On the Convergence of Modeling and Simulation

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Companies today need to keep up with global competition, volatile markets, and rapidly evolving technology. To meet these challenges, it is necessary to reduce the time to market for new products while also continually improving products and services to meet ever-increasing performance demands.

These new demands on product design, however, cannot be met using a traditional approach to product development where the modeling and simulation stages remain distinct. One effective way to reduce the time and costs of product design is to make simulation available throughout the modeling process. Ideally, the designer would be able to employ analysis tools directly within the CAD environment.

The research firm Aberdeen Group has reported that manufacturers who make extensive use of simulation early in the design process hit revenue, cost, launch date, and quality targets for most of their products.[1] Thus, moving simulation and analysis to the front end of product development will enable companies to arrive at a good design earlier and to minimize the time spent in the verification and testing phase of product development.

In this article, we discuss how far we have come in merging design and analysis and what challenges lie ahead.

Product Design

Traditional product development consists of two stages: geometrical modeling to define a product's shape, followed by mechanical simulation to verify design specification. Designers most often define a product's geometry using a CAD system. Such systems offer a range of model editing tools, from high-level parametric updates to the free-form deformation of bounding curves and surfaces. A CAD model is typically a combination of a high-level parametric feature-based representation and a fully evaluated boundary representation. The latest generation of 3D CAD tools is well-suited for the development of 3D geometric models, with all details needed for manufacturing.

To meet performance requirements, the design must conform to design specifications. These need to be verified in the analysis stage, which is also called computer-aided engineering (CAE). CAE tools allow engineers to simulate and analyze a shape's mechanical behavior. Although CAE tools can be less user friendly than CAD systems, they tend to be more comprehensive and versatile.

Analysis requires solving a boundary or initial value problem defined over the geometric domain represented by the CAD model. A numerical approximation of the solution (such as the displacement field) is computed as a linear combination of some basis functions using one of many approximation methods. One common class of CAE tools is based on finite-element analysis (FEA), which requires discretizing the geometric domain. When applied to a mechanical structure, FEA tools offer engineers insight into the structure's stresses, deflections, and modal frequencies. In addition, FEA can be applied to other types of analysis, including heat transfer, electrostatic potential, and fluid mechanics.

In product design today, a designer models a shape using a CAD system, and then an expert analyst performs the analysis using a CAE tool. Often, the design is subjected to a design validation analysis to assure conformance to requirements only in the later stages of the design process. However, errors are expensive and time consuming to correct if they are not detected until final testing. A designer therefore attempts to assure conformance to the specifications by making often overly conservative design decisions. By integrating analysis into

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the design process during the early stages of conceptual and preliminary design, the designer can produce superior and possibly bolder designs within a shorter timeframe.

Making simulation and analysis pervasive throughout the modeling stage has become a critical goal.

A Unified CAD/CAE Representation

One of the challenges of CAD/CAE integration is the use of incompatible representations for the same geometry. This makes it difficult to guarantee interoperability across the wide range of commercial CAD and CAE tools. Although many of these tools support industry data standards and claim to be interoperable, the connection between them is not seamless. Any support for CAD/CAE integration depends on the ability to automatically convert a boundary representation of the CAD model into a finite-element (FE) mesh.

The reason for having different representations for the same geometry lies in the history of the two fields. Major CAE programs were technically mature long before modern CAD was widely adopted. FEA had its origins in the 1950s in the aerospace engineering field. By the late 1960s, the first commercial computer programs appeared. Subsequently, the FE method spread to other engineering and scientific disciplines, and now its use is widespread and many commercial programs are available.

Despite the fact that geometry is the underpinning of analysis, CAD had its origins later. Bézier curves were developed in the late 1960s, and the parametric surface approach became standardized in form of the nonuniform rational B-spline (NURBS) surface in the 1970s. Subdivision surfaces were also developed in the late 1970s, but they require large amounts of computer memory, and computers did not have sufficient memory to make subdivision surfaces viable for commercial use until the late 1990s. FEA uses neither NURBS nor subdivision.

