

DESIGN FOR VARIOUS MANUFACTURING METHODS



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Design for Various Manufacturing Methods (DFVMM)



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Overview

This book was developed for a class at Northeast Wisconsin Technical College. The class name is: Design for Various Manufacturing Methods (DFVMM). In this class, we will take a Mechanical Designers approach to trying to decide what would be the best manufacturing method to use for the design of our mechanical parts. Based on the many variables and constraints to consider in the design of a mechanical part, by the end of this class, we should be able to make an informed decision on the appropriate manufacturing process to use. In addition to selecting the best manufacturing method, we will be able to produce the appropriate documents, defend our selected method, and present our decision.

DFVMM is not to be confused with the engineering and manufacturing concept of Design for Manufacturing (DFM). DFM is the first concept we will consider in this book. DFM is an integral part of the DFVMM process.



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Licensing

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1: Design for Manufacturing (DFM)

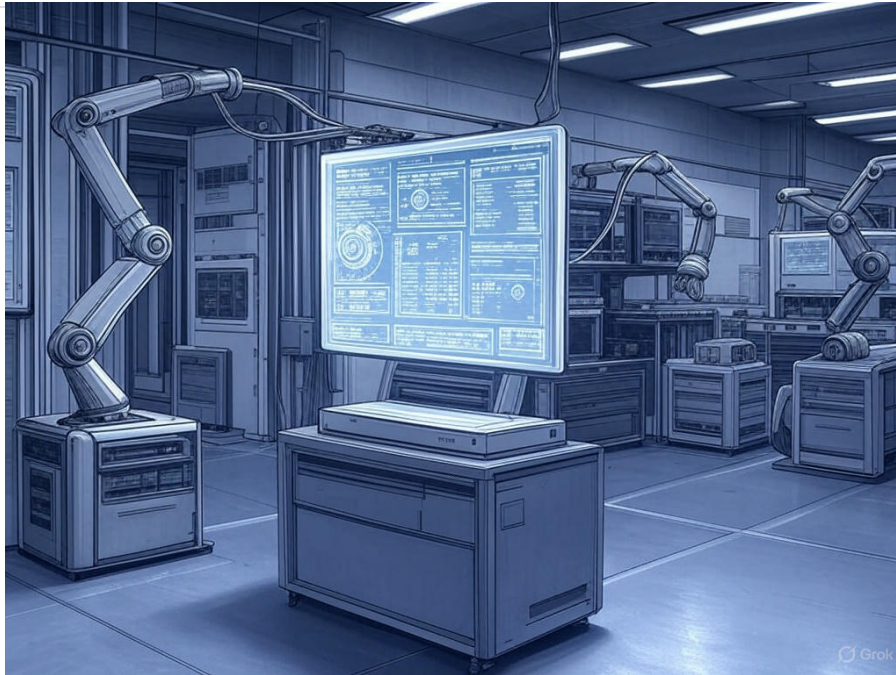


Figure 1.1: Fictional Picture of Robotic Manufacturing Lab

Introduction to Design for Manufacturing

Design for Manufacturing (DFM) is a methodical approach to product design that optimizes the manufacturing process by integrating design and production considerations early in the design cycle. Similar is Design for Assembly (DFA), and Design for Manufacturing and Assembly (DFMA). The primary goal of DFM/DFA/DFMA is to minimize manufacturing costs, increase product quality, and shorten time-to-market. All while ensuring that the design meets functional requirements. By considering manufacturing constraints during the design phase, mechanical designers can avoid costly redesigns, minimize waste, and enhance the efficiency of production systems.

DFM bridges the gap between the creative process of design and the practical realities of manufacturing. It requires collaboration between mechanical designers, manufacturing engineers, and other stakeholders to align product specifications with available processes, materials, and equipment. This chapter explores the principles, methodologies, and applications of DFM, providing tools and strategies to create manufacturable designs.

