Design for Customization

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FrancoAngeli
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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.

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Introduction

This book aims to explore the evolving landscape of customization in design, analyzing the technological and cultural shifts that are redefining how products are conceived and manufactured. Its primary aim is to investigate how emerging digital technologies can enable a transition from standardized mass production to a flexible model capable of responding to the growing demand for uniqueness.

The work grows out of long research in academia, design practice, and across sectors that are already testing new production logics. When form is no longer trapped by fixed tooling, variation becomes easier to manage, and customization can carry real functional value.

The insights gained laid the foundation for the core experimentation of this volume, which applies these digital logics to the nautical industry. Compared to other sectors, yacht building is complex and conservative, yet it also thrives on personalization. Owners expect tailored spaces, custom features, and a strong sense of authorship. This makes the sector a demanding but revealing arena for testing digital customization at scale.

The book is organized into three main parts.

Part I describes the roots of the current transition. It follows the path from standard production to mass customization, and it looks at the cultural drivers behind this change. It also introduces three emerging technologies: additive manufacturing, computational design, and generative AI. These are examined not just as tools, but as catalysts that can potentially alter the design process.

Part II moves into application. It first reads examples from different sectors that are already testing new production logics. Furniture, products for personal use, and automotive provide clear signals. In these fields, successful projects show how flexible customization is not driven by a single driver, but by different priorities, and that it can be delivered through the emerging technologies mentioned. Then it turns to the yacht industry, where the book focuses on the experimental research carried out. After reviewing current manufacturing limits and innovative case studies, we propose a digital workflow leveraging AM coupled with composite reinforcement, CD, and GenAI. Through the discussion of a pilot project, we illustrate how the developed approach can free the sector from traditional tools, overcome ongoing challenges. The findings confirm new possibilities for advanced customization. Moreover, the project demonstrated tangible industrial benefits, including reduced weight and costs, achieved through a streamlined and automated production process.

Part III examines the broader systemic impacts emerging from the research. The discussion explores the evolving role of the designer and the new competencies required, alongside the shifting perception of additively manufactured products and materials. It also addresses the ripple effects on supply chains and business strategies. Finally, the future is not framed as a single deterministic outcome, but rather as a spectrum of possible trajectories.

Given the rapid pace of technological advancement, this book captures a specific moment in a fluid evolution. However, the principles outlined here aim to provide a lasting framework for understanding the ongoing transformation of the design discipline. The goal is to offer a comprehensive guide to navigating a future where the rigid boundaries of the factory dissolve into the flexible possibilities of the digital file.

PART 1

Framing the Shift

1. Customization in Design

1.1 Overcoming standardized production models

For over a century, one principle guided industrial production: standardization. This idea changed more than just how goods were made. It reshaped their design, their use, and even how people perceived them. The Fordist model of mass production was the peak of this approach. It offered efficiency, affordability, and consistency. Products once available only to the rich became common. This change fueled modern consumer economies.

However, the strengths of standardization were also its greatest weaknesses. These were uniformity, repetition, and scale. Over time, these principles clashed with a changing world. Society began to value diversity and individual expression. Environmental awareness also grew. This chapter traces the journey of the standardized production model. It begins with its industrial origins and its link to modernism. It concludes with the crises that forced a shift toward a more flexible and personal system.

1.1.1 The industrial roots of standardization

The roots of standardization trace back to the First Industrial Revolution. However, the *American System* of manufacturing made it a core strategy in the 19th century (Hounshell, 1984). The key breakthrough was developing machine tools to produce interchangeable parts. Eli Whitney was a pioneer of this concept. His work meant that components could be made with high precision. These parts could then fit into any assembly of the same type. This innovation changed manufacturing completely. It lowered production costs an it made repairs much simpler. It also set the stage for large-scale manufacturing (Hu, 2013). Interchangeable parts were a necessary step. They paved the way for the next major shift: the Fordist system.

Henry Ford perfected mass production in the early 20th century. It was not a single invention. Instead, it combined three key ideas. These were the moving assembly line, a fully standardized product, and the use of scientific management (Womack *et al*., 2007). The introduction of the moving assembly line was a turning point. It happened at his Highland Park plant in 1913. This change drastically cut the time needed to build a Model T. Assembly time fell from over 12 hours to just 93 minutes. This huge gain in efficiency depended on total uniformity, where every part and every car had to be identical. Ford's famous comment explains this well: he said a customer could have a car "painted any color that he wants so long as it is black" (Ford, 1926). This was not about style. It was a clear statement of a new industrial rule: variety is the enemy of efficiency. The system became even more efficient with *scientific management*, a concept from Frederick W. Taylor. His method analyzed and timed work. Labor was broken down into simple, repetitive tasks. The goal was to maximize the output of every worker (Taylor, 1911). Together, these elements created a powerful engine for economic growth. The entire system was based on economies of scale. As production volume increases, the cost per item decreases (Chandler, 1977).

1.1.2 Standardization as a design philosophy

The idea of standardization expanded beyond the factory. It became a core belief of modern design. The Bauhaus, a German design school, was very influential. It was founded by Walter Gropius in 1919. The school called for a new union between art and industry. Its main goal was to create objects for the age of mass production. These objects had to be functional. They needed a clean aesthetic, free from the ornamentation of the past (Droste, 2006). Gropius had a specific vision for designers. He saw them not as creators of unique items, but as *type-makers*. A designer's job was to create prototypes, or typen, for industry to replicate (Gropius, 1965). This thinking fit perfectly with the modernist idea that *form follows function*. In this view, an object's beauty should come from its use and its structure, not from added decoration.

This vision was later developed into a formal system. The Ulm School of Design (Hochschule für Gestaltung Ulm) played a key role. The school approached design as a science. It sought to find universal solutions that could serve everyone (Maldonado, 1972). For these influential schools, standardization was more than a business choice. It was a moral and aesthetic mission. It promised to bring well-designed, affordable objects to the public. The ultimate aim was to improve society. This thinking created a standard for industrial modernism. The designer's main job was to create a single, perfect form. This form could then be reproduced endlessly. In this way, the logic of the factory was built directly into the object itself.

1.1.3 The crisis of the standardized model

The mass production model worked well for many years. By the 1970s, however, its flaws began to emerge. Internal problems and external pressures led to a *crisis of Fordism* (Piore & Sabel, 1984). In Western countries, markets for standard goods were becoming full. Most people already owned cars, refrigerators, and televisions. The old strategy of making more for less no longer worked. Products from different companies were very similar. This forced companies to compete mainly on price. As a result, profit margins shrank (Porter, 1985).

At the same time, awareness of the environmental cost was growing. The mass production model followed a *take-make-waste* logic. It consumed finite resources at a high rate. It also produced large amounts of industrial waste and pollution (McDonough & Braungart, 2002). The oil shocks of the 1970s revealed a major weakness. The industrial system depended heavily on cheap energy. This vulnerability led to calls for more efficient and sustainable models (Jackson, 2009). Consumer attitudes were also changing. As societies became wealthier, people became more individualistic. The sameness of mass-produced goods felt limiting. A new generation of consumers emerged. They wanted products that helped express their identity and values. They were tired of the uniformity of the mass market (Baudrillard, 1998).

1.1.4 Towards flexible production

The first major challenge to mass production came from Japan. The Toyota Production System (TPS) offered a new approach. It was created by Taiichi Ōno. Instead of making huge batches to lower costs, TPS focused on eliminating waste (muda). It achieved this through key principles. Two of these were *just-in-time* (JIT) production and continuous improvement (kaizen) (Ōno, 1988). This *lean manufacturing* style gave Toyota a new capability. It could produce smaller batches of different models on the same production lines. This meant the company could respond to what the market wanted. It no longer had to push standard products onto consumers (Womack *et al.*, 2007).

The success of the Japanese model was noted globally. It inspired a wider shift toward *flexible production* in the West. This movement marked the beginning of a post-Fordist era (Piore & Sabel, 1984). New ways of organizing work were developed. New manufacturing systems were created. The goal was to find a balance between efficiency and variety. For example, Reconfigurable Manufacturing Systems (RMS) were designed. These systems allowed factories to quickly change their production output and capacity (Mehrabi *et al.*, 2000; ElMaraghy, 2005). Other strategies also became popular. One was *delayed differentiation*, or *postponement*. With this method, a generic product is made in large quantities. It is then customized only at the final point in the supply chain. This industrial shift reflected a deeper change in society. Bell (1973) called this the *post-industrial society*. In this new society, economic value comes less from making physical goods. Instead, it comes more from knowledge, information, and services.

1.1.5 Cultural shifts and the Experience Economy

The move away from standardization was not just about technology or economics. Cultural changes also drove it. Toffler (1980) predicted the rise of the *prosumer* in his book *The Third Wave*. A prosumer is a consumer who is actively involved in the production process. This concept blurred the line between the maker and the user. It captured a growing desire among people for more control and involvement. They no longer wanted to be passive buyers of mass-produced goods.

This feeling grew stronger with the arrival of the *Experience Economy*. This term was coined by Pine & Gilmore (1999). He argued that consumers were starting to value experiences more than products. In this new economy, goods and services act as props. They help create memorable, personal events for the consumer. This changed the rules of competition. The goal was no longer just to deliver a quality product. It was to stage a unique and engaging experience. The rise of digital culture and social media sped up these trends. People build and share their personal identities online. In this context, objects become important tools for self-expression. Being different became a value. The one-size-fits-all logic of standardization started to look outdated. The stage was set for a new model focused on the user: mass customization.

1.2 The origins and development of mass customization

Standardized production eventually reached its limits. As its weaknesses became clear, a new idea started to take hold. This concept was mass customization. The name itself seems like a contradiction. It suggests merging two opposite ways of thinking. The first is the scale and efficiency of mass production. The second is the personal touch of custom craftsmanship. This chapter will trace the history of mass customization. It began as an intellectual concept and grew into a practical business model.

The rise of mass customization was not just a change in production strategy. It was a complete response to major shifts in the economy, culture, and technology during the late 20th century. Companies faced a new landscape. Consumers wanted more than just generic products. Technology offered new tools to meet these demands. The journey from a forward-thinking idea to a real business strategy shows a fundamental change. Designing for variety became a central challenge for businesses. It also became a major opportunity. The post-industrial era required a new approach, and mass customization provided an answer.

1.2.1 Defining a new paradigm: the apparent contradiction

The term *mass customization* was first used by Stan Davis. He introduced it in his 1987 book, *Future Perfect*. Davis saw a future where technology would allow companies to tailor goods and services to individual needs. He argued this could be done at a cost and speed similar to mass production (Davis, 1987). The idea was powerful, but it needed a clearer business framework.

That framework was provided by Pine (1993). His book described it as the ability "to provide individually designed products and services to every customer through high-process agility, flexibility and integration". The core idea was to solve a basic conflict of the industrial age. That conflict was the trade-off between efficiency and variety. For decades, customers had to choose. They could have affordable, generic products from mass production. Or they could have expensive, bespoke items from artisans. Mass customization promised to offer the best of both worlds.

As the concept developed, an important distinction became clear. This was the difference between customization and personalization. The terms are often used as if they mean the same thing, but they describe different processes. Customization is an explicit process. The customer actively makes choices to design a product. For example, a customer might use an online tool to choose the color, materials, and features of a new car. They are in control of the configuration.

Personalization, on the other hand, is an implicit process. The system proactively adapts its offerings to the individual. It does this based on the person's past behavior, their data, or their stated preferences (Hu, 2013). For example, Amazon's website shows recommendations based on a user's browsing history. This is personalization.

The system is making choices for the user. In contrast, NikeID platform allows a user to design their own unique shoe. This is customization. The user is making the choices themselves.

Furthermore, some scholars have pointed out a gap. This is the gap between the *visionary* idea of mass customization and its practical *working* definition (Kaplan & Haenlein, 2006). The visionary goal was the ability to create a truly unique product for every single customer. In reality, this is often not feasible or desirable. Most successful companies do not offer limitless choice. Instead, they provide a well-designed set of options within a pre-defined *solution space*. This approach gives customers freedom but keeps the company's operations from becoming too complex. It is a balance between choice and manageability.

1.2.2 The post-Fordist drivers: why customization became a strategic necessity

As discussed in the previous chapter, markets in the 1970s and 1980s were becoming saturated. Many companies could no longer grow by simply producing more of the same product. They needed new ways to differentiate themselves from their competitors and create value for customers. Mass customization provided a powerful strategic solution. It allowed companies to shift their competitive focus. Instead of competing only on low cost, they could compete on variety and building a closer relationship with their customers (Porter, 1985).

This strategic shift was supported by a change in economic logic. Businesses moved away from the industrial-age goal of economies of scale. They moved toward the information-age logic of economies of scope (Pine, 1993). Economies of scale are achieved by producing a large volume of a single, identical product. This lowers the cost of each unit. Economies of scope, however, are different. They are achieved when the cost of producing two or more different products together is lower than producing them separately. Flexible production systems made this possible. They allowed companies to serve many different niche markets efficiently.

