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Manufacturing for Design and the Future of CADCAM

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April 2019, n. 09

https://renir.carloalberto.org/

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Paper to be presented at the TOTO Workshop Toronto, Sept 10-11, 2018

Abstract

Ever more stringent environmental regulation has resulted in lightweighting becoming the leading edge of technological innovation in auto industry manufacturing. This, on top of the long term trend of outsourcing in the auto industry, has placed increasing challenges and opportunities on supply chain companies for both manufacturing and on shared design responsibilities in the industry, particularly for SME firms (Smitka & Warrian 2017). The paper examines the technical and cognitive capabilities of SME manufacturing firms in this new environment with regard to CADCAM software applications.

Previous research by Warrian has examined knowledge and technology transfer between public infrastructure and auto supply chain firms (Warrian 2017). A critical issue arising is that the lightweighting imperative has created a new kind of materials competition based on the proposition that the critical attribute of the new materials is not that they are lighter and stronger but that their microstructures enable new geometries, and with them allow access to physical properties not available in conventional materials. Previous field research has done a preliminary survey of what kinds of engineering software tools auto supply chain companies use. The larger firms have integrated platforms of CADCAM, CAE, CAM to supply chain logistics applications. The smaller firms have little to none of the latest CADCAM applications and even where available, they are used sparingly as individual 'instruments' to address very specific product or process issues.

The paper analyses the current generation of CADCAM applications and the 'instrumentalist' engineering culture in which they are embedded. Each design is treated as an individual object, the manifestation of an instantaneous intent. In the future, however the merging of advanced materials and software will mean at a certain scale i.e. the nano scale, the object and the material properties merge. There is a unified design space incorporated within a distribution of material properties which produces unified designs that are more than the sum of the individual components and possibly geometries that do not exist in nature. We call this 'Manufacturing for Design'.

Introduction

The current paper is part of ongoing research on the changing dynamics of innovation in the Ontario automotive supply chain.

Our definition of advanced manufacturing is that it is the interaction between advanced materials and software applications. This is the organizing principal behind the research questions being explored in the previous series of studies by Warrian.

The overarching analysis of the global automotive industry was explored in Smitka & Warrian (2017) highlighting the shift in engineering responsibility from Original Equipment Manufacturers (OEMs)[1] to SME's[2] who dominate the auto supply chain in North America in Automotive Alley. In the context of enhanced environmental regulations, which has set off a new era of materials competition, there is enormous pressure placed on the technical capacities of SME firms.

Related to our previous workshop theme of industrial resilience of traditional industrial regions such as Torino-Piedmont and Detroit-Ontario, the performance of SME firms is particularly important for assessing the robustness of regional innovation systems.

Warrian (2017) examines 34 advanced materials lightweighting research projects that a Federal metallurgy laboratory in the region collaborates with auto manufacturing firms. Public research infrastructure plays a critical role in leading metallurgical technology research for firms seeking competitive advantage against the constantly moving technology frontier. The cases also give insight into the dynamic and iterative innovation process as research scientists interact with technology and knowledge transfer particularly in the area of TRLs 3-4[3] as things move from scientific concepts to prototypes. Today, the typical product at this stage is a software artifact not a physical artifact.

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[1] "OEM" traditionally referred to the automakers themselves. However it is now used sometimes to refer to the major international parts producers such as Bosch, Magna, Federal Mogul, etc.

[2] An SME is defined in the USA as a firm having 500 employees or more. Other countries like Japan have slightly different definitions. They make up a numerical majority firms in the automotive supply chain but share the overall production volumes with the large parts international parts manufacturers.

[3] Technology Readiness Levels (TRLs) on a 1-9 scale have become common in the policy and research literature. TRLs 1-3 are the basic research activities associated with universities and government research laboratories. TRL 4-7 are prototyping and system integration. TRL 8 and 9 are low volume and mass production in the commercial marketplace.

