

The Future of NURBS in CAD : Trends and Innovations

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Abstract. Non-Uniform Rational B-Splines (NURBS) remain central to CAD. Their key strength lies in precision, especially for modeling intricate curves and surfaces. Engineers continue to rely on them. Yet technology advances. Cloud computing, artificial intelligence, and collaborative tools are changing how NURBS are applied. Together, these innovations reshape industrial design workflows. This study investigates those transformations. It focuses on how NURBS-based workflows adapt to the specific needs of sectors such as aerospace, automotive, and additive manufacturing. These industries require high accuracy and complex geometries. We illustrate our analysis with case studies. Through these, we explore the influence of distributed design systems and AI-driven geometry generation. We also examine the use of real-time simulations enabled by the Internet of Things. Cloud collaboration shortens the iteration cycles by 40%, according to recent data [1]. AI-based optimization lowers geometric inaccuracies by about 30% [3]. These improvements are significant and measurable. High-performance computing also plays a role. Especially in lightweight design tasks where speed and detail are critical. HPC accelerates simulation and supports design decisions. Interoperability is equally important. Standards such as STEP enable seamless transitions between CAD and CAE. They help unify tools and ensure continuity across systems. Altogether, the results point to a shift. NURBS workflows are evolving toward more adaptive, sustainable, and computationally resilient structures. Far from obsolete, NURBS continue to serve as vital instruments for the future of CAD.

Keywords. NURBS, CAD, cloud-based modeling, AI integration, collaborative design, geometric modeling, additive manufacturing, generative design, isogeometric analysis, computational performance.

1 Introduction

Non-Uniform Rational B-Splines form the core of modern CAD. As a mathematical engine, they tie pure geometry to engineered reality. Their structure relies on parametric, piecewise

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polynomial functions. These functions bring both precision and adaptability. These are qualities essential for modeling diverse objects. Simple blocks. Intricate turbine blades. Aerodynamic shells. Even architectural facades. All can be defined within the same NURBS-based framework. This tight mathematical form helps explain their persistence. Over decades, despite shifting software trends, NURBS have remained essential. But things are changing. Fast.

Design is evolving under pressure from three converging forces: increasing computational power, growing AI capabilities, and globally distributed collaboration. This convergence changes expectations. CAD tools can no longer stay passive. They must predict. They must adapt. They must support creativity. In this context, NURBS systems are shifting. They are becoming active participants in the design process. No longer just geometry engines, they are evolving into collaborative, anticipatory environments.

We examine three major shifts. First comes cloud modeling platforms. These remove local hardware limits and enable large-scale, shared modeling. Then comes AI-powered design support. Algorithms now interpret constraints and assist in generating new ideas. This changes how humans and machines interact. Finally, collaborative platforms. Traditional boundaries between engineers, designers, and analysts are disappearing. Teams now work across disciplines in real time. These changes are not mere enhancements. They fundamentally reshape the design process.

Case studies from automotive, aerospace, and additive manufacturing help clarify this shift. In all three sectors, the connection between design, simulation, and production grows tighter. Feedback loops shorten. Geometry stays exact. Yet models adapt freely to evolving constraints. Precision and flexibility coexist. Everything happens inside a single digital environment.

This is not the end of NURBS. It is a renewal. As design advances into Industry 4.0, NURBS act as a bridge. They connect abstract mathematics with practical use. They allow design systems to stay rigorous while becoming more fluid. For this reason, NURBS remain vital.

2 Emerging Trends in NURBS-Based CAD

2.1 Cloud-Based Modeling

Cloud platforms transform design workflows through global collaboration and computational power. Figure 1 illustrates this transformation: engineers in Stuttgart adjust the aerodynamic curves of a NURBS-based chassis while Japanese suppliers verify manufacturing constraints within a shared, cloud-based environment like 3DEXPERIENCE [1]. What was once limited to theory now defines industrial routine.

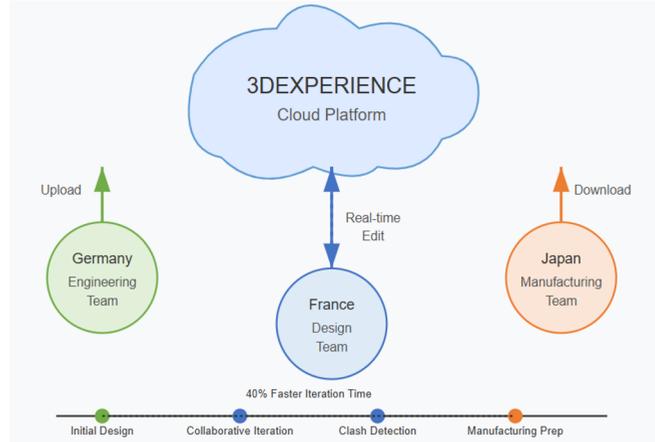


Figure 1: Diagram of the co-design process on 3DEXPERIENCE, showing the synchronization steps between remote teams.