Because FEA requires discretizing the problem, a smooth CAD model is approximated by a polygon mesh (simulation mesh) with triangular or quadrilateral faces. The size of faces controls the approximation's quality and thus the simulation's reliability. The choice of the simulation mesh greatly influences the quality of the analysis results. Often, it is only an analyst's experience that enables him/her to define the mesh layout that leads to improved convergence rates in the simulation for a specific problem. Typically, generating a simulation mesh from CAD data creates inaccuracies and consumes more time than the actual analysis.[2]

Shape and topological optimization are examples where a CAD model is repeatedly modified based on CAE results. Because product development designs are typically encapsulated in CAD systems and simulation meshes are generated from CAD data, human designers still perform shape optimization manually, by interpreting the results of the analysis and deciding which changes to apply to the CAD model. Automating this process is possible only if it is assured a prior that the geometric representation of the mechanical domain and the approximate solution of the analysis problem are compatible—changes to one must be easily translated into desired modifications of the other. Interfacing models between the different representations used in design and analysis seriously limits the state of the art in shape or topological optimization.

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An important step in bridging the gap between CAD and CAE is to define a unified representation that can serve the needs of both design and simulation. CAD currently has a much bigger market than CAE. Current estimates are that CAE is a \$1 to \$2 billion dollar industry, whereas the CAD industry is in the \$8 to \$10 billion dollar range.[33] Therefore, it makes sense to adapt FEA, such that surface geometries generated by a CAD module can be directly utilized by the analysis module without the need for any intervening geometrical manipulation.

A CAD boundary representation has a control mesh, which like the simulation mesh consists of faces, edges, and vertices. The explicit mesh-generation process is avoided by employing the same basis functions that generate the smooth CAD surface from the control mesh to also approximate the field solution in FEA. This is referred to as *isogeometric analysis* (IGA), and it has been successfully applied using geometry representations commonly employed in the CAD or entertainment industry, namely B-splines,[4] NURBS,[2,5] subdivision surfaces,[6,7] and more recently, T-splines.[8,9] For analysis purposes, the CAD model needs to be watertight and it requires a good parameterization, so differential quantities like tangents and derivatives, which are required for analysis, are correctly evaluated. The basis functions that describe the geometry need to have compact support and be linearly independent in order to efficiently and accurately approximate the FEA solution.[10]

NURBS is the standard CAD representation and an obvious choice as a common representation for design and analysis. But a parametric representation suffers from geometric inaccuracies caused by their restriction to a regular grid parameter domain (patch). Freeform geometry of arbitrary topology must be decomposed into a set of NURBS patches, which are joined together to form a smooth model. Continuity problems that may appear at patch boundaries present a problem for analysis. Efforts to correct problems caused by a patch-based representation are expensive and tend to negate the advantages of IGA.[5,11]

To interpret the IGA results correctly, designers must be aware of the CAD representation's limitations and how these may affect analysis.

Subdivision surfaces[12] and T-splines[13] support extraordinary vertices (EVs)—namely, vertices with a valence other than regular. They have the ability to represent arbitrary geometry with a single continuous watertight surface and therefore solve all the problems involved in a patch-based approach. Catmull-Clark subdivision surfaces[14] are the most prominent subdivision surfaces, and they generalize tensor product bicubic B-splines to meshes of arbitrary topology—that is, the limit surface has a piecewise parametric surface representation. Problems in the evaluation of differential quantities around EVs have recently been solved.[15] Catmull-Clark surfaces are the standard representation in the entertainment industry and are becoming increasingly important for the high-quality surface design required in CAD. Software like Solidworks SWID and CATIA Imagine and Shape already provide Catmull-Clark subdivision surfaces for CAD.

Unlike NURBS or subdivision surfaces, T-splines also allow T-junctions in their geometry description. This offers the flexibility of local refinement, which can make analysis more efficient.[8] To guarantee the linear independence of basis functions at T-junctions, it is necessary to define a restricted subset of analysis-suitable T-Splines.[16] To evaluate the surface for analysis, the surface around the EV is approximated arbitrarily close by a set of Bézier patches.[9] T-splines are available in Autodesk Fusion 360 and as a plug-in for Rhino.

Unfortunately, IGA does not eliminate the heuristic nature of generating a model suitable for analysis. In general, the CAD model contains considerably more detail than is required for analysis. Attempting to analyze the detailed CAD model may overtax the analysis tool. For efficient analysis, some features can be ignored, but this involves deterministic procedures for deciding which features to ignore. Today, the adopted industry-wide solution is to simplify the geometric model (for example, by smoothing or by removing blends and fillets) and to defeature it (such as by eliminating small holes and protrusions). These steps can distort the original geometry, remove potentially important geometric features, and thus undermine the CAD/CAE integration. To better integrate design and analysis, we need to define new methods of synthesizing and organizing the CAD/CAE model in order to develop CAD models that are suitable for analysis.