This entire strategic change would have been impossible without the Information and Communication Technology (ICT) revolution. The development of powerful enterprise software was critical. Systems like Enterprise Resource Planning (ERP) gave companies the tools to manage enormous complexity. Producing a wide variety of product configurations generates a huge amount of information. ICT provided the digital backbone to manage it all. It connected and coordinated everything, from customer orders to the supply chain and the factory floor (Fogliatto *et al*., 2012).

Finally, the supply chain itself had to be completely re-engineered. The traditional model was a *push* system. Companies produced goods based on forecasts of future demand. They then pushed these goods onto the market. This system was slow. It often resulted in large amounts of unsold inventory, which was a major cost. Mass customization required a *pull* system. In a pull system, production is triggered directly by a specific customer's order. This *build-to-order* approach was famously used by companies like Dell. It dramatically reduced inventory costs. It also ensured that every product that was made had already been sold (Kaplan & Haenlein, 2006).

1.2.3 The architectural foundation: designing for variety

While ICT provided the informational nervous system for mass customization, its physical and structural logic was initially built upon a new approach to product architecture. Initially, the key architectural principle that made mass customization viable on an industrial scale was modularity. A modular architecture involves breaking down a product into a system of independent and standardized modules with well-defined interfaces (Baldwin & Clark, 2000). By designing a variety of interchangeable modules, a vast number of unique end products can be created by simply combining them in different ways, much like building with LEGO bricks.

Closely related to modularity is the concept of a product platform. A platform is a common set of components, technologies, and design rules upon which a whole family of related products can be built (Robertson & Ulrich, 1998). The automotive industry, for example, has mastered this approach, using a single underlying platform to produce dozens of different models, each with a distinct look and feel but sharing a common, cost-effective core.

These architectural strategies are often combined with operational strategies like postponement or *delayed differentiation*. This involves keeping a product in a generic, semi-finished state for as long as possible in the production process, and only performing the final customization steps after a specific customer order is received (Lee & Tang, 1997). A classic example is Hewlett-Packard, which for years produced universal power supplies and only added the country-specific plug at the last possible moment, drastically reducing the complexity of managing global inventory (Feitzinger & Lee, 1997).

The final piece of this puzzle is the configurator, the digital tool that allows the customer to navigate the *solution space* and create their desired product. Von Hippel (2001) described these as “toolkits for user innovation”, empowering users to become co-designers. However, a poorly designed solution space can lead to the *paradox of choice*, overwhelming customers with too many options (Piller, 2004). While these architectural strategies were revolutionary, they still confined customization within a predefined system of combinations. The dream of true, unconstrained uniqueness would have to wait for a new class of digital tools and production technologies.

1.2.4 The digital evolution of customization

The history of mass customization is tied to the history of digital technology. Its development can be seen in distinct phases. Each phase was marked by new technologies that made customization more powerful and more accessible.

The first phase took place in the 1990s. At this time, customization was a large-scale, industrial process led by companies. Pioneers like Dell and BMW had the resources to build their own complex IT systems. They also re-engineered their supply chains. The customization process itself was often managed by sales staff or through early, often clunky, software. Success depended on a company’s internal mastery of logistics and its build-to-order processes.

A major shift happened in the 2000s with the rise of the internet. This second phase opened up customization to many more businesses. The web-based configurator became a key tool. It allowed companies of all sizes to offer tailored products to customers around the world. Anderson (2006) explained this change. He argued that the internet lowered distribution costs. This made it profitable for companies to serve a large number of niche markets.

Mass customization platforms became the engine driving this new economic model.

The current phase is defined by a mix of technologies. These include social media, advanced digital design tools, and direct digital manufacturing. Customization has become a social activity. Users share their unique designs on platforms like Pinterest and Instagram. A more fundamental change is also occurring, driven by technologies that challenge the old logic of modularity. Instead of simply combining pre-defined parts, they can generate truly unique shapes from the ground up. This marks a shift from creating variety through combination to achieving genuine mass individualization (Koren *et al.*, 2015).

This convergence of advanced software and direct digital production is a turning point. It creates a clear path toward the original, visionary goal of mass customization.

1.3 The influence of customization on value perception

1.3.1 From function to meaning

As mentioned in the previous paragraphs, the impact of customization goes far beyond the factory. Infact, its real power is not just making varied products, but it is in changing how people value those products.

Today's market is full of products that are functionally the same. Value is no longer based only on utility or price. Instead, value comes from personal meanings and experiences. It comes from the stories that objects carry. Customization is a process. It invites consumers to give personal meaning to items, turning simple goods into meaningful artifacts.

1.3.2 Value beyond utility

The concept of value is central to economic and social theory. For centuries, it was framed by a simple division. On one side was *use value*, which is an object's utility. On the other was *exchange value*, which is its market price. This framework, largely from Marx, was useful for the industrial age.

However, in modern post-industrial societies, it is no longer enough to explain why people buy things.
Thinkers like Baudrillard (1998) offered new ideas. He argued that objects have a *symbolic value*. This value is separate from their function. Objects work as markers in a system of social signs. They communicate meaning about their owner. Similarly, the work of sociologist and intellectual Bourdieu (1984) showed how taste and possessions act as cultural capital. People use them to signal their social position and create distinction.

Building on these theories, modern design and marketing have adopted a broader view of value. The work of Holbrook (2006), for example, expanded the concept. His model includes dimensions like aesthetics, playfulness (or hedonic value), and ethics.

In this new context, design has a different role. It is no longer just about creating material value. It is about mediating perceived value. The focus shifts from *design for consumption* to *design for identity*. The product becomes a tool for self-expression and for telling a personal story. The value of a customized product, therefore, is not just in the object. It is co-created during the interaction between the user and the design system (Schreier, 2006).

1.3.3 Customization and the psychology of ownership

Customization creates value by fostering a sense of psychological ownership. This concept describes the feeling that an object is truly *mine*. This feeling is not just legal, but emotional (Pierce *et al*., 2001). When consumers make choices that shape a product, they invest a part of themselves in it. This personal investment creates a powerful cognitive bias. It is famously called the *IKEA effect* (Norton *et al*., 2012).

The researchers found that people place a much higher value on products they help create. This happens even if the effort is as simple as assembling flat-pack furniture. The higher value comes from a sense of competence and the satisfaction of the effort invested. We love what we create.

This effect is central to mass customization. The user is guided by a digital toolkit. They become a co-creator. They are the author of their own unique product. This changes their relationship with the object. It is no longer a passive purchase.

It is the result of a personal creative journey. Many studies have shown that this feeling of co-creation directly increases the perceived value of a product. The value, therefore, is not just in the finished object. It is also embedded in the experience of the creation process itself (Valenzuela *et al.*, 2009).

1.3.4 Symbolic and cultural dimensions of customization

Customization is also a powerful tool for self-expression. In a world of mass-produced goods, being unique is valuable. Personalizing a product is an act of distinction (Bourdieu, 1984). It is a way to differentiate oneself from the crowd and express a unique identity. The customized object is more than just a functional item. It becomes a statement. It is a tangible piece of a personal narrative. It works like a form of autobiography. Each feature chosen by the owner tells a part of their story, their tastes, and their value (Nurkka, 2013).

This is strengthened by modern digital culture. Social media platforms encourage users to perform their identity. People carefully build and showcase their uniqueness online. Customized products are ideal props for this performance. The value of a customized object is therefore not just personal. It is also social. Its value is tied to its ability to communicate a desired identity to others. This changes the idea of a status symbol. It is no longer just about the rare material or the exclusive brand. It is about the *scarcity of the experience* and the originality of the personal expression. The focus moves from *what I have* to *what I have created*. As stated by Abdul Kudus *et al.* (2016), the ability to hold a truly unique object, one that exists only because of your choices, greatly increases the sense of ownership and attachment.

1.3.5 Economic and strategic perspectives on perceived value

The value created through customization has clear economic benefits. When consumers perceive a product as unique and personally relevant, they are often willing to pay a premium price for it. This price is significantly higher than the price of a standard equivalent (Schreier, 2006). This extra value is a direct return on the company's investment in customization platforms. Companies are no longer selling just a product. They are selling the experience of co-creation and the value of self-expression.

This also changes marketing strategies. The goal shifts from simple *customer satisfaction* to active *customer participation*. By involving consumers in the design process, brands can build much stronger relationships. This co-creation process fosters deep brand loyalty, where the customer feels like a valued partner and not just a passive buyer. Moreover, the data generated from customization toolkits is a valuable asset. It gives companies direct insight into what customers want. It reveals market preferences and emerging trends. This information can be used to improve products and services (Powell *et al*., 2024).

2. Enabling Technologies

2.1 Overview

The idea of value has changed, moving from pure function to personal meaning and experience. This shift requires more than just new business models. It needs a strong technological foundation. This technology must be able to turn individual desires into tangible, unique objects. This paragraph explores the key technologies that provide this foundation. The discussion moves from why customization is valuable to how it is made possible.

The current phase of customization is defined by a combination of advanced digital design tools and direct digital manufacturing. This is a clear departure from the first wave of mass customization. That earlier wave relied on the logic of modularity, which involved combining pre-defined parts in various ways. We are now seeing a new paradigm being developed. Technologies are now capable of creating truly unique shapes, enabling genuine “mass individualization” (Koren *et al.*, 2015). This move from combining existing parts to generating new forms is a turning point. It brings the original, visionary goal of mass customization within reach. To understand this transformation, the following sections will explore some emerging components of this new technological landscape. In particular, Additive Manufacturing, Computational Design, and Generative Artificial Intelligence were identified as core drivers in this context (Huang, 2019; Manavis *et al*., 2024; Regenwetter *et al*., 2022; Urquhart, *et al*., 2022). Each will be analyzed for its specific principles and its individual contribution to making the production of flexible, personalized, and meaningful products a reality.

2.2 Additive Manufacturing

Among the modern customization technologies, additive manufacturing (AM) is one of the most transformative and beneficial (Weller *et al*., 2015). Commonly referred to as 3D printing, AM represents a fundamental shift away from old manufacturing methods that have dominated industry for over a century.

Traditional manufacturing is typically either subtractive or formative. Subtractive methods begin with a solid block of material. A machine then removes material to create the final shape. Milling and carving are common examples of this. This approach can be slow and often creates significant waste material. Formative methods use molds, dies, or presses to shape a material into a desired form. Injection molding and casting are formative processes. This approach is very efficient for producing thousands of identical items. However, creating a custom mold for a single, unique product is extremely expensive and time-consuming. The high cost of tooling makes it unsuitable for customization.

AM inverts this logic completely, as a process of joining materials to make objects from 3D model data. Instead of starting with a block and cutting material away, it builds the object layer upon layer (Gibson *et al*., 2015). The foundation of any AM process is a consistent digital-to-physical workflow. The process begins with a three-dimensional digital model. This model is the blueprint for the physical object. It is typically created using Computer-Aided Design (CAD) software. Then, the final design is sent to a slicing software. It translates the 3D model into a series of two-dimensional cross-sectional layers. The output is a file, often in a standard format like G-code, which contains the instructions for the machine.

The AM machine follows the digital instructions to build the object. It adds, cures, or fuses material carefully, layer by layer. This recreates each slice of the 3D model precisely until the part is finished. The object object often needs post-processing, such as removing temporary support structures that held the part during 3D printing. Post-processing operations may also include smoothing rough surfaces or applying heat treatments to enhance the part's strength and durability. The workflow is direct and data-driven. It removes the need for any special molds or tools for each part.

Additive manufacturing is an umbrella term that refers to a group of technologies, differentiated by the materials used and the processes involved. The "American Society for Testing and Materials" (ASTM) F42 committee identified seven main categories (International Organization for Standardization & ASTM International, 2021):

1. Material extrusion (MEX) Material extrusion is arguably the most widespread and recognizable. One of the most common types is fused filament fabrication (FFF), also known as Fused deposition modeling (FDM). It works by feeding a thin thermoplastic filament into a heated nozzle. The nozzle melts the plastic and extrudes it onto a platform. The melted plastic cools and hardens into place. The part is built up gradually, since the nozzle of the extruder robot follows precise paths to create one layer at a time. The popularity of FFF comes from its simplicity, low cost, and wide availability of polymer materials. It is used broadly in prototyping, education, and, more recently, to produce also end-use products (Attaran, 2017).
2. Powder bed fusion (PBF) These technologies use a high-energy source, such as a laser or an electron beam, to fuse fine particles of material in a powder bed (Sun *et al.*, 2017). This method works both with polymers and metals and is known for producing parts with high mechanical strength and complex geometries, often without the need for support structures.

