Learner Centric Advanced Manufacturing Platform

GENERATIVE DESIGN AND TOPOLOGY OPTIMIZATION

WPN° 3 Observatory

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GLOSSARY AND/OR ACRONYMS

AI - Artificial Intelligence

AM - Advanced Manufacturing

Cedefop - European Centre for the Development of Vocational Training

CoVE - Centres of Vocational Excellence

DfM - Design for Manufacturing

EAfA - European Alliance for Apprenticeships

EC - European Commission

ECVET - European Credit System for Vocational Education and Training

EntreComp - The Entrepreneurship Competence Framework

EQAVET - European Quality Assurance in Vocational Education and Training

EQF - European Qualifications Framework

ESCO - European Skills, Competences and Occupations

ETF - European Training Foundation

EU - European Union

GE - Generative Design

HE - Higher Education

HVET - Higher Vocational Education and Training

I4.0 - Industry 4.0

KET - Key Enabling Technology

OECD - Organisation for Economic Cooperation and Development

SME - Small and Medium Enterprises

SWOT - Strengths, Weaknesses, Opportunities, Threats

TO - Topology Optimization

TVET - Technical and Vocational Education and Training

VET - Vocational Education and Training

WBL - Work Based Learning

CONTENT TABLE

EXECUTIVE SUMMARY

Advanced Manufacturing (AM) and Higher Vocational Education and Training (HVET) need to update training, implement new technologies, and get quick access to data.

The causes behind these needs are technological factors (Industry 4.0), factors conditioned by education systems and education methodologies, social factors and environmental factors (the European Green Deal with its emphasis on the greening industry).

Under the CoVE initiative, the LCAMP project aims to support regional skill ecosystems and various stakeholders in providing new skills and implementing new or updated technologies in VET centres. LCAMP will tackle this by incorporating a permanent European Platform of Vocational Excellence for Advanced Manufacturing.

By collaborating across borders, LCAMP's goal is to support and empower regional Advanced Manufacturing CoVEs to become more resilient, innovative, and better equipped to train, upskill, and reskill young and adult students, to successfully face the digital and green transitions. We will help European regions and countries grow and be more competitive through their VET systems.

Therefore, the LCAMP OBSERVATORY is one of the services in the LCAMP platform. The observatory is led by the French cluster *Mecanic Vallée* and the French VET provider *Campus des Métiers et des Qualifications d'Excellence Industrie du Futur*.

This present document details the first results of the LCAMP Observatory, through the methodology that the LCAMP consortium used to set up and run the Observatory. We had set up a process cycle for the observation consisting of 5 stages:

- Stage 1: Diagnosis and priority
- Stage 2: Search and information gathering
- Stage 3: Information Analysis
- Stage 4: Creating value. Elaboration of LCAMP reports
- Stage 5: Dissemination and communication.

1. INTRODUCTION

The LCAMP observatory is one of the services of the LCAMP platform.

The LCAMP Observatory must be a reliable and easily accessible source of information and data for trainers, VET teachers, and professionals, updated on Digital / Advanced Manufacturing / Smart Industry, delivered through a multimedia and interactive platform -LCAMP platform-, that can be customized according to individual interests (Work in progress in WP8).

This observatory must feed other Work packages (WP), for instance, WP 5 on Learner Centric Training, or Open innovation Community in the WP4.

In a first document about methodology, are set up a process cycle for the observation consisting in 5 stages:

- Stage 1: Diagnosis and priority
- Stage 2: Search and information gathering
- Stage 3: Information Analysis
- Stage 4: Create value. Elaboration of LCAMP reports
- Stage 5: Disseminate-communicate.

Following this process cycle, are detailed the main aspects of the observation methodology:

- Identify reliable sources that we can find in Europe about Advanced Manufacturing.
- Classify and filter data gathered from different sources.
- Present several ways to collect data and to analyse them.
- Define the methods for the creation of annual reports.
- Validate process for those reports.

The observatory will publish periodical reports for VET and HVET target audiences about technology trends, labour market changes, skill needs, and occupations in Advanced Manufacturing. It is expected that SMEs, industry clusters and other associations will also find valuable information in the observatory.

The publication of a yearly report is planned.

- Report 1: June 2023,
- Report 2: June 2024,
- Report 3: June 2025.

This first annual report is gathering sub-reports written by around twenty different writers, from the main partners involved in the LCAMP project. 39 Topics were determined, and 22 TOPICS were analysed and worked on during this first period.

2. TOPICS: GENERATIVE DESIGN AND TOPOLOGY OPTIMIZATION

The purpose of this chapter is to present some of the development areas related to AM.