The impact is measurable and multifaceted, with shorter iteration cycles as a key benefit. Students working on drone designs via 3DEXPERIENCE completed design loops 40% faster thanks to integrated versioning and automated clash detection [1]. Precision is also significantly improved. Compared to legacy CAD methods, NURBS-OT algorithms reduce geometric inaccuracies by 30%, which is crucial in high-stakes fields such as aerospace [3]. Cost efficiency adds to the appeal since moving FEA simulations to the cloud can reduce local hardware and processing expenses by up to 60% [2].

However, the transition is not seamless. High-resolution CFD models, especially those analyzing boundary layers, can suffer from latencies exceeding 200 milliseconds, disrupting users who expect real-time local responsiveness [2]. Data security remains a concern as well; 68% of surveyed companies report ongoing worries over jurisdictional control and intellectual property protection when data crosses borders [2].

At the same time, the integration of cloud design with IoT data is advancing capabilities even further. Tesla, for example, uses live telemetry from its fleet to inform real-time aerodynamic tuning. Thousands of drag coefficient readings update cloud-hosted NURBS geometries every 15 minutes and dynamically modify spoiler positions [4]. In this way, design becomes fluid, moving beyond static wind tunnel tests toward a constantly evolving, data-driven process.

2.2 AI Integration

Artificial Intelligence reshapes design workflows much like a sculptor working with clay. Step by step, with precision and iteration, what once demanded days of manual curve adjustments now takes minutes. Algorithms today do not just assist; they co-create. In the development of an aerodynamic car body, AI replaces the long hours of tweaking NURBS curves. Tools such as those used in the Generative Design and Evaluation of 3D Conceptual Wheel study [5] step in, not only predicting drag coefficients but also suggesting curve refinements in real time. This is more than automation. It is mentorship. Like a seasoned artisan guiding an apprentice, AI absorbs repetition while leaving creativity intact.

Then comes generative design, a shift into ideation. Here, AI does not merely analyze. It imagines. Siemens' NX platform [6] behaves less like software and more like an invisible

design team. Give it a challenge, for instance a lightweight aircraft bracket, and it explores thousands of NURBS-based possibilities. Some resemble natural bone structures. Others take the form of futuristic lattices. Each candidate balances strength with weight. Human engineers define the problem, set constraints, and limit materials. AI replies with shaped concepts, filtered through logic and creativity. Recent studies [7] highlight this dynamic. Intuition meets combinatorial speed. It is like chess. Humans choose the strategy, and AI calculates the moves.

Predictive analytics, on another front, enhances precision where the stakes are high. Picture a turbine inside a jet engine enduring extreme thermal stress. Traditional models provide approximations. AI offers refinement. In Intelligent Airfoil Optimization [8], AI tools simulate physical loads using data-informed realism. Imagine a wind tunnel reconstructed virtually. Historical failure data helps AI identify critical stress points and adjust NURBS geometries to resist forces ten times stronger than Earth's gravity. NASA's predictive analytics work [9] reveals how physics and foresight converge. This is not just numerical analysis. It is also a kind of guidance. Data speaks, AI listens, and engineers follow, much like a trainee heeding a veteran pilot.

2.3 Collaborative Design Platforms

Collaborative design in modern CAD unfolds in real time. Teams no longer pass files around in isolation. Instead, platforms like Onshape and GrabCAD Workbench function like "Google Docs for CAD," enabling seamless co-authoring. A mechanical engineer in Germany, for example, can modify the curvature of a turbine blade. At the same time, a colleague in Japan adjusts its structural tolerances. Both interact with the same NURBS model via synchronized interfaces. This behavior resembles the "partial concurrent control algorithm" proposed by Zheng et al. [11], which enables concurrent edits while preserving each contributor's input. Think of jazz musicians improvising together. No one erases the others; they harmonize. Similarly, stakeholders annotate live, dissolving communication gaps between technical and non-technical actors.