Key Principles of DFM

DFM is guided by several core principles that simplify manufacturing and assembly while maintaining product performance. These principles are:

1. **Minimize Part Count:** Reducing the number of components in a product reduces the assembly time, material costs, and potential failure points. For example, combining multiple features into a single part can streamline production.
2. **Standardize Components:** Using purchased (off-the-shelf) or standardized parts reduces costs and simplifies inventory management. The fewer parts in the design, the fewer parts to keep track of.
3. **Simplify Manufacturing Processes:** Designs should leverage processes that are efficient and repeatable, such as minimizing complex machining operations or favoring injection molding over multi-step fabrication for mass produced parts.
4. **Design for Assembly (DFA):** A subset of DFM, DFA focuses on simplifying the assembly process by making sure parts are easy to handle, orient, and join. This includes designing parts with self-aligning features or making parts symmetrical as opposed to a right and left-handed part.
5. **Material Selection:** Choose materials that are compatible with the manufacturing process and readily available. For example, Hot Rolled Steel is readily available and is a great selection for welding.

6. **Tolerancing and Geometry:** Specify tolerances that are achievable with standard manufacturing techniques, avoiding overly tight tolerances that increase costs without significant functional benefit.
7. **Minimize Secondary Operations:** Reduce the need for post-processing steps (e.g., painting, grinding, or drilling) by designing features that can be produced in a single operation.

DFM/DFA/DFMA Methodologies

Several methodologies support the implementation of DFM. Two widely adopted approaches are outlined below:

Boothroyd-Dewhurst DFM Method

Developed in the 1980's by Geoffrey Boothroyd and Peter Dewhurst, this method emphasizes quantitative analysis of design efficiency, particularly in assembly. It involves:

- **Part Count Reduction:** Evaluating whether each part is necessary by asking:
 1. Can this part move in relation to another part?
 2. Is the part made of a different material?
 3. Does the part need to be a separate part for assembly or maintenance?

If the answer to all 3 is "no," the part can potentially be eliminated or combined with other parts into one single part.

- **Assembly Time Estimation:** Using standardized tables to estimate handling and insertion times based on part geometry and assembly complexity:

There is no universally standardized table for estimating handling and insertion times based solely on part geometry and assembly complexity. Such tables are often proprietary, context-specific, or derived from established methodologies like the Boothroyd Dewhurst Design for Assembly (DFA) method, which provides structured data but requires specific inputs tailored to the product in question. The following are guidelines for assembly time estimation practices.

Overview of Assembly Time Estimation

Estimating handling and insertion times in manufacturing and assembly processes involves analyzing the physical characteristics of parts (e.g., size, weight, symmetry, and geometry) and the complexity of the assembly tasks (e.g., orientation requirements, alignment difficulty, and fastening methods). These estimates are critical for optimizing design efficiency, reducing manufacturing costs, and improving productivity. While this book cannot reproduce a copyrighted table verbatim (e.g., from Boothroyd et al.'s "Product Design for Manufacture and Assembly"), these are a generalized framework based on DFA principles, which are widely accepted in engineering practice. This framework will include illustrative categories and approximate time values.

Generalized Framework for Handling and Insertion Times

Below is a structured table that outlines key factors affecting handling and insertion times, along with indicative time ranges. These values are derived from general DFA methodologies and assume manual assembly conditions. Times are expressed in seconds and represent averages for a skilled operator under standard conditions. Note that actual times may vary based on operator experience, tooling, and specific design details.

Table 1.1: Estimated Handling Times Based on Part Geometry

Handling refers to the process of grasping, transporting, and orienting a part prior to insertion.

Part Geometry/Handling Factor	Description	Estimated Time (seconds)
Small, Simple Parts	Lightweight (<0.5 kg), symmetric, easy to grasp	1.5 - 2.0
Medium, Symmetric Parts	Moderate size (0.5-2 kg), no special gripping needs	2.0 - 3.0
Large or Heavy Parts	Heavy (>2 kg), requires two hands or tools	3.5 - 5.0
Asymmetric Parts	Requires specific orientation, moderate complexity	2.5 - 4.0
Fragile or Flexible Parts	Needs careful handling to avoid damage	3.0 - 5.0
Parts with Handling Aids	Features like grips or tabs simplify grasping	1.5 - 2.5

Note

- Times increase if parts are tangled, sticky, or require precise orientation.
- Handling aids (e.g., chamfers, tabs) reduce time by improving “*grasp ability*”.