These are topics that concern all or some of the stakeholders

- CoVEs and VETs: teachers, trainers and heads of VET schools;
- Learners: students, active workers, job seekers;
- Companies;
- Policy makers and other stakeholders.

2.1 MAIN USED SOURCES

Table 1 : Main used sources

Title	Description	Scope	Sector	Link
PUBLIC SOURCES				
Additive Manufacturing	Advocacy for additive manufacturing in industry	Global	Manufacturing	https://www.additivemanufacturing.media/
ACADEMIC SOURCES				
Engineering.com	Journal that shares in-depth original paired with a customizable platform called ProjectBoard	Global	Multisector	https://www.engineering.com/
Nature	International journal for peer-reviewed research	Global	Multisector	https://www.nature.com/
INDUSTRY SOURCES				
Autodesk	Design Technology Firm	Global	Multisector	https://www.autodesk.com/
Bugatti	Car Manufacturer	Global	Automotive	https://www.bugatti.com/
Fractory	Engineering service for increased	UK+EU	Manufacturing	https://fractory.com/

	manufacturing sustainability			
Inceptra	Project Lifecycle Management Company	North America	Multisector	https://www.inceptra.com/
McKinsey & Company	Market Investment Company	Global	Finance	https://www.mckinsey.com/

2.1.1 CONTEXT AND LIMITATIONS

Sources are largely drawn from industrial publications and websites. As discussed below, academic sources for these topics are commonly either limited or outdated, and industry sources provide the most up-to-date information available.

Relevance

CoVE's and VETs are dedicated to remaining current in the advanced manufacturing landscape, and key to this goal is maintaining an understanding of topics and technologies. This section focuses on generative design and topology optimization which are helping firms re-imagine the ideation process from concept through manufacturing.

2.1.2 MAIN DATA

Table 2 : Main data

Identification	Topic Name	Link
PUBLIC SOURCES		
Additive Manufacturing	3D Printed Tool for Machining Electric Vehicle Motors: The Cool Parts Show #39	https://www.additivemanufacturing.media/articles/3d-printed-tool-for-machining-electric-vehicle-motors-the-cool-parts-show-39
ACADEMIC SOURCES		
Engineering.com	Can You Use Generative Design for Internal Fluid Flow?	https://www.engineering.com/story/can-you-use-generative-design-for-internal-fluid-flow
Nature	Eco-engineering: Living in a materials world	https://www.nature.com/articles/494172a
INDUSTRY SOURCES		
Autodesk	Topology Optimization	https://www.autodesk.com/solutions/topology-optimization

Bugatti	World Premiere: Brake Caliper from 3-D Printer	https://www.bugatti.com/media/news/2018/world-premiere-brake-caliper-from-3-d-printer/
Fractory	Generative Design – the Future of Engineering?	https://fractory.com/generative-design/
Fractory	Topology Optimisation	https://fractory.com/topology-optimisation/
Inceptra	Need to Lightweight your Products Quickly and Efficiently?	https://www.inceptra.com/need-to-lightweight-your-products-quickly-and-efficiently/
McKinsey & Company	How generative design could reshape the future of product development	https://www.mckinsey.com/capabilities/operations/our-insights/how-generative-design-could-reshape-the-future-of-product-development

Context and presentation

Sources largely draw from a mixture of top-level information for interested industry partners and specific examples of processes used in actual projects.

Summary and synthesis

Generative Design (GD) and Topology Optimization (TO) are both computer-aided design techniques, using algorithms to optimize design for specific goals through opposing design features. These design techniques operate in conjunction with one another, with Generative Design serving at the start of a design project and Topology Optimization taking place at the end. The objective of this report is to provide a summary of the considerations, potential, and opportunities created by Generative Design and Topology Optimization. This report will study manufacturing criteria, the current industrial and educational states of GD and TO, and the current trends in their uptake, with conclusions regarding our desired path forward. Elements address include the uses of generative design, applicable software, industrial applications, manufacturing considerations, manufacturing trends, and education trends. Both generative design and topology optimization are in growing usage in the manufacturing industry, but academic institutes are lagging behind. The situation is complicated by the use of proprietary technology in GD and TO. Many of the industries currently making use of GD and TO, especially in the aerospace and automotive industries, are doing so using proprietary software and with the goal of developing proprietary parts for specific corporations. Nevertheless, generative design and topology optimization are vital tools in need of uptake.

2.2 DATA ANALYSIS

2.2.1 INTRODUCTION

Design for Manufacturing (DfM) is the process of designing a product or component with consideration for its manufacturing requirements. It involves designing products that are easy and cost-effective to manufacture, while also meeting performance requirements. This includes factors such as material selection, part size, geometry, complexity, and ease of assembly. By incorporating DfM principles, designers can improve product quality, reduce costs, and shorten production times. Generative Design and Topology Optimization are two key techniques utilized in DfM procedures.

