From the editors of

cadalyst

An Introduction to **Generative Design**

Generative design is opening new opportunities for solving design problems — and turning traditional workflows upside down, moving simulation ahead of model creation. Understanding the basics of the technology can help you decide if it's time to share your AEC or MCAD workload with generative design tools.

Includes links to in-CAD and stand-alone generative design tools on the market today

An Introduction to Generative Design

This latest design technology trend taps computer power to help architects and product designers automatically optimize products, spaces, and processes.

By Monica Schnitger

» ***Cover image:*** *Part iterations created using generative design in Solid Edge.*

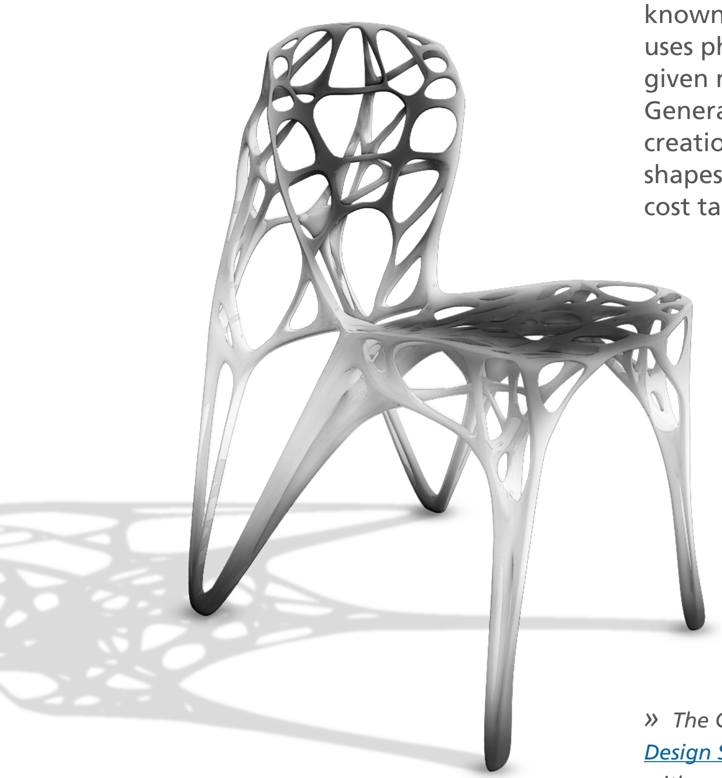
As a CAD professional, you've used software to create many designs — but what if the software itself could shoulder some of the design work? Just imagine: You enter the general criteria for your design, a four-legged chair with a seat and a backrest. The chair must be able to support a 300-lb load, but it can't weigh more than 15 pounds. Your sales department tells you this chair can retail for $150, so you figure your budget for materials and production is $50. Marketing would like it in walnut. And your boss wants 25 design alternatives to review by Friday. If you were relying on traditional tools and methods, that would be a tall order — but an emerging class of software can help get the job done with generative design technology.

Defining Generative Design

Let's start at the beginning: What is generative design? It's a category of technologies that suggests design options, or optimizes an existing design, to meet criteria defined by the user. The best-known of these technologies is topology optimization, which uses physics to find the most appropriate shape for an object, given material specifications, loads, weight, and other conditions. Generative design also includes rules-driven parametric CAD model creation, which automates the design of complex but repetitive shapes (and can incorporate non-geometric aspects as well, such as cost targeting and manufacturing optimization).