In the same way as the simulation mesh influences analysis in traditional FEA, CAD model parameterizations have been shown to affect analysis results in an IGA setting.[17] To interpret the IGA results correctly, designers must be aware of the CAD representation's limitations and how these may affect analysis. One example is the appearance of artifacts due to the representation. When using NURBS, subdivision surfaces, or T-splines, designers will always avoid modeling features on the surface that run skew to the orientation of the control mesh to avoid the appearance of ripples in the surface.[18] When using the CAD representation for analysis, the simulation result may cause features appearing on the surface that are not aligned with the mesh grid. This will cause artifacts in the analysis result and could make it difficult for an unaware engineer to correctly interpret analysis results. In CAD, a shape's flat surface parts are described by only a few control points. However, flat areas in the design geometry may wrinkle and ripple strongly in response to environmental impact. To express the solution accurately therefore requires a denser mesh in such regions than is typically provided by the unaware CAD designer. *Analysis-aware modeling* aims to generate CAD models better suited for both design and analysis without creating representational conflicts with other tasks in the design process. To achieve this, CAD designers will require new skills.

An Integrated CAD/CAE System

Let us assume that we have achieved complete CAD/CAE integration so that we can provide all product design information from the CAD model to the CAE tool. The insertion of the analysis effort into the design process is best facilitated by integrating both design and analysis tools into one software environment. This will allow designers to immediately verify design specifications and assess structural stability. Autodesk Fusion 360 is one of only a few applications that combines CAD and CAE tools in one system, but it is not based on an IGA approach.

CAE tools today are usually intended for use by a highly trained engineer or expert analyst. Many designers either lack the expertise or do not have the software training to handle the often complex product behavior. In response, CAE suppliers are producing easy-to-use versions of their most sophisticated tools for operation by casual users. A carefully designed interface combined with additional training in the use of FEA tools is still necessary to increase the quality of designer analyzes and to ensure that results are more reliable and, consequently, yield better designs.

Having simulation available as a general tool within a modeling application provides the designer with valuable feedback on structural properties of the design to not only verify design specifications but also aid the design process. For example, having simulation available during modeling will help create designs made from highly flexible materials. Figure 1 provides one such example using a tent roof.

If a product designer is not an expert analyst, it is important to provide intuitive feedback on the analysis results. The feedback may be visual—for example, using colors in the CAD model to highlight problems, as in Figure 2—or may provide suggestions on how to improve the model to overcome potential problems.

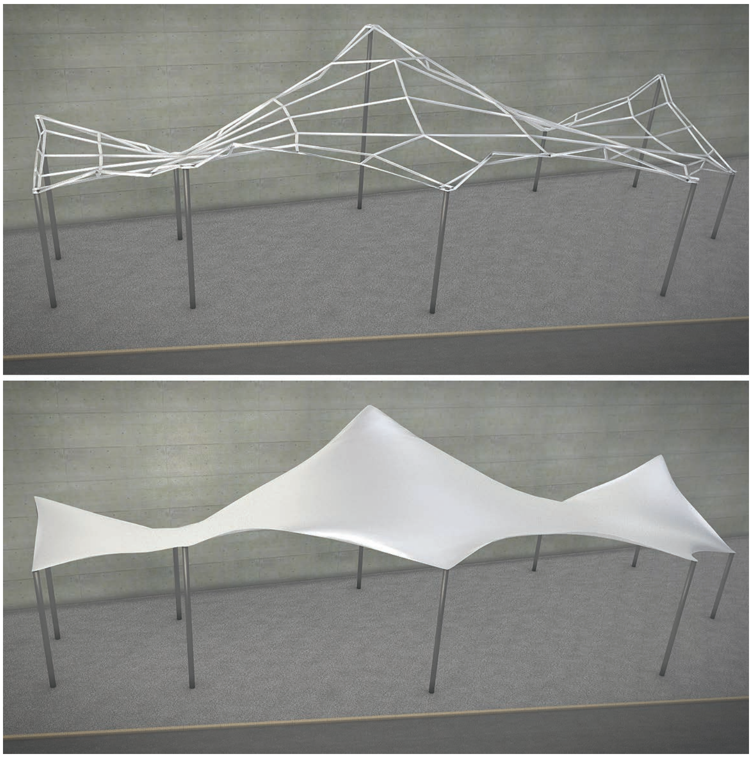

Figure 1. A constrained boundary of a mesh describing a tent roof. The designer can determine the preferred shape of the design by looking at the simulation results after varying the height of the supporting posts or after changing the layout and material properties of the roof.

