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Generative Design & AI-Assisted Optimization For Mechanical Components

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Module 1: Introduction — Safety, Ethics, and the Engineer's Role

Generative design and AI-based optimization are **powerful new tools** in mechanical engineering, capable of exploring thousands of design options quickly. They can produce innovative shapes beyond traditional human imagination, often achieving lighter weight or improved performance. However, **no algorithm can replace the Professional Engineer's judgment and responsibility**. In this introductory module, we establish the context: generative design is used to **assist, not replace**, human designers.

1.1 Engineer's Professional Accountability

By law and ethics, a licensed PE must review and approve any final design. The **PE's signature** on drawings or documents means they affirm the design meets safety and code requirements. AI-generated designs are **no exception** — they must be thoroughly checked and approved by a qualified engineer before use. The NSPE Code of Ethics is clear that **technology does not diminish the engineer's obligation to public safety**. The engineer must ensure the AI's suggestions are valid, safe, and compliant. This may include applying safety factors, verifying structural integrity, and adapting the design for manufacturability and maintenance needs.

1.2 Public Safety and Structural Integrity

Since generative design often yields non-intuitive geometries, it is critical to vet them against all expected service conditions. **Public safety** considerations are front-loaded by integrating constraints (strength, fatigue life, deflection limits) from the start and verifying them at the end. If a generative algorithm suggests removing material in an area that compromises long-term durability or triggers a stress concentration, the design must be modified — the software's output is not automatically acceptable.

Key principle: If a design fails, it is the engineer who is accountable, not the software. This course emphasizes robust check-and-balance processes to ensure that what is generated is safe.

1.3 Ethical Use of AI in Design

In line with ethical obligations and guidelines (such as NSPE's Code of Ethics), engineers using AI in design must remain **transparent and honest** about assumptions and limitations. Engineers must disclose when a design was largely AI-generated and show evidence of proper verification. Under ISO 9001's quality management principles, the generative design process is treated with rigorous control — documenting inputs, outputs, and changes — to maintain **traceability** and facilitate independent audit or peer review.

In practice, this means saving generative design session parameters, capturing the design options considered, and recording why the final design was chosen. For example: *"Design A was selected because it provided a 15% weight reduction while meeting all stress and deflection criteria with a safety factor of 2.0."*

Key message: Generative design can yield significant benefits (material savings, improved performance), but it cannot be accepted blindly. Think of it as an advanced assistant: it proposes designs that the engineer must critically evaluate, test, and refine before adoption.

Module 2: Generative Design & Topology Optimization Fundamentals

In this module we cover the basics of how generative design works and how it differs from traditional design methods.

2.1 What is Generative Design?

Generative design is a computational approach where the engineer specifies the design goals and constraints, and the software algorithm automatically generates numerous design alternatives that meet those criteria. Often, generative design uses **topology optimization** — a mathematical optimization method that finds the most material-efficient structure for a given set of loads and boundary conditions. The algorithm typically starts with a full design space and then removes or redistributes material to minimize an objective (such as weight or compliance/inverse stiffness) while keeping stresses or deflections below specified limits. The result is often a **lattice-like or branching structure** that may be much lighter than a conventional design while still carrying the required loads.

2.2 Process Overview

Typically, the engineer provides:

- **Design space:** the envelope or volume within which the part must fit (e.g., a block where material is allowed, defined by surrounding geometry and required interfaces).
- **Preserved regions:** volumes where material must remain, such as mounting points, interfaces, or areas around bolt holes.
- **Load cases and supports:** forces, pressures, and constraints representing how the part is loaded and attached.
- **Objectives:** e.g., minimize mass or maximize stiffness; secondary objectives may include maintaining symmetry or a desired frequency response.
- **Constraints:** e.g., maximum stress or displacement, regions to avoid removing material, and manufacturability constraints (detailed in Module 4).

The software employs approaches such as evolutionary algorithms or gradient-based topology optimization, running many iterations to gradually evolve shapes by carving out low-stress regions. For example, given a cantilever bracket with fixed supports and a tip load, a generative design algorithm might create a truss-like structure that uses significantly less material than a solid block while still safely carrying the load. The output is generally a complex geometry requiring post-processing before manufacture.

2.3 Benefits

Generative design can find novel solutions that achieve **significant weight reduction**, improved strength-to-weight ratio, or consolidated part counts. In a well-documented industry case, Airbus reported that a

generative design approach for an A320 cabin partition produced a component approximately 45% lighter than the original, saving fuel while meeting all structural requirements. Many companies see potential in reducing material costs and improving performance using these tools.