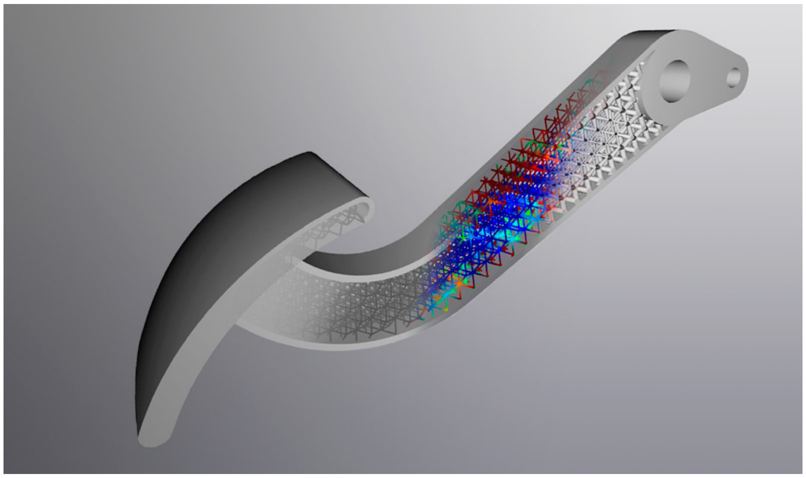
Most designers are used to creating a CAD model first, then subjecting it to simulation just before production, to predict how the final product will perform. Generative design upends this sequence, using simulation during the earliest concept stages to identify alternatives that will satisfy design criteria. The human designer then selects the most aesthetically pleasing or otherwise desirable alternative, and completes the design process.

Why do this? Because it's easier for humans to make minor design changes early in the process rather than major ones later, and because they can only process so many alternatives at once. Computers aren't biased



» *The Generico chair by designer Marco Hemmerling of the SPADE Spatial Design Studio was designed using generative techniques to combine comfort with response to load forces. The chair is 3D-printed to allow for optimal material distribution.*

nTopology



» *Element from nTopology was used to create a lattice inside this pedal, reducing weight while maintaining structural integrity and industrial manufacturability.*

toward any one concept or design, and can create hundreds or thousands of ideas in the time we take to create one. Enabling the designer to only select from alternatives that meet operating parameters, rather than considering options that might not meet these criteria, prevents wasting time on nonviable options and potentially increases innovation. In a few short hours, the designer can examine many alternatives, select one, and finally create the detailed CAD model needed for manufacturing and other downstream steps.

Generative design has many practical benefits beyond time savings and innovation. Manufacturers can optimize designs to use less material and weigh less, saving money on materials and transport. They can replace expensive materials and still meet the design criteria. Where appropriate, they can move between additive and traditional subtractive manufacturing processes, facilitating custom and short-run product development alongside traditional manufacturing. And as the technology continues to evolve, they'll be able to trade off between business and technical aspects to find the best alternative in a cost–timeline–function analytical envelope.