Warrian (2016) presented results of a survey of the software capabilities of auto supply chain firms. Large firms deploy the full spectrum of high end software tools and integrated platforms. These also firms also pursue very different intellectual property (IP) strategies, significantly impacting knowledge transfer within the industry. Among the smaller firms, there is a very disperse and uneven spectrum of software tools being employed. Beyond the base line of CADCAM[4] capabilities to enable them to accept and apply pre-packaged product design files from OEMs, there is little further engineering being done. The entry-level competencies for firms operating in the automotive advanced manufacturing space are Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) for design, development and validation of the next generation of products. These are mostly lacking in the SME firms, both with regards to human resource skills and licensed software applications. Where these are needed, the small firms resort to assistance from a local Community College or for the more technically accomplished, a government laboratory, and more rarely to specialized third-party engineering firms.

Finally, previous research by Samford, Warrian and Goracinova (2017) on the deployment of additive manufacturing (3D Printing) in Ontario manufacturing found that while 3D printing using resins and plastics is well advanced, metallics and advanced composites applications which are the most vital for automotive manufacturing are lagging at the production stage because of issues of throughput, post-processing machining costs and other processing stages that require application of significant manual labor. In the auto supply chain, to date 3D printing is primarily used for marketing and initial prototyping functions. This is important but limits the impact of the technology at the production stage. The research also found that Canada has made a very defused bet on 3D Printing, relying heavily on Community Colleges and SMEs, as compared to the large scale bet by the US government on such projects as America Makes[5].

[4] CADCAM is the acronym for **c***omputer*-**a***ided* **d***esign*/**c***omputer*-**a***ided* **m***anufacturing*, computer systems used to design and manufacture products. The term *CAD/CAM* implies that an engineer can use the system both for designing a product and for controlling manufacturing processes. For example, once a design has been produced with the CAD component, the design itself can control the machines that construct the part.

[5] America Makes is the large US Federal government additive manufacturing initiative launched under the manufacturing competitiveness policy of the Obama administration. It particularly emphasizes the development of regional 'industrial commons' of industrial, educational and research laboratories.

Moving the Technology Frontier: The Merging of Manufacturing and Design

Simple, regular geometric shapes are popular in human designs because they're easy. Easy to conceptualize and design, especially with traditional CAD software tools which in the last 30 years have been designed to represent and manipulate geometry as combinations of basic geometric primitives, and easy to manufacture in a world where manufacturing means taking a big block or sheet of material, and bending or machining a shape out of it, or pouring metals into a mold. This is the classic definition of "subtractive manufacturing". But manufacturing is starting to undergo a revolutionary change as 3D printing or additive manufacturing emerges as a viable and scalable alternative, where material is only added, usually in layers, where the shape requires it. Where traditional manufacturing incentivizes the simplest shapes as they are quick and intuitive to design, additive manufacturing is at its fastest and cheapest when you combine complex geometries with the use the least possible material for the job. (Blain 2017)

The latter are complex for a human to design, often even counter-intuitive – but fairly easy, as it turns out, for a computer. And very easy for a giant network of computers. And now, exceptionally easy for a human designer with access to Autodesk's Fusion 360 software, which has the capability built into the application architecture.

Autodesk's generative design tool works as follows: the user identifies and designs some critical areas for a mechanical component, such as mount points or cylindrical holes that a bearing needs to go into, for example. One can then choose to maintain symmetry down prescribed axes if that's important. Then the user instructs the system on what physical environment the part needs to endure, such as which structural loads, from which angles, and what physical properties it will attempt to target and prioritize – for example, stiffness and light weight. Then, with the click of a button, the computer performs a multitude of simulations, shaping the desired material and analyzing what each change does for its load bearing capacity. The process can be accelerated using the distributed power of cloud computing to get results quicker and to obtain multiple solutions, each potentially embodying a different compromise between the required physical properties.

At the end of the process, the computer generates a design, or a range of designs, that meet the design criteria while optimizing for, in this example, stiffness and weight. Unsurprisingly, there's barely a straight line to be seen. The forms are decidedly curvilinear and skeletal to look at. The computer's accelerated simulation process appears to produce a lot of the same conclusions natural evolution does. Where there's stress, shapes get thicker and denser. Where there's not, shapes get thinner and lighter. Sharp angles cause stress concentrations, thus shapes generated by the system are smooth and flowing. Now, while these forms are often prohibitively difficult to manufacture using traditional means, they're a perfect use case for 3D printing.

