transformations in production systems, technological infrastructures, and cultural expectations. The long-dominant paradigm of standardization – historically central to both industrial efficiency and modernist design ideology – has progressively lost its capacity to account for emerging demands for differentiation, adaptability, and meaning. Within this critical context, *Design for Customization* positions itself as a rigorous contribution to contemporary design studies, addressing customization not as a peripheral phenomenon, but as a key lens through which to reinterpret the evolving relationship between design, technology, and society.

Rather than treating customization as a mere extension of mass production or as a market-driven strategy, this book frames it as a design paradigm with deep cultural and epistemological implications. Through a structured historical and theoretical analysis, the author traces the transition from standardized industrial models to systems capable of managing variation as an integral design condition.

This shift is examined in relation to broader post-industrial transformations, where value is increasingly produced through experience, identity, and participation. In doing so, the volume situates customization within the core concerns of design studies, linking production logics to questions of authorship, agency, and the social construction of value.

A distinctive contribution of the book lies in its treatment of digital technologies as design epistemologies rather than neutral instruments. Additive Manufacturing, Computational Design, and Generative Artificial Intelligence are discussed as operative frameworks that reconfigure the design process itself, reshaping how form is generated, negotiated, and materialized. The text moves beyond tool-centric narratives to emphasize how these technologies support new forms of design reasoning, enabling a shift from predefined typologies toward open, parametric, and generative systems. In this perspective, customization becomes not only a technical possibility, but a mode of thinking and designing.

The empirical focus on the yacht industry offers a particularly insightful case study for design research. This sector, marked by strong craft traditions and conservative manufacturing practices, provides a critical ground for investigating the tensions between innovation and continuity, experimentation and risk aversion. The research presented demonstrates how hybrid digital workflows - integrating large-scale additive manufacturing with composite reinforcement and computational modeling - can operate as instruments of design inquiry. The resulting prototypes function not merely as technical validations, but as research artefacts that reveal new relationships between form, process, and production culture. As such, the case study contributes to a broader discourse on research-through-design and practice-based knowledge in design studies.

The volume also advances a reflective discussion on the evolving role of the designer. In an environment shaped by algorithmic processes and digitally mediated production, the designer's agency increasingly shifts from the definition of singular objects to the construction of systems capable of generating controlled variation. This transformation challenges traditional notions of authorship and expertise, calling for new competencies that combine critical thinking, technological literacy, and cultural awareness. *Design for Customization* articulates this shift with clarity, offering valuable insights for both design education and professional practice.

In a research landscape where debates on digitalization, sustainability, and customization are often fragmented across disciplinary boundaries, this book stands out for its coherence and systemic vision. It addresses scholars, educators, and practitioners engaged in design research, providing conceptual tools and methodological perspectives to critically engage with contemporary design challenges. Ultimately, the volume contributes to design studies by framing customization as a central condition of present and future design practice, rather than as an exception to established industrial norms.

Silvia Piardi
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5. Systemic Impacts and Implications Driven by Technological Innovation

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5.1 The evolving role of the designer

The research documented in the previous chapter outlines how a flexible hybrid process can work in practice and can be competitive against traditional methods in key performance indicators. Yet the deepest impact of the developed approach does not lie in swapping one manufacturing technique for another, but it requires a different way of thinking about the entire design-to-production chain. In the NEMO project, the component was initially conceived for conventional composite manufacturing and only later adapted for additive production. This approach was effective as a transition and validation procedure, but it still reflects a legacy mindset in which design is shaped around the limits of existing tools.

To fully leverage the potential of these technologies, a shift towards Design for Additive Manufacturing (DfAM) is required. DfAM is defined as a set of design methods whereby functional performance and other aspects, such as manufacturability, reliability, and cost, are optimized specifically according to the capabilities of AM technologies (Tang & Zhao, 2016). Unlike traditional Design for Manufacturing (DfM), which focuses on respecting process constraints, DfAM emphasizes the exploitation of unique additive capabilities to enhance product functionality and complexity.