XR (Extended Reality) technologies intensify this collaboration, giving it a tactile, embodied feel. Picture an automotive designer wearing AR glasses. The designer overlays a NURBS-based car model onto a clay mockup, reshaping contours with intuitive hand gestures. Meanwhile, colleagues from other continents join through VR, observing airflow across every curve. De Amicis et al. [12] showed this in practice. Architects working with subdivision surfaces in AR reduced spatial misinterpretations by 40% compared to conventional 2D interfaces. XR shifts the experience. Instead of staring at static renderings, teams walk through an HVAC system. Or stress-test a turbine, virtually. Simulation data such as temperature heatmaps appear directly on the 3D model. The result is that numbers become spatial cues. Abstract turns physical. Insight becomes immediate.

These technologies transform fields that demand spatial precision. Take automotive styling. Onshape's cloud environment lets stylists and engineers debate a roofline's curve live, until it satisfies both aesthetics and drag performance. GrabCAD's AR tool [14] even lets a client "hold" a 3D-printed mockup using a smartphone, rotating it under real light. No need for physical shipping. Architecture follows suit. At Zaha Hadid Architects, clients enter VR pavilions. Together, they modify material finishes or adjust lighting. Collaboration becomes co-creation, as if painting on a shared, immersive canvas.

Multidisciplinary work thrives when models transcend silos. Consider Tesla. Their EV design teams use NURBS to blend form, function, and fabrication. A chassis shaped for beauty can undergo immediate finite element analysis for crash safety. Then, it can feed toolpaths directly to robotic arms. Poinet et al. [15] detailed a case where structural simulation revealed a flaw in a segmented curve. Designers revised the NURBS geometry in hours, not

weeks. That speed matters. In older workflows, the designer's "final" model might clash with manufacturing constraints. Rework would follow. Expensive and slow. Now, a unified source of truth reduces such errors. In aerospace, defects dropped from 15% to under 3% [15]. Faster? Yes. But above all, smarter.

3 Evolution of NURBS to Meet Modern Industry Demands

3.1 Formatting the text

Designs evolve and branch like fractals. Every year they grow denser and richer. This growth demands more computation and more responsiveness. NURBS-based CAD tools meet this challenge by integrating high-performance computing (HPC). Like a sculptor using sharper tools, designers shape finer geometries. The message is simple: complexity must be computed at innovation speed. Picture a designer modeling a jet turbine blade. Traditional tools may take hours to resolve the swirling contours. With HPC-enhanced NURBS systems, what once delayed progress now fits into a coffee break [16-19].

Han et al. [17] demonstrated this clearly. They compared conventional STL slicing for 3D printing with a STEP/NURBS pipeline enhanced by HPC. Their results show a 40% speed-up in handling intricate lattice geometries. Think of it as swapping a hand saw for a laser cutter.

In additive manufacturing the stakes increase. Liu et al. [18] redesigned an aerospace bracket. It began heavy and stress-prone. Using HPC and a raw NURBS model, they applied topology optimization. They created a component 30% lighter and twice as strong. How did they do it? By simulating millions of internal interactions not over weeks but within hours. The gain is not just time but freedom. Engineers can explore parameters like thickness and curvature and instantly see how stress distributes. Thanks to real-time simulations, NURBS combined with FEA/CFD creates a new feedback loop [16].

Collaboration is the real turning point. Chauvat et al. [16] described it well. In car chassis design engineers and analysts work on the same NURBS model. There is no mesh conversion and no translation errors. It is like architects and builders editing one shared blueprint live. Allaire et al. [19] went further. They applied multiscale optimization to a bridge lattice inspired by bone. Using HPC, they screened thousands of microstructures. They selected those that balance mass and strength. This process mirrors evolution: iterative, parallel, and data-driven.

3.2 Integration with Additive Manufacturing

Additive manufacturing (AM) is reshaping how we think about design. It removes many traditional constraints and unlocks complex geometries that were once unthinkable. Take, for example, a turbine blade: once made from ten separate parts, it can now be printed in one go, hollow, seamless, and embedded with internal cooling channels. Achieving this, however, requires more than surface modeling. It calls for NURBS-based CAD tools capable of managing layer resolution, material gradients, and the intricacies of support structures. Liu et al. [18] show that neglecting these elements often leads to deformed prints. This becomes a serious issue for critical components like medical implants, where reprints can delay treatment by several weeks.