Effectively, what is on the industrial horizon is a two-headed design and manufacturing revolution that not only changes the way we build things, but also the shapes of the products themselves. The implication is that in future, we will see far more organic shapes, and fewer perfect geometric ones in our industrial design, our furniture, our cars, our architecture. The expected outcome is to produce a part that uses about 50% less weight and material consumption than production by traditional manufacturing methods.

In the automotive space, General Motors has announced a major commitment to deploy the new technology.

> General Motors Co said on Thursday it was working with design software company Autodesk Inc to manufacture new, lightweight 3D-printed parts that could help the automaker meet its goals to add alternative-fuel vehicles to its product lineup.
>
> GM executives this week showed off a 3D-printed stainless steel seat bracket developed with Autodesk technology - which uses cloud computing and artificial intelligence-based algorithms to rapidly explore multiple permutations of a part design.
>
> Using conventional technology, the part would require eight components and several suppliers. With this new system, the seat bracket consists of one part - which looks like a mix between abstract art and science fiction movie - that is 40 percent lighter and 20 percent stronger.
>
> GM has used 3D printers for prototyping for years, but Kevin Quinn, the automaker’s director of additive design and manufacturing, said within a year or so GM expects these new 3D-printed parts to appear in high-end, motorsports applications. Within five years, GM hopes to produce thousands or tens of thousands of parts at scale as the technology improves, Quinn said.
>
> “That is our panacea,” Quinn said. “That’s what we want to get to.”

> In the long run, Quinn said the 3D printed parts would help reduce tooling costs, cut the amount of material used, the number of suppliers needed for one part and logistics costs.
>
> Reuters, May 2, 2018

A key factor contributing to this next step in advanced automotive manufacturing is the Generative Design engine in newest Autodesk application suite.

Generative Design

Generative design mimics nature's evolutionary approach to design. Designers or engineers input design goals into generative design software, along with parameters such as materials, manufacturing methods, and cost constraints. Unlike standalone topology optimization, the software explores all the possible permutations of a solution, quickly generating a series of design alternatives. It tests and learns from each iteration what works and what doesn't. (Autodesk 2018). For example, the "truck" of a skateboard is that piece on the underside of the deck that the wheels are attached to. Made of axles, bushes, and pins, the truck is the interface between the wheels and deck that gives the rider the necessary control through shifts in weight, bending and reacting to the board's travel. With the new approach to design, like aircraft parts, furniture, and so many other modern objects, skateboard trucks are set to change, thanks to combining the new design functions with metal additive manufacturing and advanced composites additive manufacturing.

<u>Definition</u>

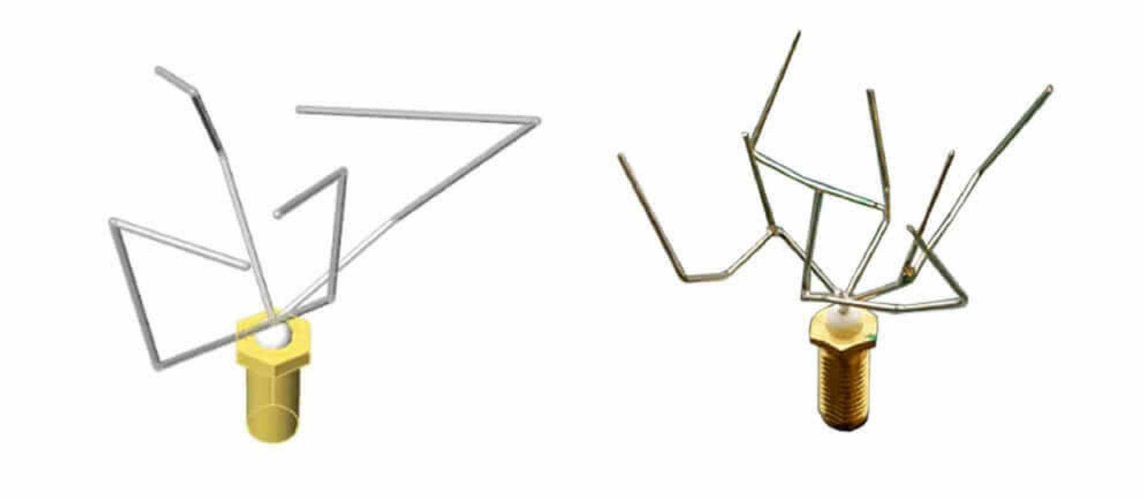
Repeating things for decades doesn't make them true. For over 50 years, people thought CAD was an acronym for computer-aided design. What it really stands for is computer-aided documentation i.e. the archiving of serialized design files. The counter-intuitive new thought is that the computer doesn't truly aid design. The design is in the engineer's head. The computer is used to document it. So what is the nature of real computer-aided design ? (Kowalski 2016)