Table 1.2: Estimated Insertion Times Based on Assembly Complexity

Insertion involves placing a part into an assembly, aligning it, and securing it (e.g., via fasteners or snap-fits).

Assembly Complexity/Insertion Factor	Description	Estimated Time (seconds)
Simple Insertion, No Resistance	Straight-line motion, self-aligning features	1.0 - 2.0
Moderate Alignment Required	Single-direction insertion, minor adjustments	2.0 - 3.5
Difficult Alignment	Multiple directions or tight tolerances	3.5 - 5.0
Obstructed Access	Limited visibility or restricted motion	4.0 - 6.0
Multiple Fasteners	Requires screws, clips, or additional securing	5.0 - 8.0 (per fastener)
Snap-Fit or Self-Locking Features	No additional fasteners, designed for quick fit	1.5 - 2.5

Note

- Times increase if parts are tangled, sticky, or require precise orientation.
- Handling aids (e.g., chamfers, tabs) reduce time by improving “*grasp ability*”.

Methodology for Application

To utilize this framework effectively:

1. **Classify Part Geometry:** Assess each part’s size, weight, symmetry, and handling features. Select the appropriate category from Table 1.1.
2. **Evaluate Assembly Complexity:** Determine the insertion task’s difficulty based on alignment, access, and fastening requirements. Choose from Table 1.2.
3. **Calculate Total Time:** For each assembly operation, sum the handling time and insertion time. Multiply by the number of identical operations if applicable.

4. **Adjust for Context:** Refine estimates based on specific conditions (e.g., automation, operator skill, or part material).

✓ Example Calculation

Consider assembling a small, symmetric plastic cover (0.3 kg) with a snap-fit mechanism:

- **Handling:** Small, simple part → 1.5 seconds.
- **Insertion:** Snap-fit, self-locking → 1.5 seconds.
- **Total Time per Operation:** $1.5 + 1.5 = 3.0$ seconds.

For 10 identical covers: $3.0 \times 10 = 30$ seconds.

Limitations and Recommendations

This generalized table provides a starting point. It is not a specific DFA analysis. For more accurate estimates:

- **Consult DFA Literature:** Refer to sources like Boothroyd, Dewhurst, and Knight's "Product Design for Manufacture and Assembly" for detailed charts and codes specific to your parts.
- **Use Software Tools:** Tools like Boothroyd Dewhurst DFA software can generate precise time estimates based on CAD models and assembly sequences.
- **Conduct Empirical Testing:** Validate estimates with physical prototypes or time studies in your manufacturing environment.

DFM Guidelines for Specific Manufacturing Processes

To maximize manufacturability, designers must tailor their approach to the constraints and capabilities of the chosen manufacturing process. In Chapter 2 we will explore detailed DFM guidelines for six common processes: injection molding, casting, sheet metal fabrication, welding, EDM Machining and CNC machining. These guidelines help mechanical designers create designs that are efficient, cost-effective, and feasible to produce.

DFM Process Workflow

The DFM process typically follows these steps:

1. **Conceptual Design:** Develop initial ideas while considering basic manufacturing feasibility.
2. **Process Selection:** Identify suitable manufacturing methods (e.g., casting, machining, additive manufacturing) based on volume, material, and complexity.
3. **Detailed Design:** Refine the design with specific manufacturing constraints in mind, such as tool access or mold parting lines.
4. **Prototyping and Validation:** Build prototypes to test manufacturability and identify issues.
5. **Feedback and Iteration:** Incorporate feedback from manufacturing teams to optimize the design.
6. **Production Release:** Finalize the design for full-scale manufacturing.

Collaboration between design, manufacturing, and assembly teams is critical at each stage to ensure alignment.