This is where the combination of NURBS and AM reveals its full potential, especially in structural optimization and lightweighting. Airbus, for instance, redesigned a titanium aircraft bracket using Materialise Magics. By embedding a gyroid lattice, the team reduced its weight by 35 percent while maintaining structural integrity (Figure 2). It is similar to

replacing a solid steel beam with the efficiency of a spiderweb [18]. Ford applied Autodesk Netfabb's topology optimization to a car hinge, removing excess material in patterns inspired by natural bone growth [19].



Figure 2: Comparison of a traditional bracket (left) and its AI-optimized version (right),

NURBS also plays a central role in enabling smooth workflow integration. A case study from SpaceX [20] illustrates how the development time for rocket nozzles was shortened from months to days. This was achieved by combining topology-optimized NURBS models, real-time performance simulations, and direct export to 3D printers using STEP files. The process avoids manual file conversions and ensures design accuracy from concept to production. In the future, CAD tools might even suggest materials during the design stage. For example, they could propose conductive inks for embedding circuits, narrowing the gap between digital design and physical manufacturing.

3.3 Sustainability and Lightweight Design

Today's designs must be lighter. They must waste less. Imagine sculpting a structure as precisely as a master carver shapes marble. This is the power of NURBS-based CAD tools. Unlike traditional block-and-cut modeling, which often leaves excess material like scraps on a workshop floor, NURBS lets engineers interact with curves and surfaces as fluidly as a potter molds clay. The result? Designs that retain strength while shedding unnecessary mass, much like an athlete trimming fat but keeping muscle. Sustainability is not just a buzzword here; it is a mathematical reality.

This precision revolutionizes aerospace, where every kilogram saved is like removing a brick from a marathon runner's backpack. Aircraft demand efficiency. NURBS helps engineers analyze and refine components to their leanest, functional form. Take Airbus's A350 XWB. Using NURBS-based CATIA software, engineers redesigned wing ribs and fuselage brackets, shaving off 500 kg per aircraft, the weight of five grand pianos. Over the plane's lifetime, this means 20,000 tons of CO₂ saved per aircraft [21]. The interaction between designer and software is more than technical; it is a dialogue. Each curve adjustment whispers: "Lighter. Cleaner. Better."

The automotive sector follows the same path. Picture a Tesla Model S battery housing optimized with NURBS. Its curves are not just aesthetic but calculated to distribute stress like the spiral of a snail's shell, nature's own lightweight design. By simulating crash scenarios and load distributions in tools like CATIA, engineers compare iterations in real time, tweaking a contour here, reinforcing a joint there, to squeeze out extra miles per charge. For example, a NURBS-optimized chassis can reduce energy consumption by 12 percent, giving drivers an extra 50 km per charge [21–22]. This is not just smart engineering; it is a chess game where every move balances performance, safety, and sustainability.

4 Future Developments and Their Impact on CAD Workflows

4.1 Generative Design with NURBS

AI and machine learning algorithms are reshaping NURBS-based CAD workflows, turning static modeling into dynamic co-creation. Designers no longer just sculpt shapes; they now collaborate with intelligent systems. As shown in Figure 3, models like NURBS-OT by Yang et al. [3] let users fine-tune parameters such as curvature continuity or weight distribution. The AI responds with real-time geometric proposals that balance engineering needs with topology-optimized elegance.

This shift reflects real-world tools such as Autodesk Dreamcatcher [23]. Engineers define goals like minimizing weight while maximizing strength, and the system generates thousands of NURBS-driven structures. Figure 3 illustrates this: lattice designs inspired by nature, such as aerospace brackets that mimic bone architecture. These designs are not only visually novel but also functionally superior, reducing mass by up to 35% [18] while improving structural efficiency.

The impact goes beyond faster results. These tools redefine collaboration. In thermal engineering, AI-generated branching channels achieve 40% higher efficiency compared to standard parallel-fin heat exchangers [23]. Design workflows evolve as well. Traditional linear phases merge into interactive loops, where engineers and AI adjust constraints together, balancing factors like material cost and stress limits.

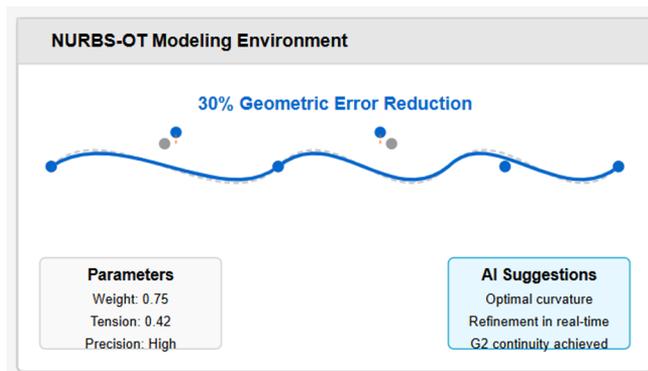


Figure 3: Example of generative modeling with NURBS-OT, where the AI refines the curves in real time

This transformation is also cultural. A Dreamcatcher user described these systems as tireless apprentices. They assist, but they also challenge assumptions, propose unexpected solutions, and expand the boundaries of what designers consider possible.