3. Binder jetting (BJT) A liquid bonding agent is deposited to join powder materials. A thin layer of powder is spread over the build platform, and a print head deposits droplets of a binder to bond the powder particles together, forming one layer of the object.
4. Directed energy deposition (DED) Thermal energy fuses materials as they are deposited. A nozzle, usually on a multi-axis arm, deposits and melts material at the same time. This material is typically metal powder or wire. The energy source can be a laser, electron beam, or plasma arc. This method is often used for repairing parts or adding material to existing ones.
5. Material jetting (MJT) Here, droplets of build material are deposited and solidified to make a part. It's like a 2D inkjet printer. But instead of ink, it deposits photopolymers or wax droplets that are cured with UV light.
6. Sheet lamination (SHL) A process in which sheets of material are bonded and cut to form an object. Layers of material, such as paper, metal, or polymer, are bonded together using heat, pressure, or adhesives. Then they are cut to shape with a laser or a blade.
7. Vat photopolymerization (VPP) It works by selectively curing a liquid photopolymer resin with a UV light source, layer by layer. These processes offer exceptional surface finish and can produce parts with very high-resolution details.

The strategic value of AM for customization is significant (Dean & Pei, 2012; Liu & Yang, 2023), as it enables better fulfillment of customer demand through greater design freedom (Khajavi *et al*., 2014). Designers are liberated from the constraints of traditional manufacturing and are facilitated to create functionally optimized, complex geometries. AM also enables part consolidation, where multiple simple components can be redesigned into a single, complex part. This reduces assembly time and potential points of failure.

AM technologies require no additional tooling and molds, offering production flexibility. The cost to produce a single unique item is virtually the same as producing a small batch of identical items. This dismantles the economic logic of economies of scale, which requires high volumes to be profitable. It makes "one-off production economically viable" (Ford & Dean, 2013; Weller *et al.*, 2015). A company can produce a series of completely different parts just by loading new digital files. This creates an agile and highly responsive manufacturing system.

AM has important sustainability benefits. As additive processes, material is deposited only where it is needed. This dramatically reduces the waste associated with subtractive processes. This approach aligns with a "zero-waste" production philosophy. When combined with computational design, which will be described in the following paragraph, AM can create parts that are strong yet lightweight. This reduces material consumption. Lighter parts can also lower the energy footprint of a final product during its use phase, especially in vehicles (Hao *et al.*, 2010).

2.3 Computational Design

Computational Design (CD) represents a fundamental transformation in how designers conceive, develop, and realize artifacts. It is not merely the use of digital tools, but a problem-solving methodology that leverages computational power to develop design solutions (Caetano *et al.*, 2020).

Its roots in fact predate modern digital tools. As early as the 1970s, Moretti (1971) theorized a "Parametric Architecture" based on mathematical rigor and parameters. With the rise of digital technology, Mitchell (1990) formalized design as a computational act, defining it as the "computation of shape information".

The crucial distinction lies in the fact that CD uses computation to actively develop the design, moving beyond the traditional Computer-Aided Design (CAD). The process harnesses computational power to automate procedures, manage large amounts of information, flexibly incorporate changes, and assist in form-finding through automated feedback. This paradigm creates a synergy between design thinking, traditionally applied to complex and ill-defined "wicked problems", and computational thinking, which involves formulating problems in a way that can be executed by an information-processing agent (Kelly & Gero, 2021).

The primary creative act becomes the design of the process (the algorithm) rather than just the product. Consequently, knowledge no longer resides solely in the finished artifact but is captured, structured, and reusable within the model itself, with profound implications for knowledge management and collaboration (Caetano *et al.*, 2020). The effectiveness of computational design depends on an ecosystem of technologies that have evolved to support this new way of designing. The transition from rigid CAD systems to Visual Programming Languages (VPLs) like Grasshopper and Dynamo was a turning point, making algorithmic concepts accessible to designers without requiring advanced textual programming skills (Manavis *et al.*, 2023; Nagy, 2017).

To navigate the complexity of computational design, it is essential to distinguish its main methodologies: parametric, generative. Although interconnected, they respond to different intentions and processes (Caetano *et al.*, 2020; Ramage, 2022).

Parametric Design is a process that uses parameters and rules to define a system, leveraging associative geometry to establish dependencies between project elements. The result is not a single design, but the symbolic representation of a family of objects or a solution space (Caetano *et al.*, 2020). The designer explores this space by manipulating input parameters, thereby generating infinite variations of a base model while maintaining its internal consistency (Manavis *et al.*, 2023).

Generative design is a more autonomous process in which the designer defines objectives and constraints, and an algorithmic system generates, evaluates, and evolves solutions independently (Gradišar *et al.*, 2022). Unlike parametric design, the process is often non-traceable: the relationship between simple input rules and the complexity of the output can be unpredictable, leading to unexpected results that the designer could not have conceived. The main engine of generative design is represented by evolutionary algorithms, particularly Genetic Algorithms (GAs). These are especially well-suited for complex design problems because they can handle large parameter spaces and multiple, conflicting objectives (Turrin *et al.*, 2011; Generative Design Primer, n.d.). The process mimics natural evolution: an initial population of solutions is generated, evaluated against a "fitness function", and "evolved" through successive generations via mechanisms of selection, recombination (crossover), and mutation, converging toward high-performance, optimized solutions (Generative Design Primer, n.d.).

The adoption of computational methodologies, particularly generative ones, is radically transforming the design process. Instead of proposing a solution based on experience and then analyzing it, the designer concentrates on the iterative formulation of the problem itself – parameters, constraints, and evaluation criteria – within a computational model (Gradišar *et al.*, 2022).

In the context of CD, it is crucial to distinguish between topology optimization and exploration (Turrin *et al.*, 2011). Topology ptimization aims to find the single "best" solution according to a quantifiable fitness function (e.g., minimum structural weight). Exploration, on the other hand, is a broader activity whose purpose is to generate a wide range of diverse solutions to help the designer understand the "lay of the land", reveal trade-offs between different objectives, and discover unexpected solutions. The two processes are not mutually exclusive: a topology optimization process can serve exploration if the designer analyzes not only the best result but the entire population of solutions to understand performance trends.

2.4 Generative Artificial Intelligence

The rapid evolution of artificial intelligence is creating a profound impact on numerous sectors, with its influence recently expanding into the domain of design and creative processes. At the forefront of this transformation is Generative AI (GenAI), a specific category of AI algorithms designed not just to analyze existing data but to create new and original content, such as text and visuals. It learns to do this by studying large amounts of data (Feuerriegel *et al.*, 2023).

This ability comes from leveraging advanced neural networks. Transformers handle language tasks, as seen in OpenAI's GPT models. For visual generation, Diffusion Models enable highly realistic outputs, powering tools like Midjourney, DALL-E, and Nano Banana. GenAI is changing the way humans and machines work together, acting not just as a passive tool but as an active collaborator in the creative process (Chen *et al.*, 2025). This shift is visible across several modes in design workflows. Text-to-text models can suggest ideas, scan trends, or draft the first version of a design brief. Another powerful impact is in visual generation. Image-to-image platforms convert short text prompts into a wide set of visual concepts within seconds. Designers use them to explore different aesthetics, break creative blocks, and build mood boards (Azzola *et al.*, 2025; Filippi, 2023). This interactive process introduces useful serendipity – unexpected images that spark new directions – and opens a vast design space that would be difficult to cover manually.

Further along, tools such as Vizcom speed the move from sketch to rendering or even sketch-to-3D. They turn rough drawings into detailed, photorealistic images or 3D models in minutes. This compresses a traditionally slow phase of the design process, supporting rapid iteration and refinement.

The role of these tools in facilitating customization lies in their immediacy and intuitive use. Some areas for improvement remain, such as the need for some skills in engineering perfect prompts and the limited understanding of material properties and practical functionalities (Azzola *et al.*, 2025; Hong *et al.*, 2023). Nevertheless, they remain powerful communicative instruments. Designers can quickly translate a user's vision into a concept tailored to their aesthetic preferences. At the same time, the intuitive nature of these tools makes them accessible even to relatively inexperienced users, allowing them to independently create drafts aligned with their desires and engage in a more accessible design process that helps them convey their ideas more effectively to professionals.

PART 2

Design in Action

3. Application Scenarios Across Relevant Sectors

3.1 Flexibility and freedom of form: the furniture sector

The furniture sector has historically been an arena for exploring the relationship between form, function, and production. It now stands as one of the most fertile grounds for the application of enabling technologies to expand the potential of customization. The pursuit of greater customization in furniture is not merely about offering choices of color or material, but about leveraging complex and unique forms to create products that are deeply personal and tailored.

In the early stages of furniture design, GenAI research is opening new possibilities for designers and businesses. AI-Generated Content (AIGC) is now an important tool for generating many ideas quickly. Designers use it to move beyond standard forms and to experiment with new styles (Li *et al.*, 2024). Work is also underway to develop interactive AI systems that guide non-expert users through making their own furniture. This helps democratize the design process and gives more people a chance to create personal items (Jiang, 2025).

Beyond the phase of idea development, AM and CD enable the creation of furniture with detailed organic shapes, internal lattice structures, and unique textures. These technologies go beyond the limits set by mass production. Catalog designs can potentially be modified and adapted according to spatial requirements or users' functional needs without complex operations. Designers can now produce one-of-a-kind pieces whenever they are needed, not just in big batches (Čavlović *et al.*, 2023; Espino *et al.*, 2024).

In public spaces, where serving the needs of the widest possible audience is essential, these technologies offer powerful tools for customizing urban furniture. This customization goes beyond mere aesthetics to actively promote inclusivity. By engaging citizens directly in the design process, the approach ensures that the resulting furniture is not just personalized, but purposefully designed to meet the community's true needs (Derrible, 2016; Kantaros *et al.*, 2025).

Model No.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
MASS CUSTOMIZATION/ ON-DEMAND PRODUCTION/ AGRICULTURAL BYPRODUCTS/ SUSTAINABLE INTERIORS

References: (Hendrison, 2024)

Category: Furniture

Overview: Model No. is a U.S.-based furniture company that keeps customization at the core of its business model by leveraging large-format additive manufacturing. For interior designers, architects and organizations, the company offers distinct pathways, from modifying existing catalog designs (adjusting dimensions, materials, finishes, and configurations) to creating entirely new pieces developed designed from the ground up. Model No. uses Titan Robotics' 3D printing setup, fabricating pieces only after an order is placed. The company partners closely with clients to refine 3D models and renderings prior to manufacture. This approach allows them to support unique spatial briefs (e.g. commercial offices, hospitality, retail environments) and maintain its sustainability ethos through on-demand and digitally-driven production. Their materials include bio-polymers derived from agricultural byproducts and food waste.

Bone Chair

References: (Joris Laarman Lab, n.d.)

Category: Furniture

Overview: Joris Laarman's "Bone Chair" from 2006 is a relevant example of CD and AM can work together. The inspiration was drawn directly from nature, mimicking the way bones develop, growing stronger and denser only where stress is applied. To achieve this, Laarman used a topology optimization software derived from the automotive and aerospace fields to digitally simulate this natural process. The result is an organic, skeletal form that strips away all non-essential material, leaving behind a structure that is both highly efficient and visually striking. To bring the chair to life, its intricate shape was first produced by casting aluminum in 3D printed ceramic molds. This method allowed for the precise creation of its complex geometry, merging digital accuracy with the hands-on touch of craft finishing. It was first shown at Friedman Benda and now is held in MoMA's permanent collection.

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
BIOMIMICRY/ STRUCTURAL EFFICIENCY/ DIGITAL CRAFTSMANSHIP

Topology-optimized furniture prototypes

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
STRUCTURAL PERFORMANCE/
FLAT-PACK ASSEMBLY/
MATERIAL EFFICIENCY

References: (Ma *et al.*, 2021)

Category: Furniture

Overview: Ma *et al.* (2021) present a series of customized furniture prototypes developed through a workflow that combines topology optimization, and advanced manufacturing techniques. The process allows designers to generate efficient and visually novel forms based on structural performance rather than intuition alone. Among the pieces created, the “Jue Chair” stands out. Inspired by the profile of an ancient Chinese vessel, it was designed through bi-directional evolutionary structural optimization (BESO) and manufactured using fused filament fabrication (FFF). The chair was printed in several parts and assembled, demonstrating the potential of AM for complex geometries. The study also includes flat-pack furniture, such as chairs and tables, made through subtractive manufacturing – CNC and laser cutting of plywood and acrylic sheets – to ensure affordability and rapid production.

Print Your City

References: (Arvaniti-Pollatou, 2019)

Category: Furniture

Overview: Print Your City is a research initiative by the Dutch studio The New Raw that transforms plastic city-waste into 3D printed urban furniture and street-elements, with citizen participation. In 2018 they collaborated with the Municipality of Thessaloniki and Coca-Cola Greece as part of a broader Zero Waste Future initiative. The project invited citizens to transform their household plastic waste into customized urban furniture through an interactive online platform. Participants could design benches, planters, and bike racks – choosing colors, shapes, and even functions such as dog-feeding bowls or tree-pots. The objects were then 3D printed locally at the city's Zero Waste Lab using robotic arms that extruded recycled plastic flakes. Over 3000 unique design proposals were submitted, recycling approximately four tons of plastic waste. The project demonstrated how circular-economy principles, public engagement, and additive manufacturing can combine to create functional, site-specific furniture. It also served as an early and influential example of citizen-driven customization in sustainable urban design.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
CITIZEN ENGAGEMENT/
PLASTIC RECYCLING/
URBAN REGENERATION/
CLOSED-LOOP CYCLE

Voxel Chair V1.0

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
STRUCTURAL TEXTURE/
VOXEL AESTHETICS/
DIGITAL ART

References: (Nagami, n.d.)