2.4 Limitations

Generative algorithms optimize exactly what they are asked to — nothing more. They lack awareness of **practical considerations not expressed in their input**. For example:

- If the algorithm is not instructed about manufacturing, the output may produce shapes that are impossible to machine or cast.
- If a certain load case or fatigue requirement is omitted, the algorithm could produce a design that is fragile under cyclic loading.
- Unless explicitly encoded, generative design generally does not directly consider buckling or dynamic stability.



Figure 1. Generative design progression from the full design space to an optimized structure.

'Garbage in, garbage out' applies: incomplete or incorrect inputs — such as missing loads or constraints — will produce an unsafe or unbuildable design. The next modules cover how to define those inputs correctly.

Module 3: Defining Constraints — Loads, Stresses, and Safety

Setting up the **right constraints and load cases** is the most critical part of a generative design process. The software cannot infer requirements you do not specify, so the engineer must comprehensively encode all conditions that a design must satisfy.

3.1 Structural Loads & Boundary Conditions

Start by identifying all relevant forces, pressures, moments, and support conditions the component will experience. This requires a careful review of the component's role in the assembly or system:

- **Static loads:** weights, forces, pressures at various points or distributed. For a bracket, this could be a downward force at a mounting point.
- **Dynamic or fluctuating loads:** inertial loads, vibrations, or cyclic stresses. These should be included when significant, to capture fatigue considerations.
- **Multiple load cases:** good practice is to run generative design for the combination of critical load scenarios. For example, a pressure vessel support might have one case with internal pressure and another with external loading (wind or seismic) — designing for just one could create weakness under the other. Where slender members or thin-walled sections are anticipated, include a buckling load case, since generative algorithms do not inherently check buckling stability.

All supports (fixtures, symmetry conditions) must be correctly set to mimic reality. Misrepresenting boundary conditions is a classic pitfall that can produce an overly optimistic design that fails under actual service conditions.

3.2 Stress and Deflection Constraints

Traditional design requires each part's stress to be below allowable values (with a safety factor, SF) and deflections within acceptable limits. Generative design algorithms typically allow you to impose constraints such as **maximum stress** or **maximum deflection** during optimization. For instance, you may specify that von Mises stress must not exceed a threshold derived from yield strength divided by the required SF.

If the software does not support direct stress constraints — some topology optimization tools primarily minimize compliance/stiffness rather than directly capping stress — then **the engineer must verify stresses after the fact** and impose an appropriate volume fraction or SF to indirectly ensure stresses will be acceptable. Note that some design codes also require an ultimate strength check in addition to a yield-based check; both should be confirmed during verification.

3.3 Fatigue and Safety Factors

Many structural failures occur due to fatigue (repeated loading) rather than static overload. Most generative design tools do not inherently account for fatigue life, so it is the engineer's responsibility to incorporate fatigue considerations:

- **Apply higher safety factors** when a part is fatigue-critical (e.g., a higher SF than for a purely static load, or target the material's endurance limit stress amplitude for high-cycle applications).
- **Minimize stress risers** introduced by complex geometry (sharp corners, thin struts). Add fillets and chamfers to reduce stress concentrations and avoid initiating fatigue cracks.
- **Include representative cyclic load cases** in the algorithm input where possible. Some advanced tools allow multi-objective optimization including fatigue criteria.

3.4 Compliance with Codes & Standards

Generative design can satisfy constraints given to it, but it does not inherently know about design codes or standards (e.g., pressure vessel codes, AISC steel guidelines) unless those requirements are explicitly translated into constraints. For example, if designing a structural bracket under a building code, ensure the resulting design has the required safety factors and minimum thicknesses. Generative design output should be treated as a **preliminary design**, which the engineer then cross-checks against all relevant standards. Any shortfalls must be corrected — either by adjusting constraints and re-running the optimization, or by manually editing the output geometry.



Figure 2. Design space setup showing applied loads, supports, preserved areas, and keep-out zones.

Summary: Every load the component will see, every condition it must survive, and every code requirement or physical limitation must be accounted for in the problem setup. Missing constraints produce an invalid design.

Module 4: Manufacturability Constraints — From Computer to Reality

A brilliant generative design is worthless if it cannot actually be built. This module covers how to incorporate **manufacturing constraints** into generative design to ensure the resulting geometry can be produced using your chosen process. Different methods have distinct limitations that must be anticipated.