So, if a DfAM perspective is embraced from the outset, this separation between "design" and "re-engineering" can largely disappear. The constraints imposed by molds – such as draft angles, parting lines, or the need to avoid undercuts – no longer define the design space in the same way. Instead, designers can start from the freedoms enabled by additive and hybrid processes. They can shape internal structures to control stiffness and weight, and they can explore more complex, even organic, geometries without being immediately blocked by tooling feasibility. In this condition, technical performance and formal expression are negotiated together within a broader, digitally enabled space of possibilities.

GenAI adds an extra layer to this shift by accelerating the earliest stages of the process. Rather than beginning from a blank screen, designers can use text-to-image tools to rapidly generate multiple concept directions around a given brief or context. This speeds up preliminary exploration and supports a more iterative dialogue between requirements and form. The AI does not replace the designer's judgement but expands the range of initial options that can be critically evaluated and further developed.

In this evolving landscape, the designer's role moves from simply drawing a final shape to defining the logic that will produce many possible shapes. This involves setting up parametric models, specifying relationships between elements, and encoding rules and constraints that reflect structural, aesthetic, and manufacturing goals. The object becomes the outcome of a system rather than a one-off gesture. Generative AI can feed this system with visual suggestions, while computational design tools translate these suggestions into coherent, controllable geometry that is ready for production.

This evolution pushes the design discipline toward a more central strategic role. By controlling both the generative rules and the way they connect to specific production technologies, designers become key actors in process innovation. They are not only responsible for how products look and perform, but also for how efficiently and flexibly they can be customized and manufactured within an integrated digital workflow.

5.2 New competencies for new technologies

The potential widespread diffusion of this technology-driven approach could establish new paradigms across the entire yacht building process, extending beyond design phases to deeply reshape production logics through Additive Manufacturing. This shift represents a fundamental transition from subtractive, manual craftsmanship to a digital production model. Such a transformation relies heavily on digital processes, effectively minimizing the amount of manual labor traditionally required for object creation (Garrett, 2014). Consequently, the reliance on a large manual workforce for tasks like assembly and finishing is likely to decrease (Ben-Ner & Siemsen, 2017). However, this does not imply a simple replacement of jobs. Instead, the role of the operator evolves from a manual executor to a process supervisor. The reduction in heavy physical tasks clears the way for higher-value activities, such as parameter monitoring, file management, and in-process quality control.

This evolution demands a specific upskilling of the workforce. A significant challenge hindering adoption remains the limited knowledge of AM technologies among current professionals (Gao *et al.*, 2015; Simpson *et al.*, 2017). To bridge this gap, a new professional profile emerges: the “technician-artisan”. This figure must possess hybrid skills, combining digital literacy with a practical understanding of material behavior. Workers need expertise not only in digital design tools but also in operating the new equipment (Roos & Fusco, 2014). In this context, automation is not blind; it relies on a collaboration where the machine handles repetitive tasks while the human provides adaptive intelligence and real-time problem solving.

Beyond skillsets, a digital manufacturing process can potentially offer a positive impact on occupational health and safety. While traditional yacht building involves heavy sanding and open-mold lamination, additive techniques can reduce harmful chemical exposures compared to conventional manufacturing (Garrett, 2014). Although risks regarding VOCs do exist (Chan *et al*., 2018; Saliakas *et al*., 2023), the automated nature of large-scale 3D printing allows for effective mitigation, especially when it is coupled with important control measures such as carbon filters (McDonnell *et al*., 2016), creating a physical barrier between the operator and emissions.

To fully realize this transition, targeted education is critical. Introducing operators to AM early on helps cultivate a mindset geared towards exploiting the technology's specific capabilities, fostering innovative problem-solving capacities (Minetola *et al*., 2015). Practical learning and hands-on experience are crucial for fostering creativity and understanding the workflow (Lacey, 2010). As outlined by Despeisse & Minshall (2017), professionals must recognize the diversity of these technologies and deeply understand the specific processes involved. While the current lack of standardized guidelines presents a challenge, it also pushes companies to develop specialized internal know-how, turning workforce competence into a strategic competitive advantage.