Category: Furniture

Overview: The Voxel Chair V1.0 from Nagami (designed by Manuel Jiménez García & Gilles Retsin) is a landmark in large-format robotic 3D printing. The piece was created using custom software that controlled thousands of line segments in real time. After structural analysis, a 2.36 km continuous filament path was generated to “draw” the chair in the air, using the intricate visible layered lines as a deliberate textural and formal element. The chair’s frame was printed in one continuous robotic print using plastic, then finished for use. It goes beyond furniture: the Voxel Chair now sits in the permanent collections of institutions such as Centre Pompidou in Paris, showing how digital design and robotic fabrication merge art, architecture and industry.

Participatory design for 3D printed chair

References: (Lundgren, 2021)

Category: Furniture

Overview: The master's thesis project for a 3D printed furniture concept for learning spaces by Lundgren (2021) is a relevant case study showing how these technologies can enable participatory design. Instead of a top-down design approach, the student engaged directly with the end-users – other students and educators – through workshops and co-design sessions. The users' needs were translated into a 3D printed lounge chair that was not only functional, but also capable of communicating and inspiring learning at an educational level, using principles of semiotics and pedagogical design. The user therefore is no longer just a consumer choosing from a list of options but an active participant in the creation of their own environment, which in turn fosters a stronger sense of ownership and attachment to the final product.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
CO-DESIGN WORKSHOPS/ EDUCATIONAL SPACES/ USER-CENTRED PROCESS/ PEDAGOGICAL DESIGN

PORTAL collection by Caracol

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
GENERATIVE AI

KEYWORDS:
SKETCH-TO-MODEL/
BIO-BASED MATERIALS/
INDUSTRIAL SCALABILITY

References: (Caracol AM, 2025)

Category: Furniture

Overview: The PORTAL collection explores how generative AI, robotic production and circular materials can reshape furniture design. Designers from around the world used Vizcom AI tool to turn sketches into 3D models. These models were then printed on Caracol's large-format robotic system Heron AM, using recycled and bio-based materials. Each chair in the series features a unique form – ranging from geometric to organic – but all were produced on the same robotic line, using high-flow extrusion and multi-planar print strategies. The printed frames were manufactured on demand, locally, reducing waste and inventory. The project was showcased at Milan Design Week 2025, allowing live printing in the exhibition space and emphasising the link between creative freedom and industrial scalability. PORTAL stands for a model of furniture production that is customizable, efficient and sustainable.

Figure 1.
Bone Chair.
Credits: Joris Laarman.

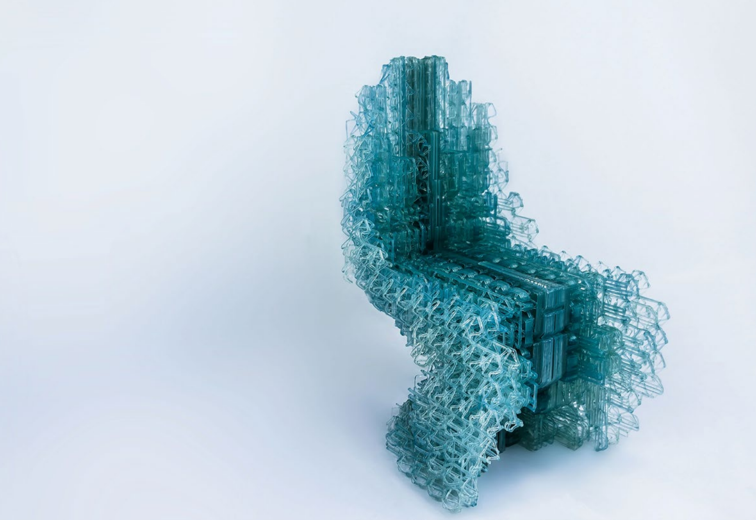

Figure 2.
Voxel Chair 1.0.
Credits: Nagami.

Figure 3.
PORTAL collection.
Credits: Caracol.

3.2 Uniqueness and ergonomics: products for personal use

The human-centered design approach is essential for personal and wearable products, which often experience continuous use and must address specific ergonomic needs tied to the particular activities or professions of users throughout their daily routines. Beyond purely mechanical fit, factors such as comfort, usability, and even the sensory experience of the user are imporant in shaping satisfaction and long-term engagement with these products. Ergonomic adaptation forms the foundation for preventing discomfort, fatigue, and injury during extended use, ultimately enhancing the quality of life and user well-being.

In recent years, the application of novel enabling technologies has elevated the possibilities for achieving this kind of product uniqueness and ergonomic optimization. AM facilitates the creation of individualized geometries in which material use is optimized to fit anatomical or functional requirements at the individual level (Eyers & Dotchev, 2010; Kermavnar *et al.*, 2021). This moves customization beyond superficial aesthetic variation to shape and internal structure adaptation that directly impacts performance and comfort (Xu *et al.*, 2023).

The shape flexibility unlocked is particularly relevant in this case. It allows for the production of complex internal structures, for example, lattices and variable-density materials, that contribute to improved comfort, resilience, and functionality (Pagliari *et al.*, 2025). This supports the design of products adapted to diverse and nuanced user morphologies, mitigating pressure points and reducing the risk of injury caused by prolonged wear or use. Such innovation is especially relevant for prosthetics, orthodontics, and orthotic devices, areas in which AM has begun to revolutionize design approaches (González *et al.*, 2018).

Aspects such as physical requirements or multiple users' unique preferences can be met through parametric modeling, allowing immediate and iterative design modifications (Van Wijngaarden, 2014). This process supports the scaling of mass customization strategies, reducing traditional bottlenecks while maintaining ergonomic rigor and personalization depth.

Within this context, incorporating 3D scanning technologies capable of collecting precise anthropometric data further facilitates the production of tailored products (Khan *et al.*, 2021). By capturing individual body measurements and anatomical features, these digital methods enable exact replication of the user's physical characteristics in the product design, augmenting the degree of personalization and ergonomic fit achievable.

Weight reduction achieved with the help of innovative materials and optimized design geometries remains essential for ergonomic improvements in wearable and held-by-hand products. Lightweight designs decrease user fatigue, increase ease of use, and add value, which is particularly significant in medical, sports, and assistive product sectors. In this scenarios, user comfort directly correlates with functional effectiveness and adoption.

These emerging technologies open new opportunities for people with disabilities (Lynxter, 2025). The fabrication of assistive devices that merge functional efficacy with aesthetic and ergonomic customization becomes more accessible and cost-effective. These users can therefore get increased autonomy and enhanced quality of life. The ability to fine-tune devices to the individual user and dynamically adapt designs propels accessibility and inclusivity forward.

While GenAI is still predominantly in an exploratory phase within this sector, Recent research shows potential for improving ergonomic aspects, mentioning the ability to gather information from end users and guide design through suggestions based on the data collected (Adhikari *et al.*, 2025). A study by Özsoy (2025) gathered the feedback from several end-users and students of engineering and industrial design on the use of GenAI in product design for home appliances. Most participants recognised the potential benefits that these tools can offer in improving functionality and ergonomics, while acknowledging that the technology is still nascent and needs further development.

Tool handle for surgeons

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
HAND ANTHROPOMETRY/
PARAMETRIC FITTING/
MEDICAL DEVICE

References: (González *et al*., 2018)

Category: Products for personal use

Overview: González *et al.* addressed the ergonomic problems surgeons face with “one-size-fits-all” laparoscopic tools, which often cause discomfort and injury. The goal was to design a fully personalized handle that adapts to each user’s unique anatomy. Researchers studied the hand anthropometry of 135 surgeons and discovered that a single measurement, the Palm Length Measured (PLM), could be used as a reliable scaling factor for a 3D parametric handle design. Using this key insight, a custom-fit handle can be generated for any surgeon by measuring their PLM and then fabricating the unique design using AM. This greatly improves comfort and functionality, which was confirmed as “completely satisfactory” in validation tests.

Shoe insole

References: (Xu *et al.*, 2023)

Category: Products for personal use

Overview: This study details a design method for a highly personalized ergonomic insole that considers an individual's joint biomechanics for improved comfort and rehabilitation. The design is tailored by capturing the user's unique foot anatomy through 3D scanning and plantar pressure mapping, which identifies high-pressure zones during movement. The insole features a lightweight lattice structure with variable porosity, based on a Triple Periodic Minimal Surface (TPMS). The density of this structure is computationally optimized to match the user's pressure map – denser in high-pressure areas like the heel and sparser under the arch, providing customized support. This 3D-printed TPU insole was validated using Finite Element Analysis (FEA). Compared to a generic insole, the custom design distributed pressure more evenly and, during a simulated walk, reduced the maximum peak stress by nearly 17%, demonstrating superior shock absorption and stability.

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
LATTICE STRUCTURES/ VARIABLE DENSITY/ SHOCK ABSORPTION

Shoe midsole

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
FOOTWEAR ERGONOMICS/ ZONAL STIFFNESS/ LATTICE STRUCTURE

References: (Hössinger-Kalteis *et al.*, 2024)

Category: Products for personal use

Overview: This research from Hössinger-Kalteis *et al.* (2024) shows a design method for creating individualized, 3D printed shoe midsoles that provide a custom ergonomic fit and improve foot comfort. The process begins with a 3D scan of a mold made from the user's foot, capturing their unique anatomy. This custom shape is then combined with a simplified stress map that divides the sole into high, medium, and low-pressure zones based on movement. The midsole is filled with a lightweight lattice structure, and using FEA simulations, the thickness of its struts is optimized for each zone. High-pressure areas receive thicker struts for more support, while low-pressure areas have thinner ones. The final designs are 3D printed using Selective Laser Sintering (SLS), a subtype of powder bed fusion, with a flexible TPU material. Although mechanical tests showed similar performance, subjective user feedback found one structure more comfortable, highlighting the importance of personal perception in ergonomics.

Office chair backrest

References: (Pagliari *et al.*, 2025)

Category: Products for personal use

Overview: Standard office chairs often lead to poor posture and musculoskeletal issues. This study presents a method to enhance ergonomic comfort by developing a highly personalized backrest. The process begins with a high-resolution 3D scan of the user's back, captured swiftly while they maintain a correct posture to record their unique anatomical shape. Using Blender software, custom cushions are digitally modeled to perfectly fill the gap between the user's back and a scan of the standard chair backrest. These personalized cushions are fabricated using cost-effective Material Extrusion (MEX) 3D printing with a flexible TPU filament. They feature a specialized internal closed-cell structure called "Polyfoam" that mimics the comfort of expanded foam. The result is a chair providing precise, tailored support, with a final comparative scan verifying a notable improvement in posture alignment. The custom fit also provides a unique "postural retraining" effect by making incorrect seating positions uncomfortable. Furthermore, the non-porous material offers superior hygiene compared to standard fabric upholstery.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
POSTURAL CORRECTION/ CUSTOM CUSHIONING/ WORKPLACE ERGONOMICS/ FLEXIBLE STRUCTURES

Camera handle

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
INCLUSIVE DESIGN/
ACCESSIBILITY/
GRIP OPTIMIZATION/
ASSISTIVE DEVICE

References: (Lynxter, 2025)

Category: Products for personal use

Overview: Lynxter developed a tailor-made camera handle for a professional photographer who has a disability in her right hand. The process began with a scan of the hand and the interface area, allowing designers to generate a personalized handle that adapts perfectly to her anatomy – curvature, grip size and support zones all designed for her specific use. The customized component was rapidly iterated and 3D printed in suitable materials, enabling the photographer to hold and control their camera more comfortably and securely. Alongside, a silicone-based ergonomic aid was printed to provide soft, supportive contact surfaces and optimized grip. The result is a product that not only facilitates daily professional work but also exemplifies how customization and ergonomics enabled by additive technologies can combine to solve real-life accessibility and usage challenges.

Hand splint

References: (Yang *et al*., 2020)

Category: Products for personal use

Overview: A study by Yang *et al*. (2020) developed accurate 3D models of hands for the customisation of ergonomic products, with the aim of overcoming scanning errors caused by variations in posture. The key to personalization is a Statistical Shape Model (SSM), which is a parametric digital 3D model of the human hand. This model was built by analyzing 59 different hand scans to understand the primary ways in which hand shapes vary across the population. This model can be quickly adjusted to precisely match an individual's hand shape with high accuracy. The rapid design of personalized items is then enabled and demonstrated with a custom-fit, 3D printed hand splint that automatically conforms to the user. The splint is specifically designed to stabilize and support the thumb. Because it is generated directly from the user's hand geometry, the fit is exact, ensuring that support is applied precisely where it's needed without causing pressure points or discomfort.