4.1 Additive Manufacturing (AM) Constraints

Generative design is often associated with 3D printing because AM can produce highly complex organic shapes that other methods cannot. However, even AM has practical limits:

- **Overhang angles and support structures:** many printing processes require supports for overhanging features angled less than approximately 45° from the horizontal build plane. Without accounting for this, a design may require extensive, hard-to-remove supports or may be unprintable. Some generative tools let you set a minimum overhang angle or preferred build direction.
- **Minimum feature size:** each AM process has a resolution — the smallest web thickness or hole it can reliably print. Specify these minima so the algorithm does not produce ribs or lattices too fine to fabricate (e.g., a 2 mm minimum thickness for metal powder-bed printing).
- **Post-processing:** consider whether surfaces require post-print machining for interface precision, or whether internal channels need to be accessible for powder removal or cleaning.

4.2 CNC Machining Constraints

If the part will be milled or turned from solid stock, constraints revolve around what cutting tools can access:

- **Tool access and direction:** many generative design tools allow a '2.5-axis' or '3-axis' constraint to ensure the shape can be milled from one or two directions without inaccessible cavities. A lattice-like design may be impossible to machine if internal voids cannot be reached by a cutting tool.
- **Undercuts:** for CNC machining, restrict undercut geometry or plan for multi-axis machining (which increases cost). Undercuts are features that cannot be reached by a cutting tool approaching from a standard direction.
- **Fastener or tool clearances:** the design must accommodate wrench access, assembly tools, and similar requirements. These become geometric constraints such as keep-out zones or required clearance volumes.

4.3 Casting & Forging Constraints

Casting: avoid thin walls and sections that cool too quickly or create hot spots; maintain relatively uniform thickness where possible to reduce shrinkage defects; and include draft angles to allow removal of the pattern from the sand mold (in sand casting) or the finished part from the die (in permanent mold and die casting). Some generative design tools have a 'casting constraint' that prohibits undercuts and ensures one pull direction.

If a casting process is intended, verify the generative output has no features that cannot be extracted from the mold. Cast parts also typically require minimum fillet radii and section sizes to ensure soundness.

Forging: forged components typically require continuous material flow paths and cannot accommodate sharp re-entrant features or large undercuts. Generative design for forging is challenging; in practice, one might restrict the geometry significantly (such as a 2D extruded profile) or plan for subsequent machining after forging a near-net shape. Generative design can be used as a conceptual tool for forged parts, with the engineer manually adapting the output to suit the forging process.

4.4 Applying Constraints in Software

Modern generative design software typically provides a way to select the manufacturing process and apply associated rules. For instance, **Autodesk Generative Design** offers options to select 'Additive (3-axis printing)', '3-axis machining', '5-axis machining', etc., which automatically impose relevant constraints such as overhang angle or tool access directions. It is important to correctly choose and configure these options.

If multiple manufacturing methods are feasible, you may run separate studies for each to compare outcomes and then select the manufacturing route that yields the best overall result considering performance, cost, and build time. Note that adding more constraints narrows the solution space and may result in designs that are less radical or slightly heavier than the theoretical optimum — this is expected. The goal is the **best design that is also practical to produce and meets all criteria**.

Module 5: Verification, Validation & Engineering Review of AI-Generated Designs

Even after obtaining a promising generative design, the engineer's job is far from over. PEs must subject any AI-generated design to the same scrutiny as a conventional design — or even more, since the shape may be unconventional.

5.1 Simulation Verification (FEA & Analysis)

The first step is to perform a detailed **finite element analysis (FEA)** or equivalent simulation of the AI-generated geometry under all relevant load cases. Although generative design software often includes a built-in FEA solver, it is good practice to export the geometry and run an independent verification in a trusted FEA tool. This confirms that **stress, displacement, and factor of safety (SF)** meet requirements:

- Verify that **peak stresses** are below allowable limits with the required SF. For example, if a part uses aluminum with a yield strength of 250 MPa and an SF of 2.0, ensure that the maximum von Mises stress is below 125 MPa in all load cases. Where applicable, also confirm that ultimate strength limits required by the governing design code are satisfied.
- Ensure **deformation** is acceptable — for example, that a bracket's deflection under load does not cause functional issues.
- For fatigue-critical designs, run a fatigue assessment. Compute stress amplitude and use S-N curves to estimate life at critical points. If the generative design introduces a notch, apply appropriate fatigue notch factors. If the assessment shows insufficient life, reinforce or redesign.
- For dynamic applications (e.g., rotating machinery supports), check **natural frequencies** to avoid resonance. Generative design may inadvertently reduce stiffness in a way that shifts frequencies into undesirable ranges.