✓ Case Study: DFM Optimization of a Gearbox Housing for an Industrial Machine in Green Bay, WI

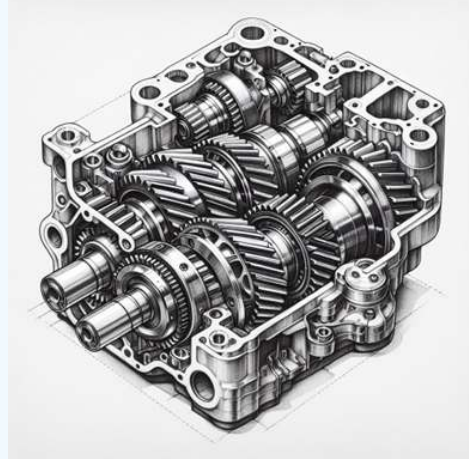


Figure 1.2: AI generated image of a cutaway gearbox showing internal gears

Background

A hypothetical mid-sized manufacturing firm, Green Bay Industrial Solutions (GBIS), located in Green Bay, Wisconsin, specializes in producing custom components for industrial machinery used in sectors such as paper processing, packaging, and material handling—industries prominent in Northeast Wisconsin. GBIS received a contract from a regional OEM (Original Equipment Manufacturer) to design and manufacture a gearbox housing for a heavy-duty conveyor system. The gearbox housing, a critical component, needed to encase a high-torque gear assembly, withstand operational stresses, and be produced cost-effectively in batches of 500 units annually.

The initial design, provided by the OEM's engineering team, was functional but not optimized for manufacturability. GBIS applied DFM principles to refine the design, leveraging local machining capabilities and expertise to reduce production costs and improve assembly efficiency.

Objective

The primary goals of the DFM process were:

1. Minimize manufacturing costs by simplifying fabrication and reducing material waste.
2. Enhance assembly efficiency by optimizing part geometry for handling and insertion.
3. Ensure structural integrity under operational loads (e.g., 500 Nm torque, 50°C operating temperature).
4. Meet the OEM's delivery timeline of 12 weeks from design approval to first batch shipment.

Initial Design Challenges

The OEM's original gearbox housing design presented several manufacturability issues:

- **Complex Geometry:** The housing featured multiple undercuts and thin-walled sections (2 mm thick in some areas), requiring intricate machining and increasing tool wear.
- **Material Selection:** Specified as cast iron (ASTM A48 Class 30), the material was durable but costly and time-consuming to cast and machine.
- **Assembly Complexity:** The design included 12 separate mounting holes with tight tolerances (± 0.01 mm), necessitating precise alignment during assembly and increasing insertion time.
- **Weight:** At 15 kg, the part was heavy, complicating handling and raising shipping costs.

DFM Analysis and Redesign Process

GBIS employed a cross-functional team of design engineers, machinists, and quality specialists to conduct a DFM analysis. The process utilized local resources, including CNC machining capabilities at BM Corporation and collaboration with TM Manufacturing. Steps included:

1. **Geometry Simplification:**

- Undercuts were eliminated by redesigning the housing with straight walls and draft angles (2°), enabling easier mold release if cast or simpler milling if machined.
- Thin-walled sections were thickened to 4 mm where feasible, balancing weight and manufacturability while maintaining strength (verified via finite element analysis).

2. Material Optimization:

- After evaluating alternatives, the team proposed switching to ductile iron (ASTM A536 Grade 65-45-12), which offered comparable strength, better machinability, and reduced casting defects compared to gray cast iron.
- A cost-benefit analysis showed a 15% reduction in material and processing costs.

3. Feature Reduction:

- The number of mounting holes was reduced from 12 to 8 by integrating mounting points into a flange design, decreasing drilling time and simplifying alignment during assembly.
- Chamfers and fillets (R3 mm) were added to edges, reducing stress concentrations and easing tool access.

4. Tooling and Process Alignment:

- The redesign aligned with GBIS's in-house CNC milling and turning capabilities, avoiding the need for specialized tooling or outsourcing.
- A single setup was devised for machining the housing's critical features, reducing setup time by 30%.