2.2.2 CONTEXTUALISATION

Generative Design (GD) and Topology Optimization (TO) are both computer-aided design techniques, using algorithms to optimize design for specific goals through opposing design features. These design techniques operate in conjunction with one another, with Generative Design serving at the start of a design project and Topology Optimization taking place at the end.

Generative Design

Generative Design[1] is a design exploration process, used in order to generate multiple design options meeting a shared set of design constraints. These options are made up of the conceptual elements that are necessary for a successful design (including required points of attachment, manufacturing material and methodology, weight, etc.) and performance objectives, made up of the requirements for a design to function effectively (including aerodynamics, heat dispersion, deflection limits, etc.) Generative Design software generates multiple potential design alternatives to meet different constraints and objectives, allowing the designer to rapidly iterate potential geometries and designs via iterative design software. It is thus most valuable at the beginning of a design process.

- https://www.autodesk.com/solutions/generative-design

[1] « What Is Generative Design », Tools Software, Autodesk, s. d., https://www.autodesk.com/solutions/generative-design.

Topology Optimization

Topology Optimization[2] begins with an existing design and narrows its focus to optimize its material distribution in order to maximize specific performance criteria, such as stiffness, weight resistance, etc. Using simulation technology, it predicts design performance without the need for expensive physical generation, and then automatically makes adjustments to improve designs. Topology Optimization typically occurs toward the end of the design process, when weight issues and material costs become a concern for manufacturers[3].

Design Criteria – Constraints and Performance Criteria

The constraints of a generative design study translate approximately into the setup conditions of the study. A project's starting geometry determines where the software can and cannot make modifications or place geometry, defined by any geometric limits known to exist for a part or object before design begins. An object may also have a maximum or minimum mass or weight required in order to function, and many parts have required safety factors depending on the industry and purpose that they will be put to.

Performance criteria include any requirement performance outputs of a part or object. These can overlap with design criteria: for example, mass or weight limits may be required due to other design restraints, or might be required as a criterion of successful performance. Parts may also require the ability to hold up under certain forces and moments without failing or may require a certain amount of flexibility in order to not break under pressure.

2.2.3 OBJECTIVE

The objective of this report is to provide a summary of the considerations, potential, and opportunities created by Generative Design and Topology Optimization. This report will study manufacturing criteria, the current industrial and educational states of GD and TO, and the current trends in their uptake, with conclusions regarding our desired path forward.

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[2] « Topology Optimization », Software And Resources, Autodesk, s. d., https://www.autodesk.com/solutions/topology-optimization.

[3] https://www.autodesk.com/solutions/topology-optimization

2.2.4 FINDINGS

Uses of Generative Design

Generative design holds the potential to reshape the nature of product development. Using traditional design processes, each iteration of a project takes significant time and expense, with the result that teams are rarely able to explore alternatives to their base assumptions. The result is designs that are functional, but not optimal for their intended usage.

Generative algorithms change these calculations. Because each iteration of generative design allows for the creation of hundreds of design alternatives, designers are able to quickly consider a wide array of strengths and weaknesses of different potential manufacturing options, allowing them to create extremely precise final refinements to develop exactly the part or object that they are seeking.

Generative Design should be thought of as computer-aided design, not as software that designs on behalf of engineers. GD software is able to rapidly process iterative design according to engineer specifications, but does so according to engineer inputs, and manual refinements are required of final designs in order to achieve the best results.

Structural Optimization[4]

Structural optimization is the standard usage of GD in most industrial settings. Through this process, engineers improve the strength and fatigue resistance of parts in the design process, especially where weight is a primary consideration, such as in the automotive or aerospace industries. By reducing the weight of parts to be developed, industries are able to improve performance, increase sustainability, reduce production costs by up to 20 percent, and reduce development times by up to 50 percent[5].

Internal Flow Optimization

Fluid flow is currently a difficult field to measure and simulate. Physical testing for either external or internal fluid flow is difficult and expensive, requiring elaborate testing facilities and costly

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[4] Mickael Brossard et al., « How generative design could reshape the future of product development | McKinsey », McKinsey, 2020, https://www.mckinsey.com/capabilities/operations/our-insights/how-generative-design-could-reshape-the-future-of-product-development.

[5] https://www.mckinsey.com/capabilities/operations/our-insights/how-generative-design-could-reshape-the-future-of-product-development

operations. The result is that outside of aeronautics and advanced automotive design, fluid optimization is rarely undertaken.

Generative design holds the potential to simulate fluid dynamics for product engineers, allowing for iterative design of internal product structure, adjusting fluid flows in ways that dramatically improve pressure requirements and reduce the weight and cost of parts.