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
PARAMETRIC MODEL/ MEDICAL REHABILITATION/ ORTHOTICS/ PRECISE FITTING

Customized sunglasses

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
BESPOKE EYEWEAR/
FACIAL ADAPTATION/
PARAMETRIC FRAMES/
SELECTIVE LASER SINTERING

References: (Van Wijngaarden, 2014)

Category: Products for personal use

Overview: The student project by van Wijngaarden (2014) focused on the development of customized sunglasses. Using photogrammetry, 3D models of faces were captured with millimeter-level accuracy. Based on these digital models, several adjustable parameters were defined within the 3D model of the sunglasses frame, allowing the geometry to be adapted to different face shapes and sizes. This parametric approach made it possible to design frames that not only fit comfortably but also maintained aesthetic consistency across variations. To assess the mechanical performance of the different frame designs, FEA models were conducted to test and compare the stiffness of the models under simulated loads. A comparative analysis between this digital workflow and traditional eyewear manufacturing methods highlighted the advantages of Additive Manufacturing technologies, particularly in terms of customization, production flexibility, and environmental sustainability. The final prototypes were produced in PA12 using Selective Laser Sintering. The project also explored potential commercial applications and the scalability of the process.

Figure 4.
Scanning process and 3D printed backrest. Credits: Pagliari *et al*., 2025.

Figure 5.
Testing of the 3D printed midsole model. Credits: Hössinger-Kalteis *et al*., 2024.

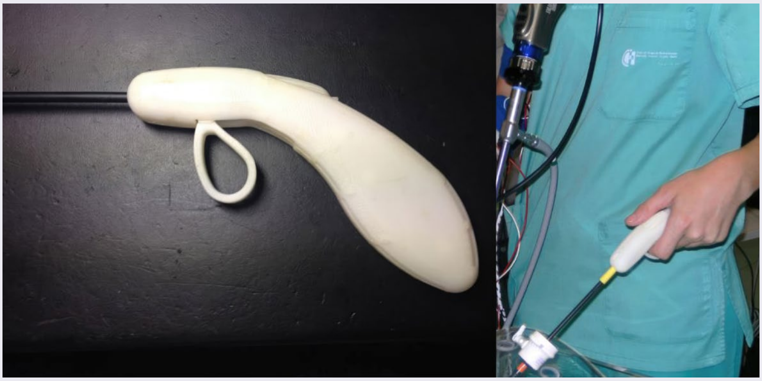

Figure 6.
Assembled prototype being tested. Credits: González *et al*., 2018.

3.3 Lightness and performance: the automotive sector

The automotive industry historically represents a leading and competitive sector for pushing innovation across various areas (Vasco, 2021), with particular focus on lightweight design, performance optimization, and manufacturing efficiency. The rising demands for sustainability, vehicle customization, and cutting-edge aesthetics have further accelerated the adoption of advanced technologies. AM and CD have extended the limits of traditional production, enabling great opportunities in performance advancements (Hamza *et al*., 2025). The geometries derived from the use of these methods result in important improvements in weight reduction, as the material usage is reduced to minimum (Sarvankar & Yewale, 2019). Therefore, in this case, customization becomes also functional and potentially cost-effective (Sarma & Srivastava, 2024).

These applications primarily involve the redesign of individual components, including the possibility of integrating functional consolidation. Multiple sub-assemblies can be merged into monolithic structures that enhance overall vehicle dynamics and fuel efficiency. This not only reduces weight, but also minimizes assembly joints, decreasing points of failure and maintenance needs in high-performance applications.

In some more advanced applications, these technologies extend beyond single elements to encompass larger-scale implementations, where they account for a substantial portion of a vehicle's structural or functional architecture. For instance, entire chassis frames or propulsion assemblies can be reimagined.

While production benefits and performance enhancements have traditionally motivated automotive innovation, an equally transformative shift involves the aesthetic and formal freedom unlocked by these technologies. These approaches favor the emergence of shapes that echo natural load paths and bionic processes rather than adhering strictly to conventional automotive archetypes (Jankovics & Barari, 2019; Wischeropp *et al*., 2019). The results are singular, often iconic components that blend structure and form in a data-driven synthesis of engineering and creativity.

GenAI in the automotive industry remains largely a technology tied to the early stages of the design process, from concept ideation to concept presentation (Li *et al.*, 2024). However, recent research is developing new ways to integrate it with quantitative evaluation criteria (Aréchiga *et al.*, 2023; Dey, 2023). This can potentially drive a shift toward data-centric design paradigms where GenAI not only accelerates ideation but also enables predictive simulations that forecast real-world performance metrics.

Toyota GenAI tool

TECHNOLOGIES:
GENERATIVE AI

KEYWORDS:
INNOVATIVE TEXT-TO-TIMAGE/ PHYSICS-GUIDED DESIGN/ AERODYNAMIC OPTIMIZATION

References: (Aréchiga *et al.*, 2023; Dey, 2023)

Category: Automotive

Overview: Toyota Research Institute developed a generative AI tool based on the StableDiffusion denoising model to aid vehicle designers. It directly addresses the limitation of standard text-to-image models, which struggle to parse and enforce quantitative engineering constraints alongside stylistic prompts. While designers can generate initial sketches using text prompts for stylistic attributes, the institute integrated physics-based guidance into the process. During image generation, a surrogate model trained on fluid-dynamics (CFD) simulation data predicts the vehicle's drag coefficient from intermediate 2D renderings. Gradients from this drag estimator then guide the diffusion sampling, optimizing the vehicle's shape for lower aerodynamic drag – a key factor in fuel efficiency – while simultaneously preserving the user's stylistic intent. This approach aims to accelerate the design process by shortening the traditionally lengthy iteration loop between aesthetic design and engineering validation.

Motorcycle throttle cam

References: (Ferretti *et al.*, 2023)

Category: Automotive

Overview: This study details the redesign of a motorbike throttle cam to create a customized, ergonomic solution for a rider with limited wrist mobility. To optimize the design, the cam's central body was targeted for lightweighting using nTop software. FEA simulations analyzed stress under key load conditions and a stress-based lattice structure (Tet-oct vertex centroid type) was then generated, varying the strut thickness (from 0.8 mm to 2.5 mm) according to the local stress levels. Thicker struts were placed in high-stress areas. This approach significantly reduced weight and material usage while maintaining the necessary stiffness. The final, optimized component was manufactured using MSLA (Masked Stereolithography) 3D printing with a tough resin, resulting in a lighter, cheaper, and ergonomically superior part tailored to the rider's specific needs.

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
ADAPTIVE EQUIPMENT/ STRESS-BASED LATTICE STRUCTURE/ CUSTOM ERGONOMICS

Formula Student A-arm

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
SAFETY-CRITICAL PART/ CHASSIS LIGHTWEIGHTING/ CONVERGENT MODELING

References: (Junk & Rothe, 2022)

Category: Automotive

Overview: Junk & Rothe (2022) detail the redesign of an A-arm, a highly stressed, safety-critical chassis component for a Formula Student race car, using a synergistic approach of generative design and fiber-reinforced AM. Starting with defined load cases (4800 N tension/compression), an initial, complex geometry was generated using Siemens NX software. However, this preliminary design proved challenging for optimal fiber placement due to its filigree nature. The design was subsequently refined using *Convergent Modeling* techniques to reinforce struts, creating more space to strategically embed continuous carbon fibers within the Onyx matrix material (PA6 with short carbon fibers). The final part, manufactured on a Markforged system, integrated fibers across multiple layers. Generative design and fiber-reinforced AM combination demonstrated significant improvements over the conventionally milled aluminum version, achieving a remarkable weight of just 45.3 g (vs. 286.3 g) and an 81% reduction in cost.

Bugatti brake caliper

References: (Sarvankar & Yewale, 2019; Wischeropp *et al.*, 2019)

Category: Automotive

Overview: Bugatti teamed up with Fraunhofer IAPT to rethink the brake caliper for the Chiron hypercar, demonstrating the potential of emerging technologies to work on braking gear. The Chiron packs the strongest production brakes, demanding extreme performance alongside low weight. The old caliper, made from tough aluminum, came in at about 4.9 kg. For the redesign, the team picked a Ti-6Al-4V titanium alloy, drawn to its great strength against weight. Topology optimization and inspiration from nature's designs led to an organic shape that only AM could handle. That cut the weight by more than 40%. The new design features functional integration, with brake fluid paths right into the caliper. This allowed to cut down on extra parts. The resulting component, printed via Laser Beam Melting on an SLM 500HL, was the world's largest functional 3D printed titanium part at the time.

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
TITANIUM ALLOY/ FUNCTIONAL INTEGRATION/ BIONIC STRUCTURE/TOPOLOGY OPTIMIZATION

APWorks Light Rider Project

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
ORGANIC FRAME/
LIGHTWEIGHT PRODUCTION/
E-MOBILITY

References: (Scott, 2016)

Category: Automotive

Overview: Light Rider is an electric motorcycle project, developed by APWorks. The frame draws straight from nature, using an algorithm that echoes bionic builds and growth like bird bones. What comes out is a flowing, hollow branch structure – light at just 6 kg yet tough enough for the road. Traditional methods like milling or welding could never pull this off. They built it with selective laser melting from Scalmalloy, an aluminum mix that packs nearly titanium's strength. The whole bike tips the scales at 35 kg, 30% below standard e-bikes. This approach, rooted in algorithms and 3D printing, nails the best strength-to-weight balance.

Czinger 21C

References: (Kerns, 2021)

Category: Automotive

Overview: The Czinger 21C hypercar is the most advanced production vehicle integrating CD and AM technologies at such a high level. Limited to 80 units, the car shows how customization, lighter builds, and flexible production can come together in one package. Over 350 metal parts were 3D printed in its frame, suspension, brakes, drivetrain, and even the gearbox housing. Kevin Czinger's idea took shape using special aluminum alloys built just for high speed and crash protection, going beyond what standard materials could handle. Generative design and topology optimization led to flowing, connected shapes that cut weight by 15 to 25% from already light setups. This car proves out the Divergent Adaptive Production System, or DAPS – a full setup of software and hardware to swap old-tool heavy car making for something digital and adaptable.

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
WEIGHT REDUCTION/
CUSTOM ALLOYS/
TOPOLOGY OPTIMIZATION

HV-001

TECHNOLOGIES:
ADDITIVE MANUFACTURING/
COMPUTATIONAL DESIGN

KEYWORDS:
ORGANIC SHAPES/
CONCEPTUAL DESIGN/
VISIONARY PROJECT

References: (Sheth, 2022)

Category: Automotive

Overview: The HV-001 concept car, designed by Dubai-based Ayoub Ahmad, represents a visionary and radical application of computational tools for an automotive project. Ahmad defined specific conditions, allowing algorithms to generate an organic, skeletal form optimized for strength, minimal material use, and aerodynamics – much like natural evolution designs skeletons. The car's chassis effectively becomes its body, featuring an exoskeletal framework with open spaces where material isn't structurally necessary and connective pillars supporting key stress points. Its mesh-like surfaces incorporate dimples and negative spaces, further reducing weight for energy efficiency. Such intricate geometries, rich with undercuts and complex contours, necessitate 3D printing for fabrication, extending even to the organic wheel rims and cockpit elements. This approach yields a form dictated by function and efficiency, providing a glimpse into potential future automotive designs where additive techniques enable extreme, performance-driven geometries.


Figure 7.
3D printed redesign model of the Bugatti Chiron brake caliper. Credits: Bugatti Newsroom.

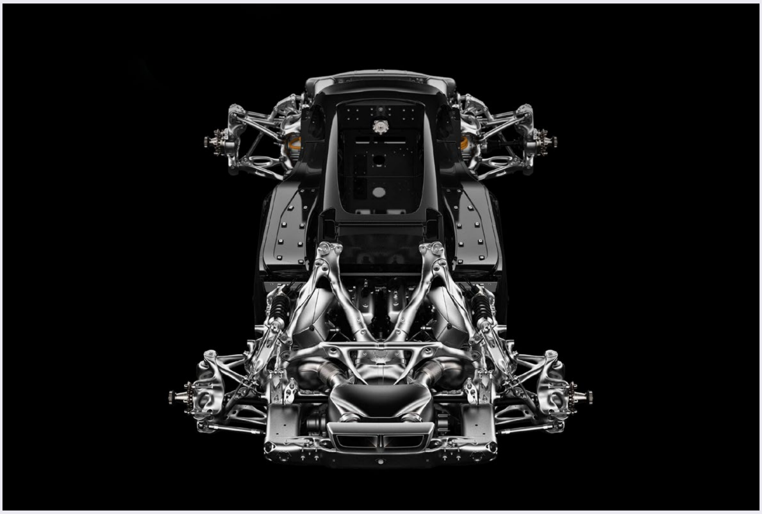
Figure 8.
Chassis of the Czinger 21C hypercar. Credits: Czinger.