How can the computer be used for something more? How can it become your partner in exploration? The newfound abilities of computers to be more creative and to learn are making this idea a reality.

Computers that creatively come up with ideas on their own are the heart of generative design. In generative design, you share your goal with the computer, tell it what you want to ultimately achieve, as well as the constraints involved, and the computer actually explores the solution space to find and create ideas that you would never think of on your own, in an iterative process of intent refinement.

Example. The graphic below is an antenna designed by NASA in the 1960s. It went out on space missions; designed by an engineer, it was considered an elegant, high-performance design.

About a decade ago, engineers developed an algorithm that created and analyzed thousands of possible antenna designs, automatically simulated their performance, and progressively evolved them to achieve higher-performing solutions. This process resulted in the design below, and although it looks odd and counter-intuitive even to a trained eye, it performs twice as well as the earlier one.



The more effective antenna was designed by a computer algorithm.

In 1915, biologist D'Arcy Wentworth Thompson said, "The form of an object is a diagram of its forces." Autodesk is adopting this concept quite literally with Dreamcatcher, the company's research project that lets designers describe the forces that act on an object and then lets computers actually assist in designing and making it. These forces can be structural loads or even manufacturing methods.

In the time it would have taken to obtain just a single design, Dreamcatcher has explored a large variety of them. Its design proposals are delivered back to the user in an intuitive interface to enable navigation through the various designs and understanding the trade-offs between various solutions.

An Automotive Manufacturing Example of Generative Design

Today, car parts are manufactured using giant industrial tools like milling machines and injection molds. Because these tools are so costly to purchase and integrate into a production process, there's little business incentive for car companies to experiment with new modes of manufacturing. 3D printing on the other hand, requires just one piece of equipment to make many different types of parts with intricate structures that traditional tools previously couldn't handle.

An Organic Seat Belt Bracket

GM is starting with an unglamorous component that most of us probably don't think about: the seat belt bracket, which secures the seat belt fastener to the seat. After engineers communicated specific parameters, like the location where the bracket has to attach to the seat, the generative design algorithm produced 150 different possible solutions that look utterly unlike any bracket you can imagine. Sinuous and curvy, the generated designs look organic, almost like the intricate branches of a tree, or parts of an animal's skeleton. "It looks very different from what I expected a seat belt bracket to look like," says Scott Reese, who leads Autodesk's manufacturing, construction, and production products.