An example of this can be found in hydraulic manifolds. Traditionally, a hydraulic manifold is a solid block of material with ports drilled into it that act as passageways for highly pressurized hydraulic fluid. Fluid flow dynamics aren't able to be considered within the block due to restrictions in the manufacturing methods available. For example, to create a 90-degree direction change in the block for fluid flow, a machinist would drill one hole into the top or bottom of the block & drill a second hole that meets the first hole into the side of the block. This produces hard edges and unnecessary pockets due to the drill points in the cavity, and as a result creates turbulence in the flow of fluid which in turn reduces the efficiency of the manifold. Through structural generative design and 3D printing, the manifold could remove sharp corners and reduce turbulence and pressure on the manifold.

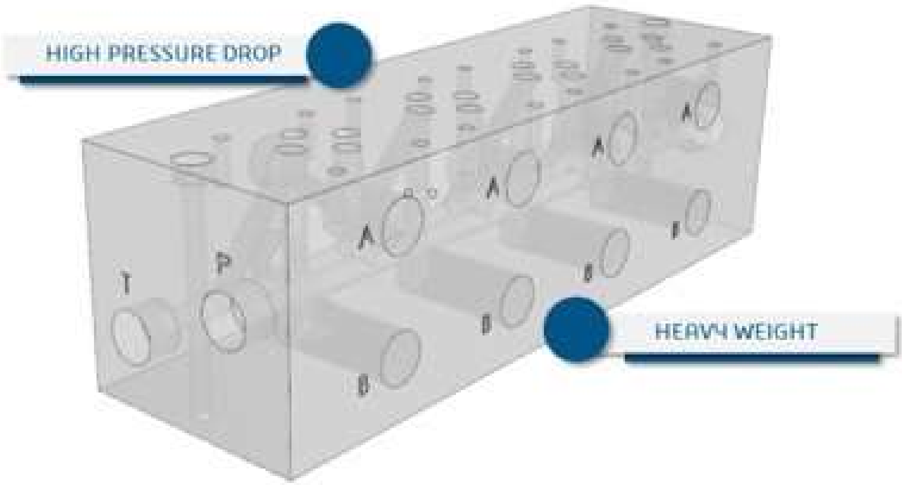

Figure 1 Legacy Design[6][7]

[6] « Can You Use Generative Design for Internal Fluid Flow? », Engineering.com, 2021, https://www.engineering.com/story/can-you-use-generative-design-for-internal-fluid-flow.

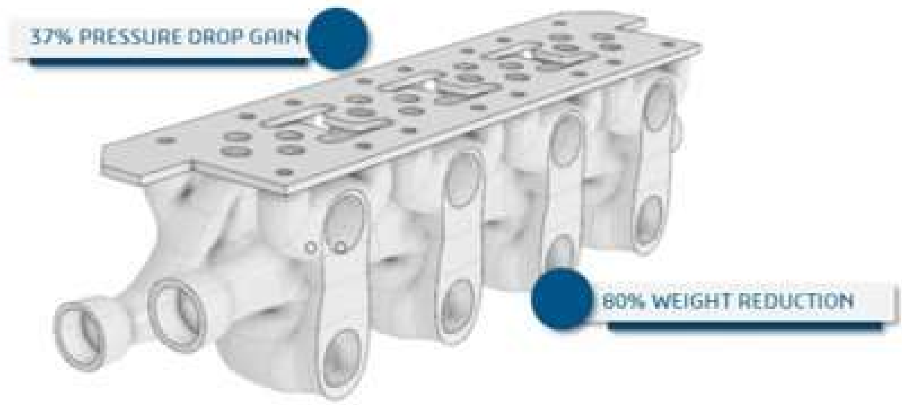

Figure 2 Structural Generative Design[8]