Figure 9.
Render of the HV-001 concept car. Credits: Ayoub Ahmad.

4. Technology-Driven Transformations in the Yacht Industry

4.1 Evolution of demand against composite manufacturing processes

4.1.1 Introduction to fiberglass construction in yacht building
Fiberglass-reinforced plastics (FRP), particularly glass fiber composites, have dominated yacht construction since the mid-20th century, representing a change from traditional wooden or metallic hulls to industrialized production (Musio-Sale *et al.*, 2020; Peterson, 2022). This shift democratized yachting and suddenly boats under 40 meters could be mass-produced in a cheaper way. Since the new materials were lightweight and didn't rust, they were practical for a wider market. The standard method became hand lay-up. Workers used a female mold, laying down glass fibers and soaking them in polyester or vinyl ester resins. This process created durable and low-maintenance boats and was easy to scale up for recreational use. This mold-based system was revolutionary after World War II. But today, it's struggling as customers want personalization and regulators demand sustainability. These new pressures are exposing the system's limits.

4.1.2 Traditional FRP construction techniques

Traditional fiberglass boat building use open-mold processes (Rubino *et al.*, 2020). The two main ones are hand lay-up and spray-up. In both, workers apply resin and fibers layer by layer to build up the boat's structure. In hand lay-up, workers cut pieces of glass fiber mat and place them in the mold. They then "wet out" the fibers with a catalyzed resin, using rollers or brushes to push out any air bubbles. The part then cures at room temperature (Andresen, 2001). Spray-up is faster for large surfaces. It uses a "chopper gun" that sprays a mix of chopped fibers and resin at the same time. This method requires a skilled operator to make sure the mix is applied evenly. Builders often sandwich a core material, like PVC foam or balsa wood, between the fiberglass layers to make the structure stiffer without adding too much weight (Cai *et al.*, 2023). The final outer finish is a UV-resistant gelcoat. After the parts are laminated, they need to be trimmed, sanded, and then assembled. Curing can take anywhere from hours to days, depending on the resin and the environment. These techniques are labor-intensive and require skilled workers, but they are very effective for building strong hulls, superstructures, and other deck parts.

4.1.3 The rising demand for customization and sustainability

The global yachting market has grown quickly in recent years. This growth is driven by a strong appetite for luxury boats and more wealthy buyers in emerging markets (Yücenur, 2021; Montigneaux & Mower, 2023). The Italian industry is the established world leader in this high-end segment (La Nautica in Cifre, 2024). At this level, buyers expect deep personalization. A custom solution isn't just an option; it's a basic requirement (Brun and Karaosman, 2019). This is tied directly to the famous craftsmanship of the "Made in Italy" brand.

This demand for custom boats, however, is running alongside new pressures. Regulators and consumers are both pushing for change. International agreements like the Paris Agreement (2016) and new rules from the International Maritime Organization (2023) are forcing the industry to clean up its act. They must reduce emissions and use fewer resources (Jacquet *et al.*, 2024). Buyers have changed too as they still want luxury, but they want it to be environmentally friendly. This makes sustainability a critical selling point for shipyards (Ansa-

Ioni *et al.*, 2024; Liang & Birmingham, 2024). In response, shipyards are adopting green design principles, as defined by contemporary frameworks for environmental sustainability (Ceschin & Gaziulusoy, 2021). These efforts often focus on specific fixes. For example, they might replace teak with an eco-friendly alternative or install a near-zero emission propulsion system (Liang & Birmingham, 2024). These are good steps, but they are usually isolated fixes and not part of a complete and systemic sustainability plan.

4.1.4 Confrontation with environmental and design flexibility issues

The mold-based system was key to the industry's growth, but it also locked it into a rigid way of manufacturing. Today, that rigidity is a serious problem. The old model is trapped between two opposing forces: the demand for customization and the push for sustainability.

Molds, by their very nature, favor standardization. It's cheaper to make many identical parts but this limits design freedom. Designers are constrained by the geometry of the mold, such as the need for draft angles (to get the part out). This can hinder innovation and force designers to compromise. The only other option is to use expensive and complex hand-crafting to create unique shapes (Musio-Sale *et al.*, 2020). Any change to the design means building a completely new mold.

From a sustainability standpoint, the issues are multiple. First, the molds themselves are waste. They are usually made of the same composite materials with thermosetting resins, which are hard to recycle. After just a few uses, these massive molds often end up in a landfill. For short production runs, where tooling costs cannot be amortized, the mold represents a significant expenditure of materials, energy, and resources. The process itself is also a problem for health and the environment. Wetting out the resins releases volatile organic compounds (VOCs), like styrene, into the air. In open-mold techniques, workers are directly exposed to these fumes (Säämänen *et al.*, 1991; Lindgren *et al.*, 2002). The European UP/VE Resin Association (2021) confirms the dangers of styrene exposure. It can cause health problems for workers, including headaches, skin irritation, and respiratory issues (Persoons *et al.*, 2018).

4.1.5 Need for a new approach

All these pressures point to the clear conclusion that the nautical industry urgently needs new ways to design and build yachts. The traditional fiberglass methods can no longer keep up with today's demands. New approaches must be flexible enough for customization and must solve the environmental problems of the old methods. The weight of these limitations threatens to slow the industry's evolution. Compared to similar fields, yacht building remains anchored in traditional models, with a spirit of innovation that is not yet deeply rooted. This conservative stance is reinforced by cultural challenges. The high-end yacht industry rightly prides itself on its incredible craftsmanship. But this pride often creates tension, pitting tradition against new technology, rather than finding a way for them to work together.

4.2 Progressive design and technical exploitation of new technologies

The clear limitations of traditional manufacturing, coupled with the urgent need for flexible and sustainable solutions, are forcing the yachting industry to confront its deep-seated conservatism. While pride in craftsmanship remains a cornerstone of the sector, the tension between tradition and innovation can no longer be ignored. In response to these escalating market and environmental pressures, yacht designers and manufacturers are now compelled to evaluate and gradually adopt new digital technologies. This move is not merely a trend but a necessary strategic adaptation to remain competitive and relevant in an industry where customization and sustainability are no longer optional demands but core expectations.

The integration of AM into the nautical sector began with applications that did not disrupt established workflows, such as creating detailed scale models for design evaluation and marketing purposes. From this entry point, its applications have expanded into several key areas with varying degrees of maturity. In the broader maritime sector, its most developed use is in the production of spare parts. Since the technology allows for the on-demand fabrication of components, it significantly reduce lead times and warehousing costs, providing a critical logistical advantage (Kostidi and Nikitakos, 2017). Within yacht building, AM is also applied to optimize existing processes through the 3D printing of molds and custom tooling. This approach makes the preparatory phase of production faster and more cost-effective, directly addressing the high expenses associated with conventional tooling (Peterson, 2021). The more forward-looking application of AM lies in the direct production of hulls, entire boats, and one-off/custom components. The first experiment was a 3D printed hull from 2012 (Peterson, 2022), which demonstrated the feasibility of producing end-use parts.

CD represents a methodological and instrumental framework that could enable a shift away from the industry's conventional design approach. However, compared to other manufacturing sectors, its integration in the nautical industry has been slow and its potential remains partially untapped. Currently, the main application is focused on the creation and optimization of hull forms (Khan *et al.*, 2022). Historical developments date back to the late 1990s (Harries & Abt, 1999; Hochkirch *et al.*, 2002), and have evolved into modern parametric plugins for common CAD software, such as Swordfish or VisualARQ (Salla, 2020). These tools offer the technical means to explore a wide range of design solutions based on performance parameters, but their widespread integration into the daily design workflow of shipyards is still limited.

In line with broader trends seen in other creative industries, yacht design is now starting to grapple with the influence of new Generative AI tools. While still in an experimental phase, these technologies are being explored for their capacity to accelerate the ideation and concept design stages. Professionals are using them to rapidly generate a wide array of visual concepts for both exteriors and interiors, allowing for a more dynamic and iterative creative process (Zaltzman, 2023; Campolongo, 2025). Furthermore, the introduction of these tools into design education curricula suggests a future consolidation of these skills within the next generation of yacht designers. Bionda & Incitti (2024) tested a pedagogical approach for teaching yacht interior design. Their framework encourages students to use multiple AI tools in a cross-referenced workflow to develop and refine their concepts, preparing them for a design landscape where technological fluency and critical thinking are essential.

In summary, while the yachting industry remains strongly anchored to its traditions, it is showing clear signs of innovation across these technological domains. The current landscape, however, is characterized by fragmented and isolated experimentation. As detailed in the case studies that follow, the vast majority of current projects tend to focus on the application of a single technology for a specific purpose. The synergy between these different domains of innovation remains a frontier that is almost entirely unexplored. This fragmentation highlights both the sector's vitality and its caution, indicating that a true paradigm shift is still on the horizon.

Optimization tool for hull design

TECHNOLOGIES:
COMPUTATIONAL DESIGN

KEYWORDS:
PARAMETRIC HULL/
GENETIC ALGORITHM/
MULTI-CRITERIA OPTIMIZATION

References: (Karczewski & Kozak, 2023)

Category: Nautical

Overview: The research by Karczewski & Kozak (2023) deveoped an interesting yacht design approach based on multi-criteria optimisation processes. The main software used was Rhinoceros with its Grasshopper plugin. Designers built a parametric model of a 12-meter sailing yacht using just nine control points. These points defined five key curves (like the keel and deck line) which, in turn, generated a single, smooth NURBS surface for the hull. An optimization tool called *Octopus* then used a genetic algorithm to explore different designs. It automatically generated a large population of hull shapes by modifying the control points. The algorithm simultaneously optimized for four goals: minimizing mass and resistance, maximizing internal space, and ensuring stability. This gave designers a wide range of high-performing options to choose from, rather than just one.

ShipHullGAN

References: (Khan *et al.*, 2023)

Category: Nautical

Overview: ShipHullGAN is a deep generative model developed to address the limitations of traditional, conservative ship design, where parametric tools typically only create minor variations of a baseline hull. Trained on a massive, validated dataset of 52,591 diverse hull geometries, this model produces a 20-dimensional generative design space (GDS) capable of generating both conventional and novel hull forms.

The study then investigated how designers interact with this vast new space by testing three human-AI exploration modes:

- Random (REM): Manual, intuition-based exploration.
- Semi-Automated (SAEM): A collaboration where the user guides an optimizer.
- Automated (AEM): An optimizer searches for the best-performing design (lowest wave resistance).

Results from a 20-participant user study showed that while REM produced the most diverse designs, the collaborative SAEM was the most effective overall, striking the best trade-off between design novelty and performance optimization.

TECHNOLOGIES:
COMPUTATIONAL DESIGN

KEYWORDS:
DEEP GENERATIVE MODEL/WAVE RESISTANCE/DESIGN SPACE EXPLORATION

WAAMpeller

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
WIRE ARC AM/ CERTIFIED AM PRODUCT/ NICKEL ALUMINIUM BRONZE/ SPARE PARTS LOGISTICS

References: (RAMLAB, 2017)

Category: Nautical

Overview: The WAAMpeller project marks a key step in applying 3D printing to maritime hardware. In 2017, RAMLAB in Rotterdam led the effort to create the first certified metal propeller for ships. The team used Wire Arc Additive Manufacturing to build the three-blade unit from Nickel Aluminium Bronze, layering 298 passes with Autodesk software for precise control. Partners included Promarin for design, Damen for testing, Bureau Veritas for approval, and Autodesk for tools. This approach cut production time to months and allowed complex shapes hard to machine otherwise. The propeller went on a Damen Stan Tug 1606 for trials in Dordrecht, including speed runs, bollard pulls, and crash stops. It matched cast versions in strength and output, even under max stress, proving 3D printing viable for real use. Built in seven months, the project cut lead times and waste, opening doors for on-site repairs and custom parts in shipping.

Ross Lovegrove megayacht concepts

References: (Parametric Architecture, 2023)

Category: Nautical

Overview: Ross Lovegrove's *SuperBiomorphic Yachts* series represents a pioneering application of generative AI in contemporary yacht design. The studio used the text-to-image tool Midjourney to create early concepts for megayachts over 100 meters long, exploring bio-organic, web-like forms that flow seamlessly across decks and hulls. A principle called *netification* turns the structure into a light, interwoven mesh that links levels, lets light penetrate the interior, and gives a sculptural effect. Starting from natural-inspired prompts, the design process cycles through dozens of AI-generated images to refine shape, volumetric flow and modular logic. While unbuilt, the project highlights how the creative use of AI can unlock forms that merge biomimicry, parametric logic and architectural ambition in large-scale yacht design.

TECHNOLOGIES:
GENERATIVE AI

KEYWORDS:
TEXT-TO-TIMAGE AI/
ORGANIC SHAPES/
GENERATION OF DESIGN ALTERNATIVES

Pegasus 88m

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
LARGE SCALE AM APPLICATION/
CUTTING-EDGE CONCEPT DESIGN/
INTEGRATED HULL-SUPERSTRUCTURE

References: (Forakis… design, n.d.)