5.3 Identity, perceived quality, and limitations of new materials

The adoption of a digital approach that leverages AM for production does not merely influence the formal definition of components, bui it can redefine the paradigms of coating and finishing. Beyond structural geometry, this shift can cause impacts on how surfaces are conceived, treating the external skin not as a separate, passive layer, but as an integrated, programmable element of the design system. Building on the results achieved with NEMO, the CYClaDEs project was launched to explore these specific aspects, focusing on strategies for enhancing customization through finishing and coating AM-produced parts.

In this context, 3D printing flexibility could enable smarter coating strategies. By integrating reversible connections such as snap-fits directly into the geometry, the finishing layer can become an easily interchangeable skin. While traditional upholstery often relies on staples or glue, this integrated approach has the potential to make assembly and removal significantly cleaner and faster. This could bring broader implications for the product's lifecycle: decoupling the aesthetic surface from the structural core can transform the finish into a truly modular element. It would allow for rapid on-site upgrades and customization, extending the object's lifespan by enabling aesthetic renewal without affecting the underlying structure.

The logic of integration could be extended to the surface texture as well. Rather than relying on post-production layers like paint or veneer to conceal the material underneath, additive processes allow the "finish" to be generated simultaneously with the geometry (Hartcher-O'Brien *et al.*, 2019). This integration, for example, could bring functional benefits, such as printing micro-textures directly onto a surface to provide grip.

Nonetheless, the visible layering typical of the process nowadays is often decoded by the brain as a defect or a sign of "unfinishedness" (Abdul Kudus *et al.*, 2016), as if the object is waiting for a final smoothing. This perception represents a significant limitation rooted in cultural factors rather than functional ones. The collective eye, conditioned by decades of traditional manufacturing standards, instinctively associates smooth surfaces with quality and finished products, while visible layers are more perceived as drafts rather than final outcomes. However, widespread diffusion of additive technologies could drive a shift in this vision. Just as exposed concrete transformed from a rough structural necessity into a refined architectural code, the layered texture of AM could evolve from a flaw into a recognized process signature. Over time, the unique identity conveyed by the visible layers could lead users to prefer this raw finish over traditional polishing. Rather than a sign of incompleteness, the texture becomes an exclusive aesthetic trait that certifies the technological DNA of the object, transforming the manufacturing process itself into a recognized element of value and distinction.

A more tangible limitation concerns the material itself, particularly the aging behavior of polymers. While traditional noble materials like wood or bronze acquire a patina over time that enhances their character, many polymers used for 3D printing tend to degrade less gracefully. Issues such as UV-induced yellowing and increased brittleness are well-documented in biopolymers like PLA when exposed to sunlight (Amza *et al.*, 2021). In nautical applications, combining UV radiation with salt spray accelerates these effects. This poses a challenge for long-term aesthetic stability. However, current research is addressing these issues. Advanced UV-stabilized bio-blends and protective coatings (Afshar *et al.*, 2020; Tung *et al.*, 2023) are being developed to improve resistance to weather and harsh conditions. Therefore, the gap between sustainability and durability is progressively closing.

5.4 Redefining market strategies and new needs for the supply chain

The operational flexibility introduced by digital manufacturing technologies has the potential to ripple through the entire business ecosystem, prompting a rethinking of broader market strategies and supply chain dynamics. As production constraints loosen, the product itself changes nature. It is no longer a static object defined by a catalog, but potentially evolves into an open, configurable system. This shift extends the concept of customization beyond the single artifact to the entire spatial environment.

In the nautical sector, for instance, this could enable complete layout customization not only on superyachts but also on smaller vessels, meeting the specific needs of a broader range of owners. The value proposition therefore can move from selling a finished good to offering a potential for total adaptation.