Uses of Topology Optimization

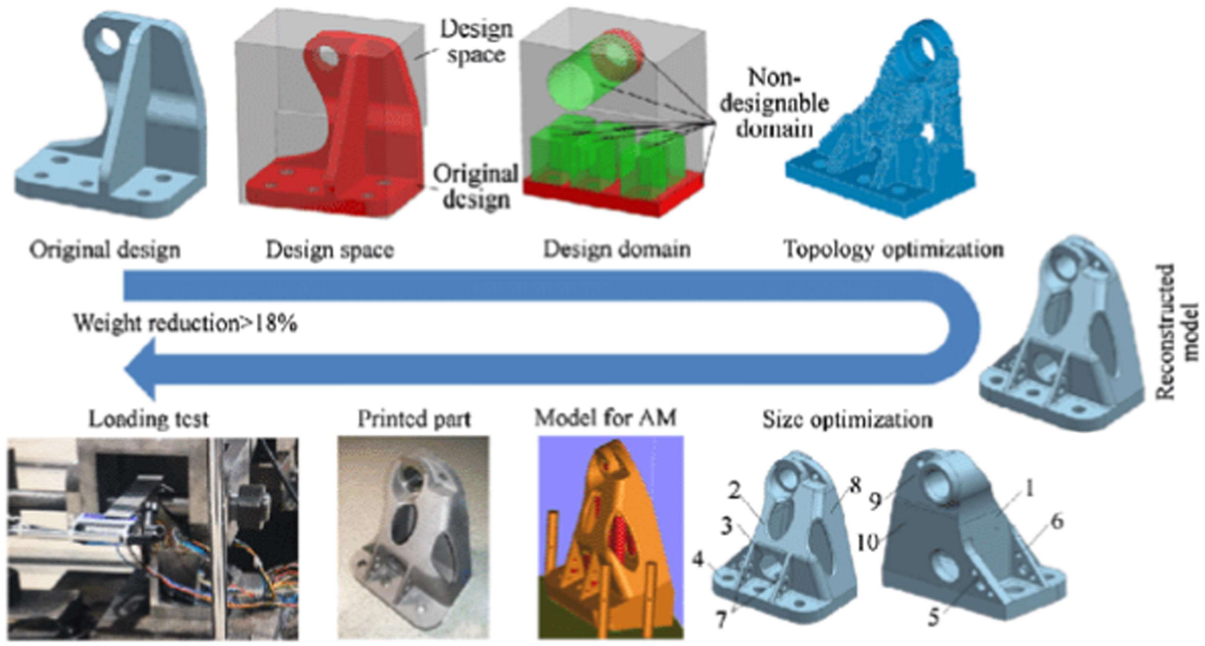

Figure 3: Topology Optimization Flowchart[9][10]

Weight Reduction and Shape Optimization

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[8] Ibid

[9] https://www.sciencedirect.com/science/article/pii/S2214785322010525

[10] A. L. R. Prathyusha et G. Raghu Babu, « A Review on Additive Manufacturing and Topology Optimization Process for Weight Reduction Studies in Various Industrial Applications », *Materials Today: Proceedings*, International Conference on Advances in Materials and Mechanical Engineering, 62 (1 janvier 2022): 109-17, https://doi.org/10.1016/j.matpr.2022.02.604.

The primary current usage of Topology Optimization lies in weight reduction of manufactured parts. Designers begin by developing a CAD model of the part to be optimized, defining the material to manufacture the part from and the magnitude and direction of forces that will act on the part in operation. TO software analyzes the stresses that will apply to the part, removes any materials that do not affect its functionality, and then provides a final simulation for manufacture. These components cannot be manufactured using traditional processes, requiring an additive manufacturing process. Part areas can be optimized based on several varying requirements, such as load, boundary conditions, deformation, and stiffness constraints, producing parts with enhanced performance in the best possible structure.

Shape optimization technology helps inform certain geometry decisions to specific constraints such as manufacturing methods. Shape Optimization is available through customized CAD programs and models, and is typically used as a component of other functions, especially weight optimization.

Applicable Software

At this time, there are five major applicable software models for generative design. The most common is Autodesk's **Fusion 360 Generative Design Module**, which is available to students, educators, and industry professional. Users start with a set of initial conditions and design constraints, and the solver will generate multiple outcome models that will perform the functions set. This means that the setup is extremely important, and a user who is not familiar with correctly setting up Finite Element Analysis (FEA) studies will struggle with correctly completing a generative design study.

SolidThinking Inspire is a software package that takes design constraints and an initial starting shape, and performs topological shape optimization to find an ideal solution. The system is highly proficient at structural analysis and dynamic motion simulation, but is designed only for industry professionals.

Siemens NX Generative Design and Siemens NX Topology Optimization are a pair of engineering software solutions that integrate GD and TO for industrial designers. This system has the advantage of integrating both processes, embedding topology optimization within generative design systems to enable unified 3D modelling capabilities.

Hexagon's Generative Design Suite MSC Apex GD[11] is advertised to take designers from screen to machine faster with less human intervention than any other software on the market. It does this using a proprietary "Generative Design Engine" based on Finite Element Analysis (FEA), diverging from traditional density field computation to use very fine meshes with well defined/stable elements. The software is focused primarily on additive manufacturing optimization with the target of sending the result to a printer with no corrections/edits required. See this link for case studies & detailed program information:

Dassault Systemes includes Topology Optimization in the Simulation-Level license of SolidWorks, and the study options contain 3 objectives: Best Stiffness to Weight Ratio, Minimize Maximum Displacement (under a given loading), and Minimize Mass. SolidWorks requires a starting point (solid model), this means true Generative Design which is the AI creation of a part from nothing but constraints isn't offered by Dassault Systemes at this time. The Topology Optimization is embedded in their FEA software and uses the same process for stress determination/meshing creation combined with an iterative solver provided by SIMULIA's Tosca range for shape production. Results can be obtained for both additive and subtractive manufacturing methods.