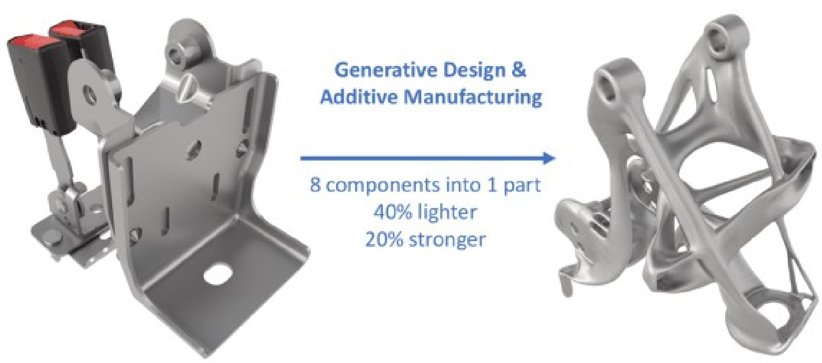
The resulting brackets are in sharp contrast to the bulky brackets you'd typically find in GM cars. "Why are things boxy? That's the manufacturing capability we had," Reese says. "When you feed the computer the problem, it doesn't care about things that were historical constraints humans had. The best answer often mimics the things you see in nature. And now our manufacturing capabilities are catching up."

Of the 150 possibilities, the design GM decided to use is 40% lighter in weight and 20% stronger than the previous version. This kind of weight reduction, applied more broadly to a vehicle, could result in greater fuel efficiency for gas cars and longer range for electric ones.

Generative Design and the Next Step of 3DP/CAD

From GM's business perspective, the most important aspect of the new part is that it combines eight components into a single one that can be 3D-printed, and updated over time without the need for re-tooling. That means they can eliminate the cost, both economic and environmental, of shipping parts from eight different suppliers. It can also eliminate the cost of welding or bolting each piece together. It is no longer required that all the tools needed to create all the different pieces–just a 3D printer–nor would you need all the employees who currently work at various points along this process.

The company's engineers are now evaluating which of the thousands of car parts should undergo the process next. According to Kevin Quinn, director of additive design and manufacturing at GM, it probably won't be a tremendous number of parts because 3D printers aren't yet fast enough to efficiently make larger parts. But even 1% or 2% of the 30,000+ parts in a car could save the company money and improve car performance.



It is expected to take a few years longer for the technique to enter the more general production process because right now the company's 3D-printing capabilities are limited to prototyping. But Quinn, who leads a team that's 10 months old, is in charge of integrating 3D printing into the production-level manufacturing process. While GM starts to add this ability to its factories, Quinn is also seeking external partners to bring generative design to the company's cars sooner–which could mean simplification of its supply chain. They need to identify the companies that have the required technical capacities.

Looking further into the future, Quinn sees potential in using generative design to customize car interiors, whether that be knobs or switches or the entire inside of the car. Without the need to create an entirely new production process and invest in new equipment to create a special type of car, the technology could help GM try things that may not have been feasible, business-wise, before. Quinn thinks this will start to manifest in GM's cars in the next few years, particularly for small batches of cars that are designed for specific purposes like speed or off-roading. Generative design might also act like an extra layer of features that customers could request on top of the basic design of a car. "Just as we customize the screens of our phones, can we do that in our vehicles?" he says.

Autodesk Solution for the Design Space

A key task for Autodesk is to articulate the new technology against traditional definitions, technical functions and expectations from application earlier users and their skills.

Define: Tools for Defining Problems

Dreamcatcher's problem definition is a format for designers to communicate their intent and therefore describe design problems. Through pattern-based description, solutions become modular and accretive, thereby expanding the quality and number of alternatives that are searched in a Dreamcatcher design session. The Dreamcatcher design knowledge base, created through machine learning techniques, is a classified index of pre-existing objects that perform functions, or satisfy constraints, similar to those the user has defined in their problem definition.

Diversifying Input Modalities

Mimicking the variety of reference material in a typical design brief, in Dreamcatcher the designer explicitly and implicitly documents goals and constraints through a number of input modalities including natural language, image inference and CAD geometry. An individual or team may manipulate the problem definition through these multiple modes of input and verify or modify the inferred changes to the problem definition document. Focused efforts on modeling problem definitions and performing design synthesis on full system models rather than individual parts is an active area of investigation for the research and development team.

Shape Synthesis

The Dreamcatcher team is developing several, purpose-built design synthesis methods that algorithmically generate designs of different types from a broad set of input criteria. Synthesis objectives include structural, thermal and fluid physical requirements. Dreamcatcher's design synthesis methods compete against each-other to solve problems most effectively through its high-performance computing servers. A focused research effort into incorporating manufacturing constraints for various methods of fabrication are incorporated into the design synthesis process itself, so that only manufacturable designs are returned to the users. The system enables designers to truly leverage an emerging class of manufacturing tools that release designers from hundreds of years of predicating design decisions on tool based constraints.