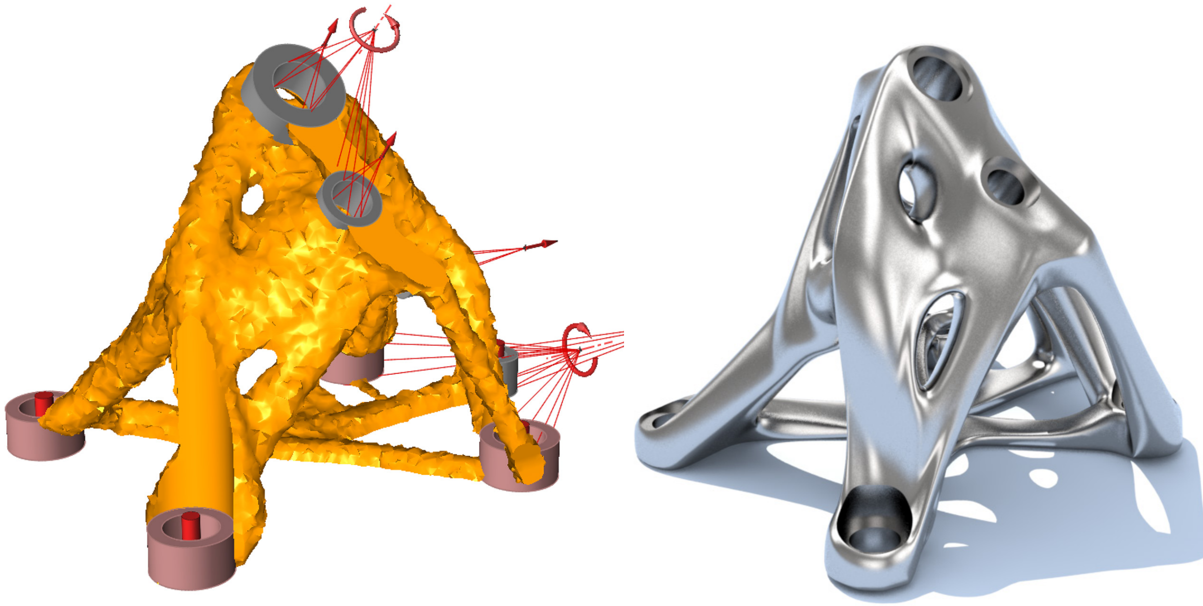
Types of Software Tools

There are two broad categories of generative design tools: specialist, or stand-alone tools, and in-CAD tools, which are incorporated within CAD solutions. Several of the in-CAD tools specifically cater to the design needs of additive manufacturing (often referred to with the umbrella term 3D printing). This type of manufacturing enables the creation of shapes that can't be milled or formed using traditional methods, and is especially well suited to lattices, internal voids, and other structures that reduce weight. But generative design isn't limited to product development; there are AEC-focused tools as well (see the table on pages 5 and 6 for examples of the various types).

Each software developer has taken its own approach to generative design, and the solutions are evolving quickly.

Topology Optimization

The best-known technology in the generative design bucket is topology optimization, which uses finite-element analysis (FEA) to optimize material layout within a design space. A typical topology optimization process starts by defining the shape of a part to be optimized. (If it is part of an assembly, the designer can also define what not to optimize.) Next, the designer sets the loads, constraints, and goals for the optimization. Lastly, he or she defines how and where the optimization will run. This



Altair

» *This engine mount was designed using Altair solidThinking Inspire. Starting with a block of material, factoring in constraints, forces, and material type, the software creates optimized geometry for the part.*

step varies depending on the software used, and might include which algorithm to use, and whether calculations will be run on a local workstation, in the cloud, or elsewhere. The result will be one or more design options that meet criteria. Today, the results are likely to be shapes made up of mesh elements, plus visual representations of physical forces on components. From these, the designer identifies a single, best option.

What happens next depends on the use case. For an object destined for additive manufacturing, a designer might add fillets, etch part numbers, and perform the other final steps necessary to support 3D printing before running one last simulation to ensure that the manipulations haven't affected the part's viability.

If the part is destined for traditional manufacturing or other downstream processes that require adding solids or surfaces, there are two alternatives: Use the optimization output as a template and model solids/surfaces over the mesh, or use specialized software to automate this task. The final part or assembly should undergo simulation again before moving to manufacturing.

Appearances matter. Topology optimization algorithms can be based on many different principles; the one most familiar to us is based on research into bone growth patterns. Bone responds to external stimuli by only growing as needed — the body adds no excess material.

Bone-like and other visually unusual structures are often beautiful, in a way — and, because of the optimization, we know they're functional — but they're certainly different from traditional designs. Many designs created via topology optimization don't meet the accepted design aesthetic, and must be modified to appeal to buyers' sensibilities, especially in the case of consumer goods. A designer might use the structure created by the topology optimization tool as a starting point, and edit that geometry or overlay it with more traditional-looking solids to create and end result that's more conventional.

A Sampling of Generative Design Tools

Stand-Alone Tools for AEC and MCAD

CAE-focused stand-alone tools can be used in many design applications, for manufacturing or AEC designs.

Company Name	Product Examples	Technology Applications
Altair	**OptiStruct**	Altair OptiStruct was one of the first solutions of this type, and has been used across industries for lightweighting. OptiStruct is parallelized, meaning that it can be executed on hundreds of cores to quickly perform large-scale optimization runs.
ANSYS	**ANSYS Mechanical**	ANSYS Topology Optimization technology is part of the ANSYS Mechanical offering, and can be launched from within the Workbench to fit into a simulation workflow.
Dassault Systèmes	**Tosca Structure, Tosca Fluid**	Dassault Systèmes Tosca is a structural optimization suite that that works with ABAQUS, ANSYS, and MSC Nastran finite-element solvers to integrate with an existing CAE environment.
ESI Group	**PAM-STAMP, ProCAST, SYSTUS**	ESI Group embeds generative design techniques into its PAM-STAMP, ProCAST, and other manufacturing solutions, and offers specific shape optimization in its SYSTUS simulation suite.
MSC Software	**MSC Nastran Optimization**	MSC Software offers several types of design optimization solutions, from shape and topology optimization in MSC Nastran Optimization to process management solutions that optimize designs across multiple disciplines.