ANSYS Generative Design, despite the name, is a topology optimization tool exclusively. It takes in shaped parts or objects and undergoes real-time topology optimization, allowing the designer to observe the system in motion and make any adjustments as necessary.

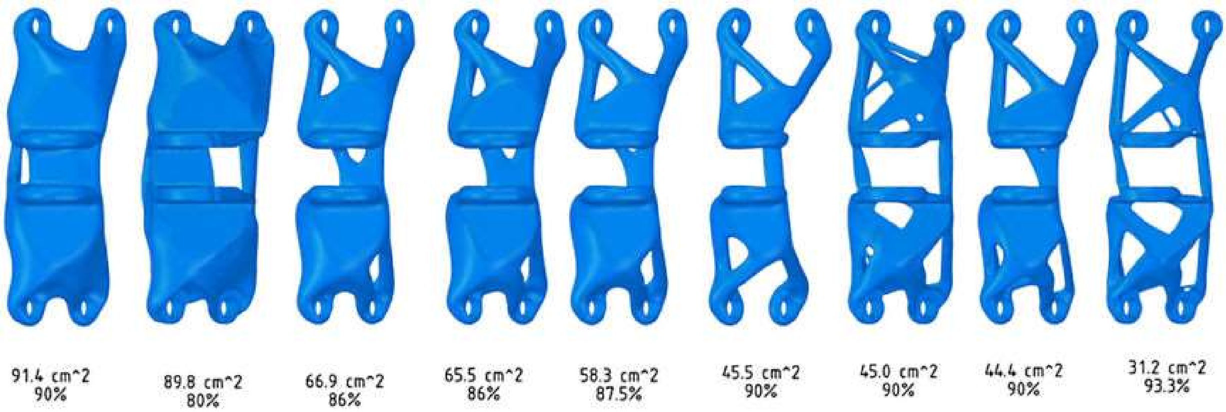

Figure 4: ANSYS Topology Optimization of an established bracket.

[11] « MSC Apex Generative Design », Hexagon, s. d., https://hexagon.com/products/msc-apex-generative-design?accordId=47C305DC8B9D47C0858D99096802A4E4.

Industrial Applications

Aerospace and Automotive Manufacturing[12] [13] [14] [15]

Generative design has begun to take hold in the aerospace and automotive manufacturing fields. Airbus, in collaboration with Autodesk, has been applying generative design to aircraft manufacturing for nearly a decade. Their “Bionic Partition 2.0” separates seating components from one another and from the gallery of a plane, creating a final design that is 45% lighter than comparable aircraft; once applied to the current Airbus fleet, this design will save over 500,000 metric tons of CO2 emissions per year.

In the automotive field, Autodesk is working with General Motors to employ GD & TO across their entire range of vehicles, with the goal of reducing the weight of Electric Vehicle (EV) batteries, which will not only improve their range but reduce wear and tear on brakes and tires.

Czinger, an automotive supercar maker based in Los Angeles, California, develops extremely high-performance cars through generative design & metal 3D-printing. By employing an advanced proprietary AI-powered generative design known as Divergent Adaptive Production Systems (DAPS) alongside metal 3D printing, Czinger is able to produce entire car chassis without the traditional multi-million-dollar infrastructure and tooling of a mass-market OEM. Their methodology and process has caught the eyes of major OEM automakers, with several contracting Czinger to generate optimized versions of their traditionally designed components & manufacture them on a contract basis. Aerospace and Automotive Sources:

- https://www.aero-mag.com/airbus-autodesk-generative-design-aircraft-components-200120/
- https://www.autodesk.com/customer-stories/general-motors-generative-design
- https://www.motortrend.com/features/czinger-21c-3-d-hypercar-details-photos/
- https://www.thefabricator.com/thefabricator/blog/metalsmaterials/how-kevin-czinger-is-changing-the-automotive-assembly-game-with-3d-printing

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12 « Building with a New Generation », Aerospace Manufacturing, 20 janvier 2020, https://aero-mag.com/airbus-autodesk-generative-design-aircraft-components-200120.

13 « General Motors | Generative Design in Car Manufacturing », Autodesk, s. d., https://www.autodesk.com/customer-stories/general-motors-generative-design.

14 Alex Leanse, « The Czinger 21C Is So Much More Than an American-Made Hypercar », MotorTrend, 26 août 2021, https://www.motortrend.com/features/czinger-21c-3-d-hypercar-details-photos/.