Advances in Cloud-Based Computing and Optimization

Through a purpose-built, scalable and parallelized cloud computing framework, Dreamcatcher is able to generate and evaluate solution sets with complexity well beyond that of Generative Design Systems of the past. The system provides the high-performance computing infrastructure necessary to run the computationally intense optimization and analysis engines, including multi-physics simulations.

Design Space Visualization and Decision Making

After a number of solutions have been computationally generated from a problem definition, the Dreamcatcher design explorer presents to the user a set of possible solutions and their associated solution strategies. This user interface provides a sense of the shape of the valid design space and variable interactions. It also assists users in building a mental model of which alternatives are high performing relative to all others in the set. Once the solution has been adequately explored, the designer can modify the problem definition to iteratively generate more relevant solutions.

Traditional optimization workflows like that of the NASA ST-5 antenna are 'bottom-up' where a design space must be defined by the user and then searched by a genetic algorithm or similar optimization function. By contrast, Dreamcatcher uses a 'top-down' approach where higher level goals are specified. This is the major differentiator between design optimization tools and Dreamcatcher's exploratory design synthesis process.

Arguments for the incorporation of AI into design often default to concerns around replacing the human designer. Many elements that are commonly modeled from scratch such as brackets, adapters and stiffeners may be created more effectively by a system such as Dreamcatcher. Complex elements and aspects that are difficult to quantify will require new types of interaction to leverage human intuition and computational rigor in partnership.

Generative Design and the Future of Manufacturing

Information flows are a critical part of the cyber-physical systems we refer to as Industry 4.0. Using artificial intelligence (AI) software and the computing power of the cloud, generative design enables engineers to create thousands of design options by simply defining their design problem - inputting basic parameters such as height, weight it must support, strength, and material options. (Akella 2018)

Generative design leverages machine learning to mimic nature’s evolutionary approach to design. Designers or engineers input design parameters (such as materials, size, weight, strength, manufacturing methods, and cost constraints) into the generative design software and it then explores all the possible combinations of a solution, quickly generating hundreds or even thousands of design options. From there, the designers or engineers can filter and select the outcomes to best meet their needs.

Imagine if instead of starting a “drawing” or CAD design based on what you already know or ideas that are in your head, you could tell a computer what you want to accomplish or what problem you are trying to solve. For example, say you want to design a chair. Instead of drawing two or three options (maybe 10 if you’re really creative), you can tell the computer you want a chair that supports X amount of weight, costs X much, and uses X material. The computer can then deliver hundreds, if not thousands, of practically and easily manufacturable design options that all meet those criteria.

This process allows to address one of the most challenging issues humans face in discovering novel designs: bias. Multiple forms of bias greatly reduce our chances to leverage the freedoms afforded by additive manufacturing and advanced materials.