5. Assembly Considerations:

- Self-aligning features, such as tapered locating pins, were incorporated to reduce insertion time from 6 seconds to 2 seconds per operation.
- The weight was reduced to 12 kg by optimizing wall thickness and removing non-critical material, easing manual handling.

Manufacturing Process

- **Fabrication:** The housing was cast using a local foundry in Green Bay, followed by CNC machining at GBIS's facility. The simplified geometry allowed for a reusable sand mold, lowering per-unit casting costs.
- **Machining:** A 4-axis CNC mill was used to finish the housing's mating surfaces and mounting flange, achieving tolerances of ± 0.05 mm—less stringent than the original ± 0.01 mm but sufficient for the application.
- **Quality Control:** Coordinate Measuring Machine (CMM) inspection ensured dimensional accuracy, with a focus on critical mating surfaces.

Results

The DFM-optimized gearbox housing yielded significant improvements:

- **Cost Reduction:** Manufacturing cost per unit decreased by 20% (from \$150 to \$120), driven by material savings, reduced machining time, and fewer process steps.
- **Time Savings:** Production lead time for the first batch was reduced from 14 weeks to 10 weeks, meeting the OEM's deadline.
- **Assembly Efficiency:** Handling and insertion time dropped from 15 seconds to 8 seconds per unit, a 47% improvement, due to lighter weight and self-aligning features.
- **Performance:** The redesigned housing passed all stress tests (500 Nm torque, 1,000-hour durability cycle), confirming no compromise in functionality.

Conclusion

This case study exemplifies how DFM principles can transform an industrial part's design for efficient manufacturing. By leveraging local machining expertise and focusing on simplicity, material efficiency, and assembly optimization, GBIS delivered a cost-effective, high-quality gearbox housing that strengthened its partnership with the OEM.

DFM Tools and Software

Modern engineering relies on software to implement DFM effectively:

- **CAD Software:** Tools like SolidWorks, Inventor or Autodesk Fusion 360 include DFM modules to analyze part geometry for manufacturability (e.g., draft analysis, mold flow simulation).
- **Simulation Tools:** Finite Element Analysis (FEA) and process simulation (e.g., Moldflow) predict how designs behave during manufacturing.

Benefits and Challenges of DFM

The benefits of DFM include:

- **Cost Reduction:** Lower material, labor, and tooling costs.
- **Improved Quality:** Fewer defects due to simplified designs and processes.
- **Faster Time-to-Market:** Reduced iterations and streamlined production.

Challenges include:

- **Upfront Effort:** DFM requires more time in the design phase, which can conflict with tight project schedules.
- **Knowledge Gap:** Designers may lack detailed manufacturing expertise, necessitating close collaboration with production teams.
- **Trade-Offs:** Optimizing for manufacturing may compromise aesthetics or performance, requiring careful balance.

Practical Guidelines for DFM

To apply DFM effectively, consider the following:

1. **Engage Manufacturing Early:** Consult production engineers during concept development.
2. **Leverage Prototyping:** Use 3D printing or soft tooling to test designs affordably.
3. **Document Decisions:** Maintain a DFM log to track trade-offs and rationale.
4. **Iterate Based on Feedback:** Treat manufacturing as a partner, not an afterthought.

Conclusion

Design for Manufacturing is a critical discipline that ensures products are not only functional but also economically and efficiently produced. By embedding manufacturing considerations into the design process, mechanical designers can create robust, cost-effective solutions that meet market demands. As manufacturing technologies evolve—such as the rise of additive manufacturing, automation, and AI—DFM principles will continue to adapt, offering new opportunities for you to innovate.

? Exercises

1. Analyze a simple product (e.g., monitor arm in classroom) and propose three DFM improvements.
2. Using the Boothroyd-Dewhurst method, evaluate a multi-part assembly (e.g., caster wheel and bracket assembly) and suggest ways to reduce part count.

Further Reading

Boothroyd, G., Dewhurst, P., & Knight, W. (2010). *Product Design for Manufacture and Assembly*.