In-CAD Generative Design Tools

In-CAD tools can be CAE solutions from one of the suppliers listed above, accessed from within the CAD design environment and then returning to it with the suggested design, or designer-specific tools that are part of the CAD workflow. The user defines a few inputs — usually loads, the design space, constraints or boundary conditions and, in some cases, manufacturing methods — and then runs an iterative algorithm to compute the geometry. The solutions listed below are examples of CAD tools with designer-specific generative design capabilities.

Company Name	Product Examples	Technology Applications
Autodesk	**Fusion 360, Inventor**	Autodesk Fusion 360 and Inventor, in premium subscriptions, include access to optimization setup and calculation capabilities, as well as to cloud computing resources.
Dassault Systèmes	**TOSCA suite**	Dassault Systèmes offers access to its TOSCA optimization suite from within its CATIA and SOLIDWORKS CAD offerings.
Robert McNeel & Associates	**Rhino**	Rhino, a CAD package used for both manufacturing and AEC, relies on the Grasshopper visual programming language and environment to automate design. Users drag components onto a canvas and connect them logically to specify how a design is created. They can vary parameters to generate design variants for further exploration.
PTC	**Creo Simulate**	PTC Creo Simulate uses Vanderplaats R&D GENESIS to power its optimization technology. It uses the familiar Creo interaction and workflow, and results are converted to freestyle (B-rep) objects, which eliminates the need to rebuild or recreate faceted geometry.
Siemens	**NX, Solid Edge**	Siemens NX and Solid Edge integrate Frustum's Generate kernel to generate optimized design alternatives. Users can then manipulate the geometry with Siemens's proprietary Convergent Modeling technology.
Altair	**solidThinking Inspire**	SolidThinking Inspire, Altair's brand for mid-market CAD and simulation, integrates topology optimization as part of the CAD modeling process.

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A Sampling of Generative Design Tools *Continued from page 5*

Optimization-Focused CAD

Several tools combine CAD and topology optimization to emphasize design and/or manufacturing optimization over other design goals.

Company Name	Product Examples	Technology Applications
Frustum	**Generate**	Frustum's geometry kernel and cloud-based app, Generate, combines the company's voxel-based design algorithm with finite-element analysis to generate iterations of a topology-optimized design. It is available as a stand-alone product or integrated into Siemens NX and Solid Edge.
nTopology	**Element**	NTopology's Element is a generative, function-based engineering application that provides instant feedback during design, to optimize both an object's shape and the industrial manufacturing process.
ParaMatters	**CogniCAD**	The CogniCAD platform from ParaMatters is a cloud-based design platform targeted at additive manufacturing processes. Users import CAD files into the platform, define load and design criteria, and set it to calculate.