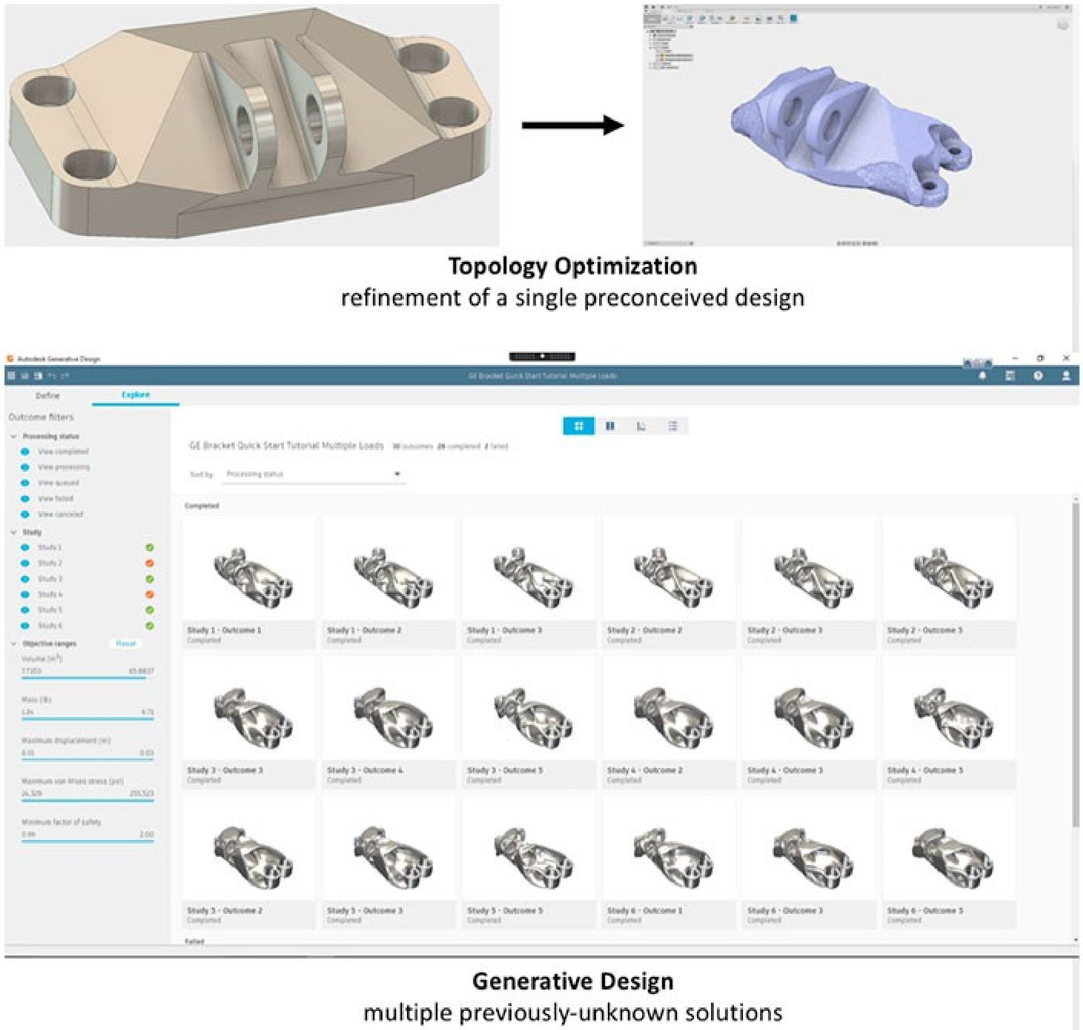
Generative design is software that augments an engineer’s capabilities, rather than replacing him/her, and uses the power of cloud computation and machine learning to explore a whole set of new solutions. It expands the engineer’s or designer’s known universe of valid solutions to their design challenge.

By contrast, many of the technologies that masquerade as generative design - topology optimization, lattice optimization, parametrics or similar technologies -- are focused on improving a pre-existing design, not creating new design possibilities.

In addition to creating entirely new solutions, another area where generative design differs and stands out is that it takes manufacturability into account. That means the process of testing products and going back to the drawing board is drastically reduced. Traditional optimization focuses on refining a known solution, which usually involves removing excess material with limited notion of how something is made or used. Additional modeling, traditional simulation and testing are then required steps at the end of the design process to ensure .

With generative design, the manufacturing process characteristics and simulation are built into the design process. The user can specify the required manufacturing method, such as additive, CNC, casting, etc. at the outset; the software then only produces designs that can be fabricated with the specified method. Alternatively, the engineer can select multiple manufacturing methods and explore, compare and contrast designs generated for all of them at once.