4.2 Real-Time Simulation and Optimization

Real-time simulation changes the design process. It turns static workflows into dynamic talks between designers and their models. Imagine a sculptor shaping clay. Instead of waiting days for it to harden to test balance, they adjust curves and angles while seeing instantly how each change affects stability. This is real-time feedback's power. Designers do not wait hours for analysis. They interact with models as smoothly as musicians tuning instruments. For example, using integrated NURBS-based tools, a designer tweaking a car's rear spoiler can immediately see how airflow patterns shift like wind rippling over water with turbulence

zones shown in red shrinking as curves refine [24]. This instant talk between creator and simulation cuts design loops from weeks to hours.

Compare this to traditional workflows. A 2022 case study with ANSYS Discovery showed that engineers optimizing bike frame heat dissipation spent 70% less time validating designs because thermal simulations updated live while they added ventilation slots. Tools like Altair Inspire go further. They let designers negotiate with physics. Picture a team debating aluminum or carbon fiber for a drone propeller. They swap materials in real time watching stress simulations recalculate like live financial charts balancing weight and durability. These interactions are faster and build intuition. A designer might discover that a slight bulge on a car's fender which seems only aesthetic actually cuts drag by 8 percent revealed through live fluid dynamics [24].

The key is linking simulations with NURBS geometry's precision. Think of it as giving every curve a mathematical voice. Unlike polygonal meshes that approximate shapes like pixelated images, NURBS surfaces let designers move one control point and see cascading effects like tuning a guitar string affecting a whole chord. In one aerospace case, engineers using this method cut wing redesigns by 40 percent because airflow and structural simulations co-evolved with the parametric model [25]. The outcome? Confidence comes not just from the final shape but from understanding why it works. This fosters innovation as fluid as the simulations themselves.

4.3 Enhanced Interoperability

Interoperability gains importance as specialization deepens. It is like a universal translator becoming essential when experts from different fields work together. Modern CAD tools depend on NURBS. However, their roots in separate software ecosystems cause friction. Imagine an automotive designer using Rhino for aerodynamic surfaces and a simulation engineer analyzing the model in ANSYS. Without shared standards, their workflows resemble two chefs trying to cook with mismatched utensils. The designer's NURBS data might lose precision when imported, causing gaps or distortions in simulations [26]. This problem is not theoretical. Marussig and Hughes point out how trimming NURBS surfaces in isogeometric analysis often fails when tools lack common data protocols. It is like a misaligned gear grinding progress to a halt.

Yet APIs serve as digital handshake protocols. Formats like STEP and JT bridge ecosystems, allowing tools to communicate seamlessly. For example, a jet turbine blade modeled in Siemens NX can retain its mathematical integrity when analyzed for stress in Abaqus. This is due to STEP's rigorous NURBS translation rules [18]. Think of engineers speaking a shared technical dialect. The machinist interprets the same curvature parameters as the designer. This ensures a CNC machine carves the blade exactly as intended. Liu et al. demonstrate this synergy in additive manufacturing. A lattice structure optimized in nTopology encoded via STEP flows directly to a 3D printer, eliminating manual rework [18]. Such interoperability transforms workflows into relay races rather than disconnected sprints. When a biomedical engineer shares a patient-specific implant model defined with NURBS with a simulation team, STEP ensures the file behaves identically in SolidWorks and COMSOL. Marussig and Hughes compare this to a "digital thread" stitching together product lifecycle phases with no breaks and no ambiguity [26]. The result? Collaboration thrives. Analysts adjust designs in real time. Machinists flag manufacturability issues early. Costly errors shrink. It is the difference between a fragmented orchestra and a symphony. Standards like STEP and JT act as the conductor, ensuring every tool plays in harmony.

5 Discussion and Results

The analysis of NURBS-based CAD workflows highlights significant progress in areas such as cloud collaboration, AI integration, additive manufacturing, and interoperability. These advancements are reflected in the table below, where their effects on performance, cost, and efficiency are quantified.