Optimization Tools for AEC

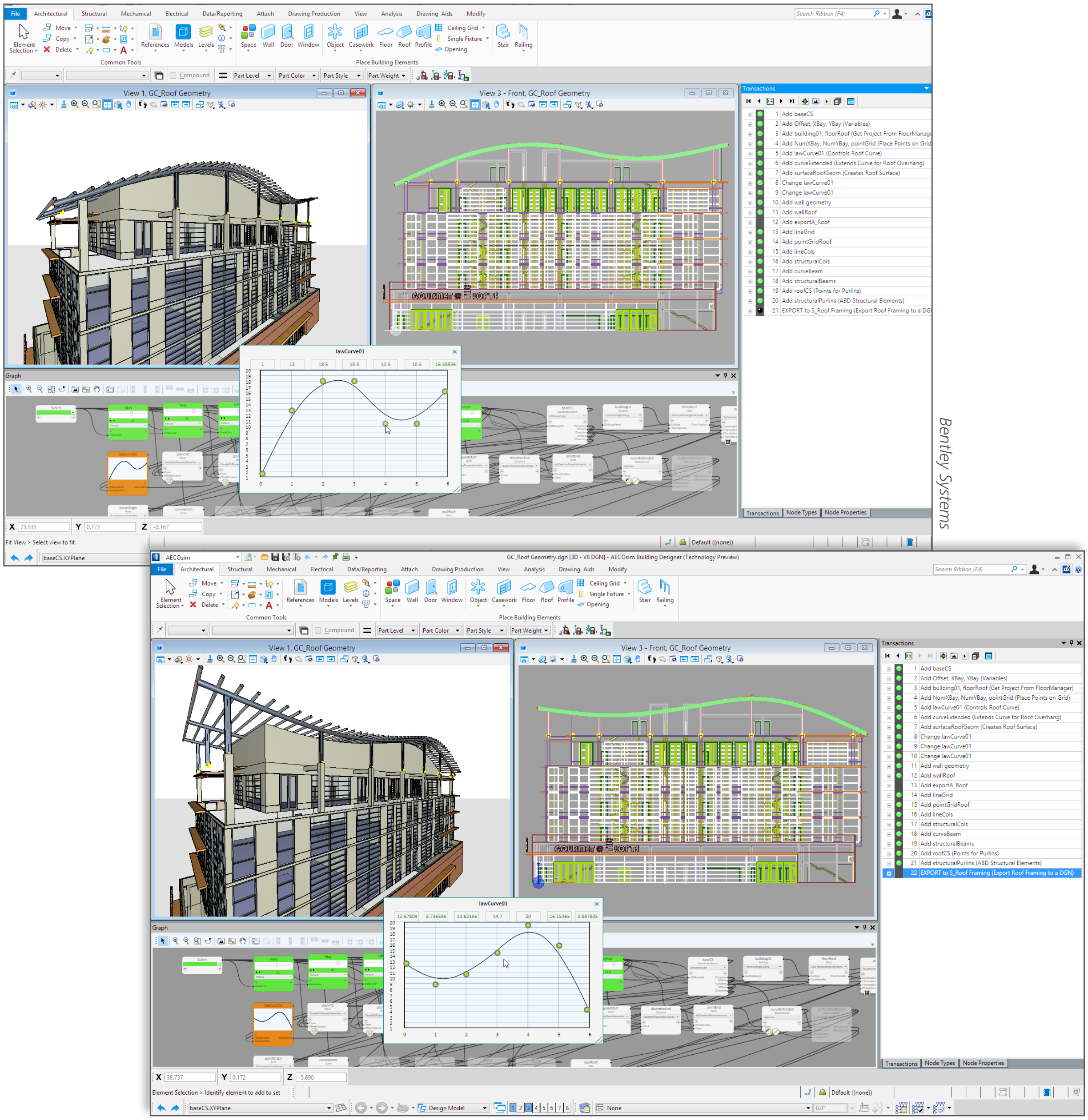
Many AEC workflows use standard CAE tools to optimize structural members, facades, and other features. In addition, the repetitive nature of buildings and other types of infrastructure has led to the creation of computational parametric tools.

Company Name	Product Examples	Technology Applications
Autodesk	**Dynamo Studio**	Autodesk Dynamo Studio is a rule-based parametric scripting language that works with Autodesk Revit to extend building information modeling with the data and logic of a graphical algorithm editor. Dynamo enables designers to create visual logic to explore parametric conceptual designs and automate tasks.
Bentley Systems	**Generative-Components**	Bentley Systems GenerativeComponents is computational design software that automates the design process by defining and controlling parametric object attributes and relationships. This enables designers to explore alternative building forms without manually building a detailed design model for each possible scenario.
Nemetschek Allplan and Graphisoft	**ARCHICAD**	Nemetschek Allplan and Graphisoft, and other AEC design software suppliers, offer algorithmic design capabilities via partnerships with Rhino/Grasshopper. Graphisoft ARCHICAD, for example, has a bidirectional connection to Grasshopper that allows architects and designers to define the parameters of a design and quickly explore many alternatives.