Once we have a unified representation for the CAD/CAE model, we can easily facilitate automatic shape optimization based on user-defined

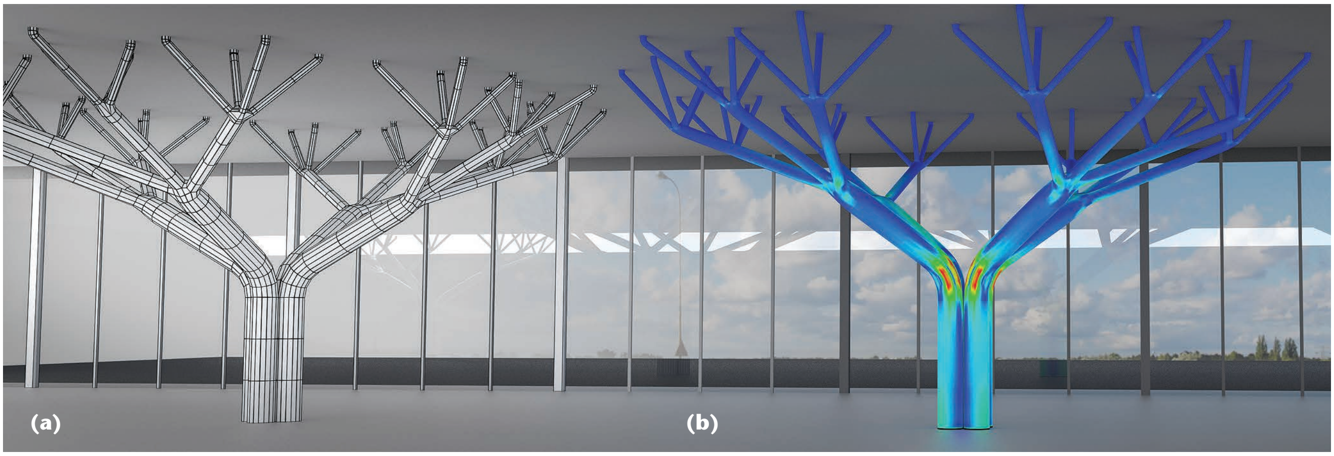

Figure 2. Tree-like roof support structure modeled using a single subdivision surface. (a) The parameterization is shown on the CAD model, which is used directly for analysis. (b) The von Mises stress is a scalar value that can be compared with the yield strength of a material to predict structural problems can be visualized directly on the CAD model in the modeling application. If the maximum value of the color ramp used to visualize the stresses is set to the yield strength of the material chosen by the designer, the visualization can help the designer detect structural problems. The designer can then alter either the shape or material properties to improve the design with respect to structural stability.