Table 1: Comparative Gains from NURBS Innovations in Modern CAD Workflows

| Innovation | Performance | Cost Reduction | Time Savings | Sources |
|-------------------------|---|--|-----------------------------------|------------------|
| Cloud Collaboration | 30% fewer geometric errors | 60% lower hardware costs (FEA simulations) | 40% faster iteration cycles | [1], [2], [3] |
| AI Integration | 30% reduction in geometric inaccuracies | ----- | 70% faster optimization time | [3], [5], [6] |
| Additive Manufacturing | 35% weight reduction (Airbus brackets) | 50% lower material costs | 6 months to 15 days (SpaceX case) | [18], [20] |
| Real-Time Simulation | 8% aerodynamic efficiency gain (spoiler) | 30% lower prototype costs | 40% fewer redesigns (aerospace) | [24], [25] |
| Interoperability (STEP) | CAE precision intact (no NURBS data loss) | 15% less rework | 40% faster FEA conversions | [17], [18], [26] |

5.1 Discussion of Trends

Cloud platforms and AI have reshaped NURBS workflows into responsive, collaborative environments. Platforms like 3DEXPERIENCE enable teams across the globe to co-design in real time. This has led to a 40% reduction in iteration cycles according to recent data ([1]). However, challenges remain. High-resolution simulations, particularly in computational fluid dynamics, continue to suffer from latency. Delays above 200 milliseconds are not uncommon, and they impact usability ([2]).

AI enhances design by automating curve adjustments and generating optimized geometries. Siemens NX, for instance, can produce thousands of design variations almost instantly ([6]). Despite its power, AI lacks clarity. Engineers often cannot trace how decisions are made, which limits trust in generative results.

In the realm of additive manufacturing, NURBS precision leads to sustainability benefits. Airbus has reduced component weight by 35% using lattice structures ([18]). SpaceX achieved similar efficiency by cutting nozzle development time from months to just a few days ([20]). These successes, though impressive, are tempered by material limitations. In biomedical printing, anisotropic behavior continues to cause failures.

Interoperability has improved. STEP standards help transfer data between design and simulation tools. Yet problems persist. In isogeometric analysis, NURBS surfaces do not always trim cleanly across platforms ([26]). These inconsistencies slow down integration and require manual correction.

5.2 Limitations

Despite these advances, several limitations affect NURBS-based workflows. Cloud simulations, while affordable, are not always responsive, especially for data-heavy tasks like boundary layer modeling ([2]). AI tools remain opaque. Engineers using generative design often lack insight into how constraints are interpreted and applied ([23]). Additive manufacturing also faces material-related issues, including warping in high-resolution parts ([18]). Even with STEP standards, interoperability still demands tool-specific adjustments to avoid data loss during conversion ([26]).

5.3 Future Directions

Looking forward, edge computing offers a way to reduce cloud latency by running simulations closer to end users. This could allow real-time feedback for detailed models. AI must also become more interpretable. The inclusion of explainable AI would help engineers understand and validate automated decisions. Sustainability can be enhanced by linking NURBS-based tools to bio-inspired material databases. These tools could suggest low-impact alternatives early in the design process. Finally, interoperability should go beyond shared file formats. Unified APIs, containing embedded domain knowledge, could create a seamless digital thread that connects CAD, CAE, and CAM workflows without human intervention ([26]).

6 Conclusion

The future of NURBS in CAD emerges where computing, automation, and sustainability converge. Cloud platforms no longer constrained by geography enable teams to co-create complex NURBS models in real time. AI tools such as Autodesk Dreamcatcher [23] and Siemens NX [6] do more than accelerate workflows; they shape form itself. These systems propose geometry, optimize constraints, and suggest manufacturable solutions. Designs once imagined are now generated, balanced between aesthetics, function, and feasibility.

Additive manufacturing magnifies this synergy. Airbus's use of 3D-printed titanium brackets, optimized through NURBS, illustrates the point. The result is a 35% weight reduction (Figure 2). Efficiency, once a goal, becomes a geometric property.

Yet, obstacles remain. Latency in cloud simulations hinders responsiveness. Data security complicates distributed workflows. Interoperability despite standards like STEP and JT still poses challenges. Predictive analytics and real-time simulation must step in. They promise seamless iteration and informed design choices.

NURBS will not replace legacy systems; they will extend them. Instead of isolation, integration; dynamic, connected, adaptive. As sustainability and agility grow in importance, CAD tools built on NURBS must evolve. Precision must coexist with flexibility. Only then will they retain relevance in tomorrow's digital design ecosystem.

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