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2: DFM Guidelines for Specific Manufacturing Processes

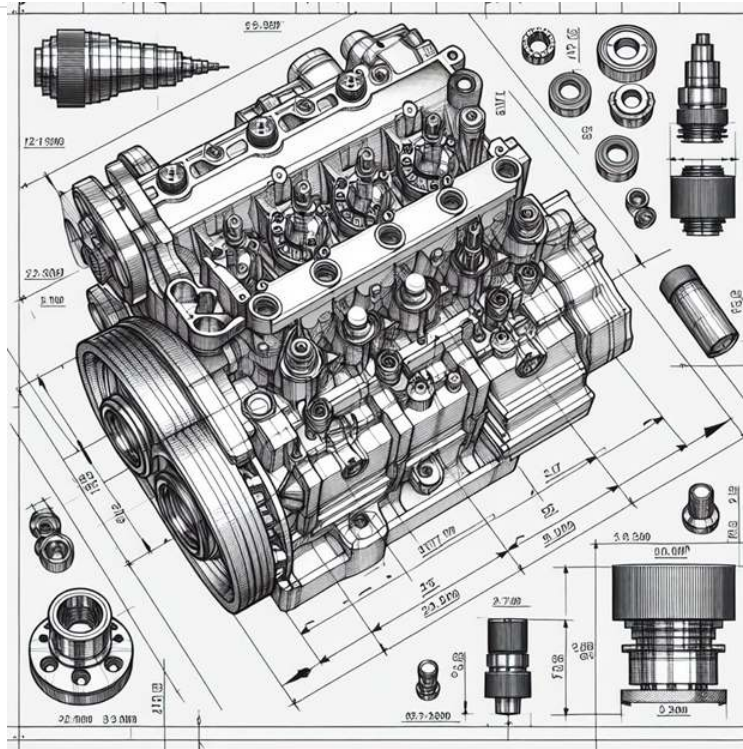


Figure 2.1: AI generated picture of automobile engine and parts

To maximize manufacturability, designers must tailor their approach to the constraints and capabilities of the chosen manufacturing process. In this Chapter, we will explore detailed DFM guidelines for five common processes: injection molding, casting, sheet metal fabrication, welding, and CNC machining. These guidelines help mechanical designers create designs that are efficient, cost-effective, and feasible to produce.

Injection Molding

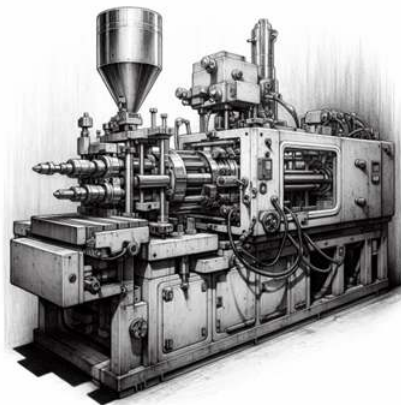


Figure 2.2: AI generated picture of an injection molding machine

Injection molding is a high-volume process for producing precise plastic parts by injecting molten material into a mold. DFM considerations include:

- **Uniform Wall Thickness:** Maintain consistent wall thickness (typically 1–3 mm) to ensure even cooling and prevent warping or sink marks. Avoid abrupt transitions; use gradual tapers if thickness changes are necessary.
 - *Example:* A phone case with uniform 2 mm walls cools evenly, while a design with a 1 mm wall next to a 4 mm rib risks visible defects.

- **Draft Angles:** Add a taper (1–2° per side) to vertical walls to facilitate part ejection from the mold without damage.
 - *Pitfall:* A vertical wall with no draft may stick, requiring costly mold modifications.
- **Ribs and Bosses:** Use ribs (50–60% of wall thickness) for stiffness instead of thick sections. Design bosses (e.g., for screws) with sufficient wall support to avoid sink marks.
- **Avoid Sharp Corners:** Incorporate fillets (minimum radius 0.5 mm) to reduce stress concentrations and improve mold flow.
- **Gate and Parting Line Placement:** Position gates (material entry points) in non-visible areas and align parting lines to minimize secondary finishing.
 - *Example:* A toy car's gate on the underside avoids visible seams on the body.