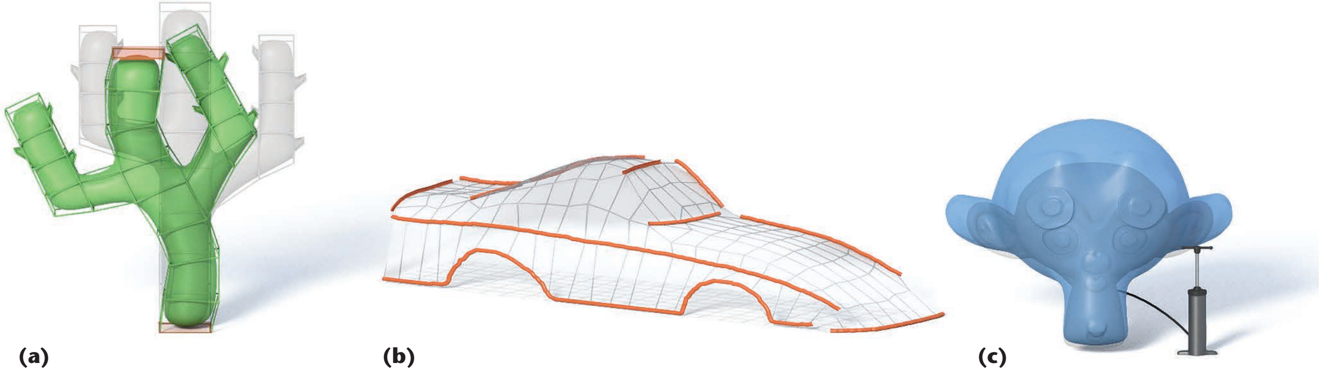

Figure 3. Integrating simulation into the CAD system can provide designers with a range of physics-based modeling tools. (a) The orange areas on the control mesh of a cactus, the bottom of which has been constrained to the floor, indicate constraints. (b) This car was modeled from a plane sheet of metal using a sketch-based interface to constrain the limit surface such that it passes through given points. (c) The monkey model was inflated like a balloon by introducing a uniformly distributed force on its inner surface.

constraints. Using shape optimization techniques to find an input shape's optimal geometry and topology with respect to its intended functionality minimizes certain objective functions, such as total stress on a shape or maximizing stiffness.[19] An automatic solution to correcting structural problems could fix problems that can occur during 3D printing or subsequent handling of computer-generated objects.[20] The design of a product's mechanical structure is often driven by conflicting goals, and automated optimization could help a designer balance a product's aesthetics and functionality.

By merging CAD and CAE tools in one system based on a unified framework for design and simulation, a system could also offer designers a range of physics-based modeling tools in addition to standard model editing tools. New instruments may emerge that provide designers with a range of innovative tools supporting new approaches to the design process.

A product's geometry can be modified either by setting constraints or defining the forces acting on the geometry that cause deformations, much like modeling virtual clay. Typically, constraints and forces are used together to define deformations. Constraints are used to fix parts of the surface in place, whereas forces are applied to other parts of the surface, causing the deformation. Forces can also be defined to specify interesting new modeling operations, like inflation (see Figure 3). In addition, physics-based modeling tools can help make 3D model design an intuitive task for casual designers.

The main challenge to achieving a tight design-analysis integration is a unified model that facilitates both design and simulation. Using IGA solves many of the problems inherit in interfacing between two representations, but it does not eliminate the heuristic nature of finding a good mesh for reliable analysis. Analysis-aware modeling requires the CAD designer to lay out the CAD representation in a way that best facilitates model analysis. We expect this to entail finding new strategies to organize a CAD model so it can be quickly adapted for efficient analysis. This may include developing a good method for synthesizing models to easily and temporarily remove detail from the CAD model. Also, the designer needs to be aware of how the parameterization of the representation may affect analysis.

Having a more user-friendly interface will help inexperienced users employ the tools more reliably. If the combined CAD/CAE system also offers the designer alternate and optimized designs throughout the design process, it could help the designer identify new innovative designs. At the very least, the ability to explore a range of design alternatives throughout the design process will lead to performance and design quality improvements. Nevertheless, before we can hand over analysis tools to designers, they must acquire new competencies. Above all, designers will require training to gain an understanding of the basic concepts of mechanics.

Today, manufacturing is entering a new phase of customization-oriented production that is less concerned with productivity and efficiency and more focused on agility and responsiveness. There is a shift toward meeting individual requirements (referred to as mass customization), as opposed to traditional high-throughput, low-variability mass production. The consumer product manufacturing industry is seeing a wave of intense personalization efforts like that offered by Nike's NIKEiD initiative, which lets consumers customize running shoes and then manufactures and ships them direct. Although the NIKEiD example is limited, the emergence of rapid manufacturing is allowing manufacturers to enable the customization of a product's shape and functionality.

Lastly, as 3D printing becomes more commonplace, we expect casual designers to increasingly introduce their ideas to the real world. At the same time, 3D printing is challenging the ways that are traditionally employed to assess the structural adequacy of engineered components. 3D printing processes can create materials that, although comprised of traditional engineering isotropic materials, may not actually be isotropic. 3D printed profiles have not yet undergone the same level of material scrutiny as traditional materials. CAD/CAE software developers must make efforts to ensure that the tools and solvers are in place to characterize, model, and analyze models with the complex internal geometries of 3D printed parts and components.