15 Josh Welton, « How Kevin Czinger Is Changing the Automotive Assembly Game with 3D Printing », The fabricator, 2 novembre 2022, https://www.thefabricator.com/thefabricator/blog/metalsmaterials/how-kevin-czinger-is-changing-the-automotive-assembly-game-with-3d-printing.

Medical Applications[16]

Currently, the medical industry makes use of metal fixation plates to repair and fixate bone fractures. The high-stiffness metal plates and rods used shield the surrounding periosteum from stress. It is this boney tissue that possesses osteogenic potential, and shielding the tissue from stress results in decreased boney modeling and bone loss. By making use of topology optimization which mimics the ways in which the human body responds to stresses placed through the skeletal structure, doctors are able to develop a porous model optimized for each patient, which utilized less material, was lighter, less rigid, and structurally more reliable than a conventional plate.

- https://www.sciencedirect.com/science/article/pii/S026800332200198X

Fusion Builds[17]

Nnaisense, a Swiss-based engineering company, is in the process of developing an AI which uses optical topology in order to study laser-powered bed fusion builds, combining additive manufacturing and topology optimization. Using only a heat map and a few minor data points, this AI system is able to match layers of a fusion build to one another and create a simulated digital twin. By doing this, the model is able to recognize potential defects early in the creation process, raising concerns which can then be studied and addressed by engineers without requiring expensive testing processes.

- https://www.additivemanufacturing.media/articles/artificial-intelligence-and-additive-manufacturing-are-connected-am-radio-36

Manufacturing Considerations

The primary consideration for the use of generative design or topology optimization software is the method to be used to manufacture the resulting component. Manufacturing method considerations are just as important in generative design as they are in what can be considered "standard" computer aided design. Common manufacturing methods using GD and TO include casting, additive manufacturing, injection moulding, and CNC machining, each of which requires differing methodologies and may not be useable with all designs.

[16] Irfan Kaymaz et al., « A New Design for the Humerus Fixation Plate Using a Novel Reliability-Based Topology Optimization Approach to Mitigate the Stress Shielding Effect », *Clinical Biomechanics* 99 (1 octobre 2022): 105768, https://doi.org/10.1016/j.clinbiomech.2022.105768.

[17] Peter Zelinski, « Artificial Intelligence and Additive Manufacturing Are Connected: AM Radio #36 », 4 avril 2023, https://www.additivemanufacturing.media/articles/artificial-intelligence-and-additive-manufacturing-are-connected-am-radio-36.

To account for this, it is possible to define the manufacturing method that is intended for use when setting up a generative design study. This means that GD and TO can be used to create optimized parts regardless of manufacturing limitations such as lack of access to a metal 3D printer or 5-axis milling machine.

Manufacturing Trends[18]

Airbus is currently collaborating with Autodesk to employ generative design to multiple areas of the business. The design & manufacturing side of the business has employed generative design for nearly a decade, and the Bionic Partition 2.0 is great example of generative design & topology optimization, it separates the seating compartments from each other & the galley of the plane. Airbus estimates that the design will be 45% lighter than their previous standard design while saving almost 500,000 metric tons of C02 emissions per year if applied to all Airbus A320 planes on earth. Airbus has also employed generative design to architecture and factory workflow planning culminating in multiple concepts for a new engine assembly factory in Hamburg, Germany. Using generative design, Airbus was able to generate layouts for the new factory that maximized the space available & allows for efficient and flexible workflows for assembling the various engines[19].

Czinger[20] is an automotive supercar maker based in Los Angeles, California that has made its name in the automotive market from creating extremely high-performance cars through generative design & metal 3D-printing. By employing AI-powered generative design and metal 3D printing, Czinger is able to produce entire car chassis' without the traditional multi-million dollar infrastructure and tooling of a mass-market OEM. Their methodology and process has caught the eyes of major OEM automakers with several contracting Czinger to generate optimized versions of their traditionally designed components & manufacture them on a contract basis. The specific companies are not mentioned as it's assumed they have NDA's in place with Czinger. One company in particular came to Czinger with a mass produced component and requested a topology optimization with the goal of a 5% reduction in mass, Czinger's software & production method produced a result with a 20% reduction in mass with the same performance & the contract was awarded for Czinger to produce that component going forward[21].

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[18] « Building with a New Generation ».

[19] https://www.aero-mag.com/airbus-autodesk-generative-design-aircraft-components-200120/

[20] Leanse, « The Czinger 21C Is So Much More Than an American-Made Hypercar ».