The transformation places the consumer at the center of the process. Consequently, the buyer is provided with extended decision-making capabilities regarding the final product. In this context, co-design practices are potentially enhanced and incentivized as a standard approach. To support this, product customization interfaces must be designed for usability to facilitate the customer's creative expression. As discussed earlier in the book, GenAI plays a relevant role in the conceptualization phase due to its intuitive nature. Simultaneously, CD logic must be presented within the interface in an accessible way, allowing the user to freely modify product parameters without managing the underlying technical complexity.

From a logistical perspective, the focus moves from transporting physical products to managing data. A distributed manufacturing model becomes viable, where the core asset is the digital file rather than the finished inventory (Laplume *et al.*, 2016). Files can be transmitted instantly to any location equipped with compatible manufacturing technology, enabling production to occur close to the point of use. In this way, it becomes possible to drastically reduce shipping costs, lead times, and the environmental footprint associated with global logistics (Gebler *et al.*, 2014).

This logic invites a rethinking of the traditional warehouse concept. In a digitized scenario where the standard product gives way to on-demand customization, maintaining a massive physical inventory risks becoming an inefficient burden. As the strategic focus shifts from a Make-to-Stock to a Make-to-Order model, the need for physical storage diminishes in favor of a Digital Inventory (Araújo *et al.*, 2021). Instead of immobilizing capital in physical stock that risks becoming obsolete or unsold, companies can maintain a virtual library of files, ready to be materialized only when an order is confirmed. This ensures maximum efficiency and could eliminate the waste associated with overproduction.

A further evolution within the supply chain structure could concern the network of strategic partnerships. The reliance on suppliers linked to rigid manufacturing processes may diminish in favor of actors essential to the additive ecosystem, such as suppliers of advanced materials, hardware manufacturers, and software developers. In this context, a new servitization model could emerge between technology providers and manufacturers (Kunovjanek *et al.*, 2022). Instead of merely selling machinery, providers might offer comprehensive "Technology-as-a-Service" packages that include hardware access, software updates, material supply, and operator training. This approach would support manufacturers in adopting these new technologies by reducing initial investment risks and ensuring continuous technical alignment.

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MICS
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This book brings together the results of research carried out within the NEMO and CYClaDEs projects, funded by the Italian National Recovery and Resilience Plan (PNRR) under the Made in Italy Circular and Sustainable (MICS) programme, Spoke 2, grant number PE_00000004. MICS is a national research program dedicated to advancing the transformation of the Italian manufacturing system through circularity, digital innovation, and sustainability. It promotes collaboration between universities, research institutions, and industry to foster new models of design, production, and consumption that combine technological excellence with environmental and social responsibility. https://www.mics.tech/en/home/

Design for Customization explores the evolving landscape of customization in design, analyzing the technological and cultural shifts redefining how products are conceived and manufactured. Growing out of extensive academic research and enriched by the experimental outcomes of the *NEMO* and *CYClaDEs* projects from PNRR MICS (Made in Italy Circolare e Sostenibile), the volume investigates how Additive Manufacturing, Computational Design, and Generative AI are enabling a transition from rigid mass production to a flexible model capable of responding to the demand for uniqueness. Through a structured analysis spanning historical contexts, cross-sector application scenarios (furniture, personal use products, and automotive), and a deep empirical focus on the yacht industry, the research connects theoretical reflection with direct industrial experimentation. It explores how hybrid digital workflows—merging large-scale 3D printing with composite reinforcement—can overcome traditional tooling constraints. Furthermore, it addresses the broader systemic impacts on the evolving role of the designer, new workforce competencies, and redefined supply chain strategies. Addressed to scholars, educators, and practitioners engaged in design research, this work offers methodological perspectives to critically navigate the contemporary shift toward advanced customization.

FrancoAngeli
La passione per le conoscenze