Algorithmic Modeling and Computational Geometric Design

Generative design isn't, however, limited to physics-based concepts or, for that matter, to manufactured objects. Architects long ago discovered that computational design (also called algorithmic modeling) can replace the drudgery of modeling repeated components, such as the individual stairs in a staircase, and they now use parametrically driven tools to create such designs. This labor-saving approach is spreading from AEC to other industries where complex but repeated patterns benefit from automation.

In the staircase example, building codes govern the vertical distance between stair treads, the required depth of the tread, and other aspects of the design. Computational design techniques use these rules and surrounding geometry to drive design. Rather



Bentley Systems

» This is a designer's desktop in Bentley Systems GenerativeComponents software. At the bottom is the flow of rules that govern the design of the various elements. The user can adjust values on the left side of the desktop to vary the design (note the different roofline from one image to the next), automatically updating the building information modeling (BIM) model to add longer supports for the roof.

than modeling each staircase step by step, software automatically creates the appropriate geometry within the building CAD model.

But the software's capabilities are not limited to geometry in a traditional "CAD model" sense. Computational geometric design can also be used in space planning to determine optimum size, shape, purpose, and adjacency of rooms in a building, or the layout of homes in a subdivision. Feed room requirements and rules into the computational engine, and it creates design variations for building, campus, or neighborhood planning. (Users focused on product development can set up similar rules and calculations for the placement of weight-reducing holes in tire rims, or for aesthetic considerations in furniture surfaces.)

Getting Started with Generative Design Tools

Generative design tools create alternatives that humans might not have come up with, and they save time and money. But the technology is not right for everyone: a bit of familiarity with physics helps, as does the willingness to explore designs that might not be immediately obvious or fit into prior generations' aesthetics. You should give it a try, however, even if you're not sure. The odds are that your existing CAD tool already provides some access to these capabilities — check with your software supplier.

If generative design is something you'd like to try, consider the following:

- The conceptual design team probably doesn't include simulation specialists, and that's fine. Many CAD-embedded solutions are intended for designers: The setup is fast and easy, as is interpretation of the results.
- Computational geometry can be more difficult to use than topology optimization, because of the number and types of rules one can create. Computational geometry engines are usually set up using Python or another scripting tool as well as an understanding the rules of the design and which parameters can be varied — in other words, the ideal user is a designer who can code (or a coder who understands the design).
- Generative design optimizations rely on accurate inputs for materials, loads, and other factors very early in a design process. That may mean changing how information flows, and perhaps a more open collaboration with suppliers. Consider how you share and gather this data to protect your intellectual property.
- It's likely that a computer-generated design mesh will need to be manipulated by a human for aesthetics or downstream uses, or to add in elements that were not part of the optimization. Some CAD tools make this easier than others, but it is always possible, and developers are working hard to incorporate mesh modeling into their CAD tools. Allow time for this editing in project plans and schedules.
- Think big: Generative design isn't just about geometry and physics. Your simulation could include manufacturing process type, cost, and availability; material cost, as well as physical characteristics; supplier tradeoffs; and many other factors.
- Remember that physics-based simulation early in a design cycle doesn't guarantee that the final design meets criteria. Always run a validation simulation before deciding the design is complete.

Generative design technology is not right for everyone, but you should give it a try, even if you're not sure whether it's appropriate for your needs and abilities.

» *Frustum's Generate was used to optimize this part for 3D printing. The designer was able to precisely control how this complex geometry was built, to take full advantage of the latest additive manufacturing capabilities.*

The Bottom Line

Let's be clear: Computers will not replace designers. Humans still need to validate computer-generated designs and perform the myriad tasks that take place downstream from ideation. Generative design solutions can, however, propose concepts that humans might not have considered otherwise, and save time by pointing designers toward workable alternatives.

Computational techniques such as topology optimization enable designers to explore dozens of alternatives, all of which meet the requirements. We go from testing a single design toward the end of the process to creating capable designs right from the start.

Seeing the benefit from these solutions, however, requires organizational change and technology adoption — start now to think about how you can take advantage of these emerging tools.

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This publication was developed by Cadalyst, the leading source of information about computer-aided design and related software and hardware technologies for the AEC, civil engineering, and manufacturing markets.