[21] https://www.motortrend.com/features/czinger-21c-3-d-hypercar-details-photos/

Czinger[22] employs Divergent 3D's DAPS (Divergent Adaptive Production System), an advanced proprietary Design-Manufacturing-Assembly process to create the components for its cars. Divergent 3D was founded by Kevin Czinger with the intent of disrupting the traditional design & manufacturing market by applying generative design & industrial metal 3D printing at a scale not seen before. Divergent has been contracted by Aston Martin to generate & produce assemblies for their production cars[23].

General Motors[24] is also working with Autodesk to employ generative design & topology optimization across their range of vehicles[25].

Weight is one of the biggest issues with Electric Vehicles due to the mass of batteries they must house. The heavy weight reduces the range of the EV and hampers performance while also wearing out tires and brakes faster. This means that anything that helps to lighten the rest of the vehicle is crucial whilst lightweight battery technology is further developed. By adopting generative design and topology optimization, automakers like GM & Audi (to name just two) are finding ways to reduce the mass of many components in their EV's and also reduce manufacturing costs through employing additive manufacturing.

Education Trends

Most of what has been found is either an introduction to generative design as a concept or showing how it applies to architecture; generative design as a concept is not widely taught and an advanced course on the topic with specialized aims is yet to be found online. Examples of current offerings follow:

- University of Toronto[26] (CAN) offers a generative design course focusing on its application to architecture.
    - https://www.daniels.utoronto.ca/selected-topics-architecture-generative-design-thinking-workflows-0
- Columbia University[27] (US) offers several courses in generative design under the banner "Visual Studies Building Science & Technology Elective."

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[22] Welton, « How Kevin Czinger Is Changing the Automotive Assembly Game with 3D Printing ».

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[24] « General Motors | Generative Design in Car Manufacturing ».

[25] https://www.autodesk.com/customer-stories/general-motors-generative-design

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[27] « Generative Design I », Columbia GSAPP, s. d., https://www.arch.columbia.edu/courses/79029-1825-generative-design-i.

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- Cornell University[28] (US) offers a course aiming to familiarize students with the generative approach to the design process and allow them to explore opportunities to create novel cyber-human systems for the design/fabrication of a physical space.
  - https://classes.cornell.edu/browse/roster/SP22/class/DEA/3306
- Plymouth University[29] (UK) offers a new short course (2 weeks full-time or 8 weeks blended) introducing the concepts of generative design and how to use them in a multitude of fields.
  - https://www.plymouth.ac.uk/study/cpd/generative-design
- Illinois Tech Institute of Design[30] (US) offers an introductory course in generative design concepts and methodologies.
  - https://id.iit.edu/course/generative-design/
- Griffith University[31] (AUS) offers an online course in experimental and generative design.
  - https://www.griffith.edu.au/study/courses/experimental-and-generative-design-3642QCA#trimester-2-online
- Australia National University[32] (AUS) offers a course in Dynamic Design and Generative Systems through their school of art and design.
  - https://programsandcourses.anu.edu.au/2022/course/desn6004
- Autodesk[33] offers webinar sessions that introduce generative design concepts utilizing their software.
  - https://www.autodesk.com/campaigns/pdm-collection/webinar-series/intro-generative-design/on-demand
- Dassault Systemes[34] offers a webinar dedicated to the use of generative design in architecture.
  - https://discover.3ds.com/webinar-embrace-generative-design

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28 Cornell University Registrar Office of the University, « Spring 2022 - DEA 3306 », 2022, https://classes.cornell.edu/browse/roster/SP22/class/DEA/3306.

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3. CONCLUSION

Statement 1: Both generative design and topology optimization are in growing usage in the manufacturing industry, but academic institutes are lagging behind. Educational institutions in North America and the United Kingdom currently primarily teach both GD and TO only as introductory courses, with the goal of familiarizing students with the concepts of generative design rather than offering in-depth instruction and hands-on experience. The primary exception is in the field of architecture, with a handful of courses focusing on how generative design can be used for architectural design and construction.

Statement 2: The situation is complicated by the use of proprietary technology in GD and TO. Many of the industries currently making use of GD and TO, especially in the aerospace and automotive industries, are doing so using proprietary software and with the goal of developing proprietary parts for specific corporations. These programs and designs are not available to educational facilities or to the general public, leading to a significant duplication of effort and training across competitors. This lack of communication is slowing adoption of these methods of design outside of highly specialized or lucrative fields.

Statement 3: Generative design and topology optimization are vital tools in need of uptake. Over the past ten years it has grown dramatically as a field and is producing impressive results across several industrial sectors. Educational facilities that are able to develop and provide advanced courses on the topic, especially those with specialized aims for specific fields, will be able to greatly improve the ability of students to enter into a revolutionary field and forward the next wave of design modernization.

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5. INDEX OF IMAGES

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