Category: Nautical

Overview: The Pegasus 88m by Jozeph Forakis is a concept superyacht that envisions the use of large-scale 3D printing to create an integrated hull and superstructure. The proposed process would fabricate a lightweight, mesh-like framework directly from the ground up, reducing material waste, construction time, and environmental impact compared to traditional shipbuilding. Designed as the world's first 3D printed superyacht, Pegasus aims to demonstrate how advanced AM techniques could enable fully customized structures of unprecedented scale, with the aim to potentially revolutionize sustainable yacht design and production in the near future.

Tanaruz

References: (https://tanaruz.boats/)

Category: Nautical

Overview: Tanaruz Boats leverages 3D printing to produce customizable leisure vessels from recycled materials. Based in Rotterdam, Netherlands, the company uses a large-scale robotic Large Format Additive Manufacturing (LFAM) system with an ABB arm and Xtrution extruder to print hulls in under 40 hours for boats up to 6.5 meters in length, reducing waste and labor compared to traditional methods. Customers can access a mobile app to select from different boat sizes, choose the colors for the hulls and select bespoke interiors. Sustainability is core, with boats made from reclaimed polypropylene reinforced by 30% glass fiber, resistant to heat, fire, and chemicals. At end-of-life, vessels can be shredded and reprinted, embodying circular economy principles and minimizing environmental impact in yachting.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
MARKET-AVAILABLE AM VESSELS/ APP-BASED CUSTOMIZATION/ CIRCULAR ECONOMY PRINCIPLES

Figure 10.
Biomorphic megayacht concept by Ross Lovegorve, generated with text-to-image AI tools.
Credits: Parametric Architecture.

Figure 11.
Render of concept Pegasus 88m.
Credits: Forakis ... Design.

Figure 12.
3D printed electric leisure boat.
Credits: Tanaruz.

LSAM skiff mold by Thermwood

References: (https://www.thermwood.com/lsam_home.htm)

Category: Nautical

Overview: In 2017, the U.S.-based company Thermwood demonstrated a new method for producing marine molds using its Large-Scale Additive Manufacturing (LSAM) system. The project involved 3D printing a positive plug mold for a small production skiff to test the feasibility of FFF in boat manufacturing. The mold was printed in six ABS plastic segments, which were then assembled and precision-milled on a large-format CNC machine to achieve the final surface quality. Afterward, the form was coated with FRP and polished for use in composite layups. The entire process, from printing to finishing, was completed in less than two weeks, significantly reducing the time typically required for mold fabrication in traditional boatbuilding. While the printed parts were heavier than optimal due to the thick extrusion beads, the project proved that hybrid additive–subtractive workflows can accelerate production and lower costs in small-scale marine manufacturing.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
HYBRID MANUFACTURING/ AM MOLD ASSEMBLY/ RAPID TOOLING

Catamaran hull mold by Oak Ridge National Laboratory and Alliance MG

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
HYBRID MANUFACTURING/ AM MOLD ASSEMBLY/ RAPID TOOLING

References: (Post *et al.*, 2018)

Category: Nautical

Overview: Oak Ridge National Laboratory (ORNL) and Alliance MG, LLC collaborated to fabricate a 10.36-meter (34ft) catamaran boat hull mold using Big Area Additive Manufacturing (BAAM). The primary goal was to bypass the traditional, time-consuming plug-making process and avoid the need for thick, expensive surface coatings or a steel support frame. The massive mold was printed in 12 individual sections over five days using 20% chopped carbon fiber reinforced ABS, a material chosen to reduce thermal distortion. After printing, the critical surfaces of each section were CNC-machined to achieve the desired smooth finish. The sections were then assembled and made self-supporting using an innovative post-tensioning system with steel rods. The mold was finished with only a thin vinyl ester coating and was successfully used to manufacture a final hull, demonstrating BAAM's significant time and cost savings for large-scale tooling.

3Dirigo

References: (Saltonstall, n.d.)

Category: Nautical

Overview: In 2019, the Advanced Structures and Composites Center at the University of Maine produced 3Dirigo, a 7.62-meter-long boat hull based on Navatek's Seablade 25 design. Using the world's largest polymer printer from Ingersoll Machine Tools – capable of objects up to 100 feet long – the team printed the two-ton vessel in just 72 hours from carbon fiber-reinforced thermoplastic. Remarkably, the entire hull was fabricated in one uninterrupted 3D printing operation.

The process layered bio-based plastic via wide-bead extrusion, creating a hollow, deep-vee hull that floated during wave basin tests with officials aboard.

As one of the first AM applications for creating hulls, 3Dirigo proved watertight potential in controlled simulations, evaluating long-term resistance to osmosis and environmental stress.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
SINGLE-PIECE HULL/ BIO-BASED THERMOPLASTIC

MAMBO

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
AM ASSEMBLY OF PARTS/ PIONERISTIC CASE STUDY/ LIGHTWEIGHT PRODUCTION

References: (https://moicomposites.com/; Musio-Sale *et al*., 2020)
Category: Nautical
Overview: In 2020, the Italian start-up MOI Composites introduced MAMBO, the first motorboat ever built with 3D printed fiberglass. The goal was to prove that AM could create complex, lightweight hulls in ways traditional boatbuilding cannot.

The 6.5-meter, 800 kg boat was built using a hybrid process. KUKA robots printed the structure in 50 separate sections using a patented method called Continuous Fiber Manufacturing (CFM). This technique lays down continuous fiberglass threads already soaked in thermosetting resin. It can precisely orient the fibers in multiple directions, making the structure significantly stiffer.

This method resulted in a hull over 30% lighter than a standard fiberglass version. The printed parts were then assembled, bonded to a PVC core, and laminated with fiberglass fabric for the final finish. Production was split between the UK and Italy, with teams using the cloud to coordinate the robotic printing process remotely.

Water taxi by Al Seer Marine and Abu Dhabi Maritime

References: (Al Seer Marine, n.d.)

Category: Nautical

Overview: In 2023, Al Seer Marine worked with Abu Dhabi Maritime to create the world's largest 3D printed boat, a water taxi catamaran that hit a Guinness World Record at 11.99 meters long and 3.60 meters wide. The whole thing came together in-house from recycled Post-Industrial PET-G (PIPG), strengthened with 30% glass fiber, showing how AM cuts down on waste while handling complex shapes. The design focuses on functionality, with room for 29 passengers and crew, plus spots for bikes and wheelchairs to guarantee accessibility for everyone. This project pushes cleaner city travel on water and proves 3D printing works at full scale, from hull and structures to the seatings as well. It was set for deployment in Abu Dhabi's water taxi network in late 2024.

TECHNOLOGIES:
ADDITIVE MANUFACTURING

KEYWORDS:
RECYCLED PET-G/ URBAN WATER MOBILITY/ RECORD-BREAKING

Smart Wheel by Superfici

TECHNOLOGIES:
ADDITIVE MANUFACTURING/ COMPUTATIONAL DESIGN

KEYWORDS:
TECHNOLOGY INTEGRATION/ BIO-ALGORITHMIC DESIGN/ FUNCTIONAL INTEGRATION

References: (Loibner, 2020)

Category: Nautical

Overview: In 2020, the Italian design laboratory Superfici introduced Smart-Wheel, a revolutionary 3D printed steering wheel for yachts. This project stands as the sole documented example of the integration of AM and CD in the nautical industry.

The software used was Autodesk Fusion 360. This generative algorithm created organic, and optimized shapes inspired by the Physarum polycephalum organism, so that the strength was balanced and the weight reduced to minimum. Traditional CAD limits were overcome by cloud computing, producing multiple lightweight variants while accounting for forces and constraints.

The wheel was 3D printed with ABS Pro filament, with a 60 mm/s deposition rate, 15% infill, and five perimeters for durability up to 97°C. The overhang angle tool minimized material and time, enabling complex undercuts unfeasible in conventional molding. Collaborating with Raymarine, the team embedded an Axiom 7 multifunction display at the center.

Figure 13.
Smart Wheel prototype.
Credits: Superfici,
Professional BoatBuilder.

Figure 14.
3D printed electric water taxi by Al Seer Marine.
Credits: Abu Dhabi Maritime.

Figure 15.
MAMBO being tested.
Credits: Moi Composites.

4.3 New scenarios for flexible customization in yacht design

4.3.1 Technological hybridization as an Innovation tool

While the yachting sector is broadly characterized by its adherence to tradition, a growing number of pioneering efforts are pushing for meaningful innovation. In this context of emergent change, research conducted by the Design Department of Politecnico di Milano directly confronts the production challenges previously discussed. This work is formalized in the NEMO – Design 4 Yacht Flexible Customization project, developed within the PNRR MICS (Made in Italy Circolare e Sostenibile) extended partnership. The goal is to flexibly shape functional elements that meet the demand for diversification without requiring significant investments in production equipment. This has led to the development of a zero-tool, zero-waste approach that integrates computational tools and additive technologies with composite reinforcement solutions.

At the core of this research is a hybrid paneling system. This system utilizes a hollow-ribbed structure that is internally reinforced with a composite relining. This synergistic combination of different production processes ensures extreme formal freedom while simultaneously increasing the mechanical properties of the components, making the solution suitable for large-scale elements. The 3D printed material is thus reduced to a minimum, which promises lightweight final parts.

The validation of this approach is demonstrated through an experimental case study analyzing a specific yacht component. The selected piece is an integrated element of a multifunctional unit located in the aft area of the 21.5-meter wallywhy100, built by the Italian shipyard Wally. This unit serves a dual purpose as both a seating area and a bar cabinet, bridging the interior and exterior living spaces of the vessel. The component is composed of three main sections: an L-shaped primary cabinet, a seating base, and a countertop, with overall dimensions of 3 meters in length, 1.5 meters in width, and 1 meter in height.

For the research, an experimental methodology was adopted with a focus on a comparative evaluation of fabrication techniques to assess the feasibility of the developed flexible approach. The proposed hybrid method was benchmarked against the conventional hand

Figure 16.
Render of the wallwhy100 aft area, showing the seating unit case study.
Credits: Wally.

lay-up process traditionally employed by the Wally shipyard for similar components. In parallel, the research team fabricated the part using the proposed process. The comparative analysis was structured around a set of defined Key Performance Indicators (KPIs), chosen to provide a thorough assessment of both manufacturing approaches. These indicators included the total time required, the final weight of the component, and the overall costs. To ensure the reliability and comprehensiveness of the data for these parameters, the analysis covered the entire production cycle of the component, from pre-production stages to the actual manufacturing and subsequent surface finishing operations.

The following section details the process engineering behind this hybrid approach, breaking down the integrated workflow.

4.3.2 Process engineering

The hybrid manufacturing approach developed within the NEMO project is enabled by an integrated technological ecosystem. This ecosystem combines three core pillars: a robotic hardware system, a custom software workflow, and a defined process strategy.

The hardware centerpiece is a large-scale AM system. It consists of a Fanuc M8001a anthropomorphic robotic arm, whose extensive reach and six-axis freedom of movement are essential for producing large and geometrically complex components, overcoming the volume constraints of typical gantry-style 3D printers. Mounted on the robot is a custom micro-extruder, which melts and deposits the raw material in pellet form. This extrusion head is engineered for reliability, incorporating a liquid cooling system for temperature regulation and a feeding mechanism with a vibrator and suction system to ensure a continuous and uninterrupted material flow. A key feature of the robotic system is its tool change capability. This allows the robot to switch from the 3D printing head to a milling unit, transforming it into a multifunctional work cell capable of both fabricating and finishing the component within the same setup.

The intelligence driving the hardware is a custom software workflow developed within the Rhinoceros/Grasshopper environment. The process begins with a 3D model of the component. Custom Python scripts are used to automatically generate a hollow, ribbed internal structure based on the part's surfaces. This patented method (Patent No. 102020000023260) allows the operator to define key parameters, creating a complex and self-supporting lattice that provides inherent form-rigidity. The ability to automatically generate and customize this internal rib distribution is fundamental to printing unique and free-form shapes. The software then translates this

Figure 17.
3D printed hollow ribs structure.

Figure 18.
Section of the structure showing the inner composite reinforcement.

complex geometry into a machine-readable format. It slices the model into toolpaths, generating a final script in the Fanuc programming language that the robot can execute directly. This seamless integration eliminates the need for intermediate software, streamlining the path from design to production.

The process strategy brings together the hardware and software with carefully chosen materials and parameters. After a comprehensive evaluation of various polymers for their suitability in the marine environment, the material selected for this application was a polycarbonate reinforced with 20% carbon fiber (LNP™ THERMOCOMP™ DC004XXAR). This choice was driven by the material's excellent adhesion with composite resins and its stability in humid conditions. The printing itself is executed as a continuous path without any internal infill, as the structural performance is derived from the ribbed geometry.