Autodesk



At the top of the graphic, the preconceived bracket design from the [2013 GE jet engine bracket challenge](#) is refined using traditional topology optimization. Because there is no awareness of manufacturing processes, the result needs to be remodeled again 'by hand' in CAD software, which introduces differences between the solution prescribed by the optimization algorithm and the final, reconstructed shape. On the bottom, Autodesk Generative Design software uses attachment points, strength requirements, weight, materials, and manufacturing method as information to produce multiple geometric solutions for the bracket. There is no preconceived geometry as a starting point. In this case, generative design produces 30 design options, all of them being immediately manufacturable, while topology optimization offers one.

As denoted earlier, an often overlooked benefit of generative design is the ability to consolidate parts. Because generative design can employ a level of complexity that is impossible for human engineers to conceive – and because additive manufacturing can enable the fabrication of the complex geometries that generative algorithms often produce – single parts can be created that replace assemblies of 2, 3, 5, 10, 20 or even more separate parts. Consolidating parts simplifies supply chains, maintenance and can reduce overall manufacturing costs.

With its ability to quickly and efficiently explore thousands of valid design solutions, built-in simulation, awareness of manufacturability and part consolidation, the reality is that generative design impacts far more than just the traditional notion of design. It's really about the entirety of the manufacturing process. In some ways, it could be argued that 'generative manufacturing' would be a more apt term.

Discussion: How Do We Assess the Progress of Such 'Disruptive' Technologies

The above account of the technical progress of a dramatic new manufacturing technology such as digitally enhanced 3D Printing (3DP) must be qualified by how the industry moves from the "technically possible" to the "probable". The work of Mike Smitka on the definition of "disruption" in the automotive industry is particularly instructive. (Smitka 2018).

<u>Technology Readiness Level (TRL) Assessments by Private Companies</u>

We are all familiar with how TRLs have become part of the lingua franca of research policy discussion, funding evaluations (Warrian 2017A, 2017B). However, such evaluations also take place within the corporate and operational environments of private companies.

In automotive, because of the highly integrated product architecture, complex operating environment and rigorous regulatory environment, companies are going to have two validation requirements before the new manufacturing technology enters the assembly process: Such radically new materials will be rigorously tested through destructive testing to identify their failure modes. This is quite different than those indicated in computer models. Second, assembly operations also require large amounts of production variance data at high volumes before inserting new parts into actual manufacturing processes. This is very different from the data produced for validation of prototypes. Production variance data of a sufficient scale might easily take several years to accumulate.

Pre-Existing Intermediate Technology Solutions

In automotive, there are other competing, if only partial, solutions to the proposed new technologies. These may be practical alternatives but not be visible, at first glance, if the 3D Printing perspective is the sole lens on the issue. For instance, near net shape casting could complement 3DP in the next stage of the process. This could significantly ease the throughput rates that are a constant challenge, particularly for metallic 3DP.

Competing solutions are constantly emerging from the complex ecology of automotive innovation involving large and small companies, universities and public laboratories, as well as community colleges (Warrian, P. and Arif, A. 2015; Warrian, P. 2016; Samford, S., Warrian, P. and Goracinova 2017). It is unlikely that one single technology, no matter how ambitious, can be qualified as top down disruptive or transformative of the whole industry.

Conclusion

The paper has examined the current generation of CADCAM applications and the 'instrumentalist' engineering culture in which they are embedded. Each design is treated as an individual object. In the future, however the merging of advanced materials and software will mean at a certain scale i.e. the nano scale, the object and the material properties merge. There is a unified design space incorporated within a distribution of material properties which produces unified designs that are more than the sum of the individual components and possibly geometries that do not exist in nature. We call this 'Manufacturing for Design'.

The iterative generative design engine is a major first step in enabling this next step in the evolution of automotive manufacturing capabilities.

The qualifier in this story of the next generation of design, metallic additive manufacturing and advanced composites additive manufacturing is that there are still frontiers being pushed by existing subtractive manufacturing technologies, which are also being addressed by generative design. The expected 3-5 year cycle to ramp up the production stage needs to consider its synchronization with the design cycle. Also, given the issues about throughput and post processing requirements, the automotive entry point will be very low volume vehicles and small parts. But in these there may be production volumes that are too small to quickly have the large sample sizes for failure modes when stressed that need to match the engineering models to real-world data.

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