Casting



Figure 2.3: AI generated picture of a worker by a sand casting in a foundry

Casting involves pouring molten material (metal or plastic) into a mold to form complex shapes. DFM guidelines vary by type (e.g., sand casting, die casting), but common principles include:

- **Draft Angles:** Similar to injection molding, include draft (1–3° for sand casting, 0.5–2° for die casting) to ease mold removal.
- **Uniform Sections:** Avoid large variations in thickness to prevent uneven cooling, shrinkage, or porosity.
 - *Example:* A cast iron pulley with consistent 10 mm walls cools uniformly, while a design with a 5 mm hub and 20 mm rim risks internal voids.
- **Fillets and Radii:** Use generous radii (3–5 mm) at corners to improve material flow and reduce stress concentrations.
- **Risers and Feeders:** Design with adequate material reservoirs to compensate for shrinkage during solidification, consulting with foundry engineers for placement.
- **Parting Line Simplicity:** Minimize complex parting lines to reduce mold costs and machining needs.
 - *Pitfall:* A convoluted parting line on a gearbox housing increases tooling complexity and cost.

Sheet Metal Fabrication

Sheet metal fabrication involves cutting, bending, and assembling thin metal sheets. DFM focuses on optimizing bends and features:

- **Consistent Bend Radius:** Use a uniform bend radius (typically equal to sheet thickness, e.g., 1 mm for 1 mm thick steel) to avoid cracking or distortion.
 - *Example:* A bracket with a 2 mm radius on 2 mm steel bends cleanly, while a 0.5 mm radius risks tearing.
- **Minimum Bend Distance:** Place holes or cutouts at least 2–3 times the sheet thickness from bend lines to prevent deformation.
- **Flange Length:** Ensure flanges are at least 4 times the sheet thickness to maintain structural integrity during bending.
- **Relief Notches:** Add small notches at bend intersections to prevent tearing when multiple bends meet.
 - *Pitfall:* A sheet metal box with holes 1 mm from a bend distorts during forming.
- **Standard Tooling:** Design features compatible with standard punch and die sizes to avoid custom tooling costs.

Welding

Welding joins metal parts using heat and/or pressure, and DFM aims to simplify the process and ensure strong joints:

- **Minimize Welds:** Reduce the number of welds by combining features into single parts (e.g., via casting or bending) to lower labor and inspection costs.
 - *Example:* A frame with two bent sheet metal parts replaces a four-piece welded assembly.
- **Joint Accessibility:** Design weld joints to be easily reached by welding equipment, avoiding tight corners or deep recesses.
- **Consistent Material Thickness:** Match thicknesses at joints to prevent burn-through or weak bonds; step transitions gradually if needed.
- **Weld Type Selection:** Specify welds (e.g., fillet, butt) based on load requirements and ease of application. Fillet welds are simpler than full-penetration welds.
 - *Pitfall:* A thin 1 mm sheet welded to a 5 mm plate risks overheating the thinner section.
- **Tolerances:** Allow for weld shrinkage (typically 1–2% of length) in the design to avoid post-weld machining.

EDM Machining (Electrical Discharge Machining)

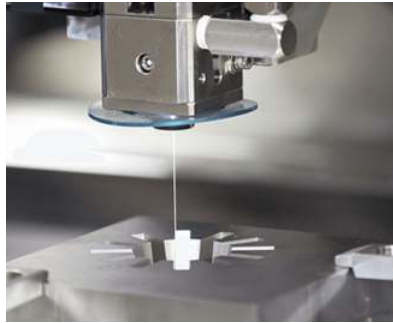


Figure 2.4: Picture of Wire EDM machine

EDM works on the principles of thermal erosion and vaporization. By sparking electricity from the electrode to the machining surface, EDM devices are able to erode and vaporize metal which is then removed from the area using a dielectric fluid.