If any requirement is not met, the engineer must iterate: thicken a strut, add a fillet, or refine the constraints and rerun the optimization.

5.2 Physical Prototyping & Testing

Depending on the criticality of the design, simulation alone may not be sufficient. For a **safety-critical load-bearing structure**, the engineer may mandate a prototype test — for example, 3D-printing a prototype and load-testing it to confirm it behaves as predicted. This is part of **validation** — ensuring the design performs in reality as the model predicts. While not required for every design, prototype testing is a valuable risk-mitigation measure for high-consequence parts.

5.3 Engineering Judgment & Post-Processing

Generative designs often require post-processing by the engineer:

- **Add fillets or chamfers** to reduce stress concentrations at sharp geometry transitions that the algorithm may not automatically include.
- **Standardize features** such as hole sizes or interface pads to match standard fasteners or to simplify inspection and maintenance.
- **Simplify overly complex geometry** where it does not significantly affect performance. Sometimes a generative design yields intricate surfaces that are difficult to inspect or not worth the slight performance gain — the engineer can simplify those regions, trading a small efficiency reduction for easier manufacturability or inspection.

5.4 Avoiding 'Black Box' Acceptance

A vital part of the engineer's review is ensuring they **understand why the design looks the way it does**. Ask: 'Does this outcome make physical sense?' If material has been removed from a region where the engineer expected high stress, that is a red flag — perhaps a load was omitted or the algorithm made an incorrect trade-off. This is a cue to revisit the setup or add a constraint. If the result defies intuition, investigate further rather than accepting it blindly. If you cannot explain how the structure carries its load, additional analysis is needed before the design can be approved.

5.5 Documenting V&V Results

After verifying a design, document the results. Include FEA plots of stress distribution, lists of safety factors in critical areas, and any changes made after the initial generative output. This evidence demonstrates that the design has been properly vetted and modified as needed by the engineer. The **approved final design** that goes into production should be the one the engineer has fully checked and refined — not the raw algorithm output. The documentation should make clear that the final geometry has been validated and explain why it was chosen among alternatives.

Module 6: Risk Management & Configuration Control in Generative Design

Generative design introduces new potential risks — it is a more complex, less transparent process than traditional design. This module discusses how to apply **risk management** and ensure design integrity throughout the generative process, using tools like **FMEA (Failure Modes and Effects Analysis)**. We also address **configuration control** of design iterations.

6.1 Potential Failure Modes in Generative Design

Even if the final product is verified, the process of reaching that design has pitfalls that require caution:

- **Missing load or constraint:** if a load case or operational scenario is not included, the output may perform poorly or fail when that scenario occurs in service.
- **Unrealistic output geometry:** the algorithm could propose a design that technically meets the given criteria but is sensitive to slight variations — for example, extremely thin members that work at exactly the specified load but provide little margin.
- **Manufacturing or maintenance issues:** the design might be impossible or very expensive to produce (e.g., internal voids requiring sacrificial cores, or shapes needing support structures that cannot be removed).
- **Misinterpretation of results or incorrect model assumptions:** a misread output or an unchecked assumption about material properties or boundary conditions could lead to an unsound design being selected, especially without proper verification skepticism.

Table 1. Partial FMEA: Generative Design Process Failure Modes.

Potential Failure Mode	Effect	Mitigation
Missing load case in generative optimization	Design fails or is unsafe under that load (e.g., buckling or fatigue under an unconsidered condition)	Thoroughly brainstorm and include all relevant load cases; after design, perform an FEA with additional 'what-if' loads beyond those used in optimization to add conservatism.
Algorithm focuses on weight at expense of stiffness	Excessive deflection or vibration issues	Impose deflection constraints or multi-objective criteria (e.g., minimize weight while keeping natural frequency above a limit); verify stiffness with analysis and adjust if necessary.
Design has inaccessible features for machining or assembly	Cannot be manufactured or serviced as-designed	Use manufacturing constraints in software; consult manufacturing engineers early; simplify or reorient features for accessibility; apply rule-based checks (e.g., minimum radii, clear tool paths).
Overreliance on algorithm output (lack of human oversight)	Violation of code or safety margins not recognized	Always have a qualified PE review each AI-generated design; use checklists to verify compliance with design codes and presence of all required features; do not allow design release without thorough human QA/QC sign-off.