The 3D printed structure provides the geometric definition and lightness of the part. The core innovation of the process, however, lies in the subsequent hybridization phase. Eversive fiberglass socks are inserted into the hollow cavities of the ribs. These sleeves are then impregnated with an epoxy resin and expanded with an internal inflatable bladder, which presses the wet composite firmly against the inner walls of the ribs. Once the resin cures, the result is a hybrid tubular structure. The 3D printed shell acts as a lightweight, customized core and integrated mold, while the internal composite reinforcement provides the necessary structural strength. The component then undergoes final finishing, including sanding and painting, to achieve the desired surface quality.

4.3.3 Application testing

To validate the hybrid manufacturing approach, a direct comparative analysis was conducted between the traditional production method and the proposed flexible process. This section describes the fabrication of the same yacht component using both techniques and presents the results of the comparative assessment.

The analysis first required establishing a benchmark based on the shipyard's established production process. The reference component, as produced by the Wally shipyard, was manufactured using a conventional hand lay-up technique. The material composition varied for different parts of the unit. The main cabinet and its base were made from an FRP composite, combining a vinyl ester resin with a 35% fiberglass content and a PVC core in specific areas. The countertop, on the other hand, was laminated with carbon fiber to achieve a higher quality surface finish.

The production process was labor-intensive and followed a standard workflow based on an eight-hour workday. The process began with a significant pre-production phase, where four operators spent five working days preparing and fabricating the necessary molds. Once the molds were ready, the component moved into the production and finishing stages. Applying the initial gelcoat and manually laminating the parts required three operators for three full days. The final stage involved bonding the different sections together and completing the surface finishing, which included sanding and painting. This was carried out by a single operator over two days. In total,

Figure 19.
Prototype during the 3D printing process, showing the robotic arm extruding the material layer by layer.

manufacturing the finished component with the traditional method required 10 working days. The final weight of the assembled unit was 209 kg, with the countertop weighing approximately 25 kg, the base 69 kg, and the main cabinet 115 kg. The total reported cost for producing the component using this method was €8,270.

In parallel with this analysis, the research team fabricated the same component using the new flexible workflow. For the proposed approach, the research team fabricated all parts of the integrated seating unit using the AM process detailed in the previous chapter. The material selected for this application was a polycarbonate filament reinforced with 20% carbon fiber (PC-CF20).

The workflow started with a digital pre-production phase dedicated to engineering the model for additive fabrication. This involved adapting the component's geometry, designing the internal sinusoidal hollow ribs for reinforcement, generating support structures for printing, and slicing the model into machine code. This entire digital preparation took a total of 15 hours. The subsequent 3D printing phase for all parts lasted 72 hours. The resulting raw prototype, printed with a layer thickness of 2 mm, had a combined weight of 62.5 kg, distributed as 30 kg for the main cabinet, 20 kg for the base, and 12.5 kg for the countertop.

Figure 20.
3D printed prototype of the Wally seating unit showcased at the MICS Innovation Forum 2025.

After printing, the prototype underwent an extensive surface finishing stage, which required 55 hours. For the base and main cabinet, this included filling, resin coating, and applying a final gelcoat. The countertop was finished by covering it with Ohoskin, a sustainable, leather-like material derived from orange and cactus by-products. These finishing operations brought the final weight of the complete component to 114 kg. The total time for the flexible approach, summing pre-production, printing, and finishing, was 142 hours. The comprehensive cost for this method amounted to approximately €6,000, which covered electricity for the robotic system, raw materials, robot maintenance, personnel, and all finishing materials and labor.

A direct comparison of the data gathered from these two fabrication processes offers a detailed view of the flexible manufacturing approach's potential. The experimental results offer a detailed view of the proposed flexible manufacturing approach's potential compared to traditional methods. A deeper analysis of the data regarding KPIs reveals a complex but highly promising picture for the future of yacht construction.

The most immediate and striking result is a significant weight reduction of approximately 45%, with the component's mass decreasing from 209 kg to 114 kg. The design freedom provided by AM enabled the creation of a hollow, rib-stiffened structure that effectively balances structural needs with material efficiency. In the nautical sector, lightweighting has profound implications, as it directly contributes to improved vessel performance and better fuel efficiency, thus reducing the yacht's operational environmental impact.

The analysis also shows a notable cost reduction of about 27%, from €8,270 down to €6,000. This saving is primarily due to the complete elimination of molds, which was identified as a core issue in the introduction. By removing the need to design, fabricate, and amortize expensive and resource-heavy tooling, the proposed approach becomes economically viable, particularly for the one-off or limited-series components that define the semi-custom yacht market.

The parameter of time, however, requires a more nuanced interpretation. At first glance, the 142 hours required for the proposed approach seems significantly longer than the 10 working days (approximately 80 hours of labor) of the traditional method. However, this comparison is misleading. The 72-hour printing phase, which accounts for the largest portion of the time, was almost entirely autonomous and required only occasional supervision. A robotic system can operate continuously, 24/7, without the constraints of standard work shifts. This means the actual lead time in calendar days can be much shorter. More importantly, the active man-hours are drastically reduced. This shifts the efficiency paradigm from measuring total hours to evaluating the impact of automation and continuous production.

	TIME		WEIGHT		COSTS	
Traditional Approach	***TOTAL***	***80 h***	***TOTAL***	***209 kg***	***TOTAL***	***8270 €***
	Preparation	*40 h*	*Main body*	*115 kg*	*Main body*	*2275 €*
	Production	*40 h*	*Base.*	*69 kg*	*Base.*	*2495 €*
			Countertop	*25 kg*	*Countertop*	*3500 €*
Proposed Approach	***TOTAL***	***142 h***	***TOTAL***	***114 kg***	***TOTAL***	***6000 €***
	Preparation	*15 h*	*Main body*	*60 kg*	*Prep. + Prod.*	*2500 €*
	Production	*72 h*	*Base.*	*40 kg*	*Surface finish.*	*3500 €*
	Surface finish.	*55 h*	*Countertop*	*14 kg*		

Table 1.
Results of the comparative analysis between the 3D printed prototype and the original component.

4.3.4 Workflow integration

The comparative analysis in the previous section validated the hybrid manufacturing approach, demonstrating clear advantages in weight, cost, and automation. However, the true potential of this production methodology extends beyond the optimization of a single component. Its most significant promise lies in its ability to facilitate product customization on a larger scale, providing an effective and economically viable answer to the market's increasing demand for design diversification. To fully leverage this capability, the production workflow must be supported by design strategies that can accelerate and streamline the creative process.

To investigate this potential, the research explored the use of GenAI as a tool to support and accelerate these customization processes. A series of experiments were conducted using Google's text-to-image model, Nano Banana. The goal was not to develop an entirely

Figure 21.
AI generated design alternatives of the Wally seating unit case study.

new project, but to explore rapid design iterations for the existing seating system case study. By keeping the surrounding context of the yacht's aft area unchanged, the experiments focused on generating localized design alternatives for the seating unit, simulating a realistic customization request.

By modulating the text prompts, the tool produced a wide range of visual outputs in a very short time. A key characteristic of these generated designs was their organic and fluid forms, featuring complex geometries that would be difficult or impossible to achieve with traditional mold-based manufacturing. To further bridge the gap from 2D concept to 3D form, the research took an additional step, using an image-to-3D tool, Rodin AI, capable of generating a preliminary 3D mesh model directly from these images. While the generated models consist of an unrefined mesh geometry, they serve as an effective starting point. This raw data can then be processed with computational design tools, where the model is cleaned, rationalized, and fully engineered. This step creates a much more fluid workflow between the different digital stages. Ultimately, this synergy between technologies enables a fully integrated process that accelerates and optimizes flexible customization, spanning the entire journey from creative exploration and model engineering to final production.

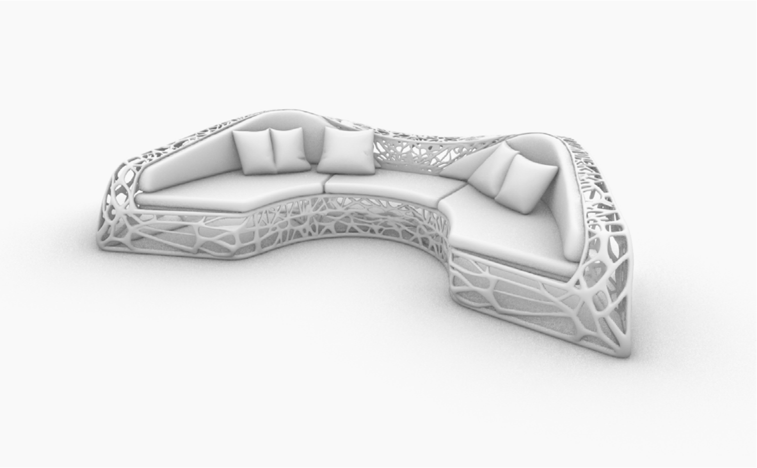

Figure 22.
3D model of a design alternative generated with Rodin AI.

PART 3

Broader Horizons

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.

6. Conclusions

This book argued that the 20th-century model of standardized mass production is no longer sufficient to meet the modern demand for customization. Additive Manufacturing, Computational Design, and Generative AI were identified as important driving forces capable of overcoming this “one-size-fits-all” rigidity. Three application sectors – furniture, products for personal use, and automotive – have been analyzed as they successfully leveraged these technologies to enhance customization. The furniture industry demonstrated how digital tools can liberate form from standardization; the personal product sector highlighted the value of ergonomic adaptation; and the automotive field proved that additive technologies can meet high-performance structural demands. This investigation confirmed that the technological maturity for mass customization exists, though the yachting industry still lags behind. Here, despite severe environmental and flexibility limitations in traditional composite manufacturing, the adoption of digital technologies remains experimental and less mature compared to other fields.

In this specific context, the research presented developed a comprehensive digital workflow aimed at directly addressing these industrial limitations. We proposed an approach that synergistically integrates the three key technologies. It leverages large-scale AM combined with targeted composite reinforcements to materialize, complex forms without molds, CD to optimize geometries for structural performance and printability, GenAI to accelerate the initial creative exploration of variants and preliminary 3D modeling.

This methodology was validated through the fabrication of a full-scale functional prototype for a production yacht, offering highly promising results. The comparative analysis against traditional processes highlighted significant benefits in terms of weight reduction, cost savings, and overall process efficiency. Moving past the historical limitations of traditional composites molding, we now enter a digital industrial context. In this new era, customization and efficiency are no longer separate goals but complementary drivers of value.

An analysis of the broader systemic impacts suggests a bright horizon for the industry, pointing toward a redefinition of professional roles and a strategic reconfiguration of the supply chain toward digital, on-demand logistics. However, the study conducted is not without its complexities, limitations and opportunities for further evolution.

At first, focusing specifically on the research outputs, it is important to acknowledge that the developed prototype did not undergo a direct FEA simulation. Structural calculations were instead conducted in parallel on different components developed within the broader study. This separation represents a current gap in the specific workflow of the prototype. However, it effectively points to the next logical evolution of the process, where structural validation will need to be fully integrated.

In this sense, a key future development could involve the transition from parametric tools to generative design systems. Here, the leverage of advanced algorithms would allow for the creation of a variety of solutions in which structural integrity is optimized in real-time alongside geometry, resulting in “born-validated” components rather than designs verified post-factum.

Secondly, the study of raw materials remains a key area for exploration. Future research could prioritize the testing of polymers reinforced with natural or recycled fibers, derived from textile waste. This shift would significantly enhance the environmental sustainability of the approach, though particular attention must be paid to achieving satisfactory mechanical properties comparable to traditional composites even with these new material formulations.

As outlined earlier, the yacht industry is a field traditionally rooted in conservatism and risk aversion. For this reason, widespread adoption could still face significant systemic inertia. To fully unlock this potential, a fundamental mindset shift is required. It is important to move beyond mere technical implementation to embrace a new culture of design and production. This cultural evolution is complex and inherently slow, as it challenges established industrial paradigms that will not be dismantled overnight. Overcoming this cultural resistance demands more than just successful prototypes, but it requires a robust framework of standardization and certification. Currently, regulatory bodies lack specific protocols for AM in maritime applications. Developing these standards is a necessary step to validate not just the final component, but the entire digital process, granting it the necessary reliability to enter the mainstream market.

Despite these challenges, the fundamental principles underlying this approach can potentially extend beyond the specific context of yacht manufacturing. The convergence of digital design and flexible production is not domain-specific but represents a broader industrial paradigm capable of addressing similar constraints across diverse fields. Beyond the scenarios explored in this book, these results could be seamlessly transferred to sectors like Recreational Vehicles (RVs) or modular micro-living architecture. This confirms that the research outcomes are not confined to the maritime domain but demonstrate a broad operational flexibility capable of addressing complex design challenges across diverse fields.

The path toward a fully digital, customized manufacturing ecosystem is open. It requires time, standardization, and a persistent cultural shift, but the direction is clear. We are moving towards a future where rigid production gives way to the flexible file, offering a smarter and more sustainable way to build the objects that inhabit our lives.

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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/

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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.

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