References

1. Aberdeen Research Group, "Simulation Driven Design Benchmark Report: Getting It Right the First Time," Oct. 2006; www.reden.nl/bestanden/Aberdeen_Simulation_Driven_Design.pdf.
2. T.J.R. Hughes, J.A. Cottrell, and Y. Bazilevs, "Isogeometric Analysis: CAD, Finite Elements, NURBS, Exact Geometry and Mesh Refinement," *Computer Methods in Applied Mechanics and Eng.*, vol. 194, nos. 39–41, 2005, pp. 4135–4195.
3. J. Peddie, "2015 CAD Report," tech. report, Jon Peddie Research, 2015; http://jonpeddie.com/publications/cad_report.
4. M.A. Sabin, "Spline Finite Elements," PhD thesis, Univ. of Leeds, 1997.
5. J. Kiendl et al., "Isogeometric Shell Analysis With Kirchhoff-Love Elements," *Computer Methods in Applied Mechanics and Eng.*, vol. 198, nos. 49–52, 2009, pp. 3902–3914.
6. F. Cirak and M. Ortiz, "Fully C1-Conforming Subdivision Elements for Finite Deformation Thin-Shell Analysis," *Int'l J. Numerical Methods in Eng.*, vol. 47, no. 12, 2000, pp. 2039–2072.
7. A. Rifinaller-Schiefer, U.H. Augsdörfer, and D.W. Fellner, "Isogeometric Shell Analysis with NURBS Compatible Subdivision Surfaces," *Applied Mathematics and Computation*, vol. 272, part 1, 2016, pp. 139–147.
8. Y. Bazilevs et al., "Isogeometric Analysis Using T-Splines," *Computer Methods in Applied Mechanics and Eng.*, vol. 199, 2010, pp. 229–263.
9. M.J. Borden et al., "Isogeometric Finite Element Data Structures Based on Bézier Extraction of T-Splines," *Int'l J. Numerical Methods in Eng.*, vol. 88, no. 2, 2011, pp. 126–156.
10. V. Shapiro, I. Tsukanov, and A. Grishin, "Geometric Issues in Computer Aided Design/Computer Aided Engineering Integration," *J. Computing and Information Science in Eng.*, vol. 11, no. 2, 2011; doi:10.1115/1.3593416.
11. J.A. Cottrell, T.J.R. Hughes, and A. Reali, "Studies of Refinement and Continuity in Isogeometric Structural Analysis," *Computer Methods in Applied Mechanics and Eng.*, vol. 196, nos. 41–44, 2007, pp. 4160–4183.
12. N. Dyn and D. Levin, "Subdivision Schemes in Geometric Modeling," *Acta Numerica*, vol. 11, 2002, pp. 73–144.
13. T.W. Sederberg et al., "T-Spline Simplification and Local Refinement," *ACM Trans. Graphics*, vol. 23, no. 3, 2004, pp. 276–283.
14. E. Catmull and J. Clark, "Recursively Generated B-Spline Surfaces on Arbitrary Topological Meshes," *Computer Aided Design*, vol. 10, no. 6, 1978, pp. 183–188.
15. A. Wawrzinek and K. Polthier, "Integration of Generalized B-Spline Functions on Catmull-Clark Surfaces at Singularities," *Computer Aided Design*, vol. 78, 2016, pp. 60–70.
16. L. Beirão da Veiga et al., "Analysis-Suitable T-Splines of Arbitrary Degree: Definition, Linear Independence and Approximation Properties," *Mathematical Models and Methods in Applied Sciences*, vol. 23, no. 11, 2013, pp. 1979–2003.
17. E. Cohen et al., "Analysis-Aware Modeling: Understanding Quality Considerations in Modeling for Isogeometric Analysis," *Computer Methods in Applied Mechanics and Eng.*, vol. 199, nos. 5–8, 2010, pp. 334–356.
18. U.H. Augsdörfer, N.A. Dodgson, and M.A. Sabin, "Artifact Analysis on B-Splines, Box-Splines and Other Surfaces Defined by Quadrilateral Polyhedral," *Computer Aided Geometric Design*, vol. 28, no. 3, 2011, pp. 177–197.
19. K. Bandara and F. Cirak, "Isogeometric Shape Optimization of Shell Structures Using Multiresolution Subdivision Surfaces," *J. Physics Conference Series*, vol. 734, no. 3, 2016.
20. O. Stava et al., "Stress Relief: Improving Structural Strength of 3D Printable Objects," *ACM Trans. Graphics*, vol. 31, no. 4, 2012, article no. 48.

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