6.2 Configuration Control

With generative design, it is easy to produce dozens or hundreds of variants. It is critical to maintain **traceability** of which design version is being evaluated or built. Under a quality system (and common sense), every design change must be documented and reviewed.

- **Assign version numbers or revision codes** to generative design outcomes. For example, 'Design 1.0' might be the initial human design, 'Design 2.0 (GD)' the first generative output, then 'Design 2.1' after modifications for stress relief, and so on. Use formal revision control just as you would for CAD drawings.
- **Document each change:** note what was changed and why. For example: 'Thickened rib section by 2 mm to improve fatigue life based on FEA results (Rev B).' If a reviewer later asks why a rib is thicker than the generative suggestion, the change record provides the answer.
- **Maintain team communication:** if the design passes between different engineers or departments (analysis, CAD, manufacturing), ensure everyone knows which iteration is current and what assumptions it is based on.

6.3 Risk-Based Design Reviews

Integrate generative design into your existing design review process. Design reviews should examine the AI-generated geometry and verify that it addresses all requirements, identifying any features that could be risky or difficult to implement. Because generative designs may appear unconventional, some organizations establish **multidisciplinary review boards** (design, analysis, manufacturing, maintenance) to assess feasibility before proceeding.

Module 7: Documentation, Traceability & Professional Defensibility

The final module ties everything together by focusing on **documenting the generative design process and outcomes**. Proper documentation ensures that designs produced with AI are transparent and can withstand scrutiny, and that they comply with professional and legal requirements.

7.1 Documentation of Design Inputs & Decisions

Start a generative design project by documenting the initial design requirements and constraints clearly. Keep a record of:

- **Design goals:** e.g., weight reduction target, performance improvements sought.
- **Constraints:** loads, materials, safety factors (SF), displacement limits, environmental conditions, and the basis for each (e.g., derived from a standard, a specification, or a prior similar project).
- **Generative design setup:** document key software parameters — the design space geometry, preserved and excluded areas, load cases, objectives, chosen optimization method, and any manufacturing constraints applied. This makes the process traceable; another engineer should be able to understand and potentially reproduce the study.

7.2 Design Iteration History

Each significant iteration or branching of the design should be archived. If you tried three different sets of constraints or manufacturing assumptions, retain the results of all three, or at minimum note their outcomes. This trail is important for traceability (ISO 9001 emphasizes controlling design changes and retaining design records). It helps to:

- Answer later questions ("Why not choose design Option B instead of Option A?").
- Support learning for future projects.
- Demonstrate due diligence if a design is ever challenged — you can show that alternatives were considered and the chosen design was best under documented criteria.

7.3 Verification and Validation Records

Document how the final design was verified:

- Summarize **FEA results** for critical load cases (e.g., include stress contour plots or tabulated stress values versus allowables).
- Note **safety factors** achieved and any code checks performed (e.g., 'all sections satisfy AISC slenderness requirements' or 'meets pressure vessel code minimum thickness with 15% margin').
- If physical testing was conducted (e.g., a prototype burst test or fatigue test), document the test plan and results, and confirm they correlate with predictions.
- Note any differences between the generative output and the final design, ideally in a table format: original dimension vs. modified dimension, with the reason for change (e.g., adding a fillet for stress relief or extra material for weld access).

This written evidence is essential for professional defensibility. A clear **paper trail** of assumptions, analyses, and modifications shows that the design was not blindly accepted from a 'black box,' but was thoroughly engineered.

7.4 Ethical and Legal Compliance

As a PE, you may need to sign and seal drawings that include generative geometry. Your professional license is on the line, so thorough documentation protects both you and the public. Many jurisdictions require design calculations to be submitted — generative design output can be part of that submission, but should always be accompanied by **verification analysis** and a narrative explaining the design's safety basis. This level of detail not only satisfies regulators and clients but aligns with professional ethics: be honest and **transparent about the role of AI** and the steps taken to ensure safety.

In conclusion: Generative design and AI-assisted optimization offer exciting opportunities to improve mechanical components — lighter, stronger, more efficient designs — but they must be harnessed with rigorous engineering practice. By thoroughly defining constraints, validating results, managing risks, and documenting everything, PEs can adopt these advanced tools without compromising on safety or quality. Generative design becomes a partner in the creative process, while the Professional Engineer remains firmly in control of the outcome and responsible for its success.

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