Primary Applications of Electrical Discharge Machining in Industry

EDM is used to achieve things that conventional machining either can't match in terms of quality or can't achieve at all. Some of the applications of EDM are:

- Drilling small holes.
- Mold and die production.
- Removal of broken tools in workpieces.
- Creating burr-free medical equipment.
- Producing turbine discs for aerospace applications.

Advantages of Using EDM for Material Removal

There are many advantages to be found in the EDM process. EDM is usually used to machine parts that can't be made with conventional machining. Some of the advantages of EDM are:

- Producing turbine discs for aerospace applications.
- It can cut complex shapes, very deep holes, and undercuts which cannot be machined with other conventional machining methods. EDM has the added advantage of not creating burrs.
- The process is not affected by the hardness of the material and will cut through hard metals just as easily as soft metals.
- No marks get left behind unless the EDM is carried out too fast and the surface is left with a “blasted” texture.
- The precision can easily be fine-tuned. Tolerances of ± 0.0002 ” are typically possible.
- Since there is no contact between the electrode and the workpiece, it imparts little to no force during machining. This allows very thin and delicate parts to be machined.

Disadvantages of Using EDM for Material Removal

Despite the wonders of EDM, there are also disadvantages to be aware of, such as:

- The machines cannot remove large amounts of material quickly, which slows the whole machining process. It's hard to achieve high throughput with EDM.
- This is an energy-intensive process, which is not good for a company's carbon footprint. Unless electricity can be sourced in a sustainable way, some organizations will be required to find an alternative to EDM.
- The time and electricity demand translate into expensive operating costs.
- The process is limited to conductive materials only. Even some conductive materials like high-grade nickel alloys are hard to machine this way.

Guideline: Use electrically conductive materials only, as EDM relies on electrical discharges to erode material.

Explanation: EDM is limited to metals and conductive alloys (e.g., steel, titanium, aluminum, copper, carbide). Non-conductive materials like ceramics or plastics cannot be machined directly with EDM unless modified with conductive additives.

Recommendation: Specify material hardness and conductivity early in the design phase, as harder materials (e.g., tool steels) are well-suited but may increase electrode wear.

Feature Geometry

Guideline: Design features with achievable corner radii and avoid sharp internal corners where possible.

Explanation: In sinking EDM, the electrode's shape dictates the workpiece geometry, and electrodes typically have a small radius at corners due to manufacturing constraints (e.g., 0.1–0.5 mm). Wire EDM, while capable of tighter radii (down to 0.025 mm with thin wires), still cannot achieve perfectly sharp internal corners due to wire diameter.

Recommendation: Incorporate a minimum internal corner radius of 0.05–0.2 mm for wire EDM and 0.1–1.0 mm for sinking EDM, depending on electrode size.

Wall Thickness and Feature Depth

Guideline: Maintain reasonable wall thicknesses and limit feature depths to 10–15 times the electrode or wire diameter.

Explanation: Thin walls (<0.5 mm) risk deformation or burn-through due to localized heat, while deep cavities increase machining time and electrode wear. The dielectric fluid's ability to flush debris diminishes in deep, narrow features, potentially causing arcing or poor surface finish.

Recommendation: Keep wall thicknesses above 0.8 mm and consult with manufacturers for depths exceeding 100 mm to ensure feasibility.

Tolerances and Surface Finish

Guideline: Specify tolerances and surface finish requirements realistically, balancing precision with cost.

Explanation: EDM can achieve tight tolerances (± 0.002 – 0.010 mm) and fine surface finishes (R_a 0.1–0.8 μm), but tighter specifications increase machining time, electrode changes, and cost due to slower material removal rates and multiple passes.

Recommendation: Use tolerances of ± 0.01 mm for standard features and reserve tighter tolerances (± 0.005 mm or less) for critical areas only.

CNC Machining

CNC machining uses computer-controlled tools to remove material from a solid block. DFM optimizes for tool access and material efficiency:

- **Tool Geometry:** Design features with radii matching standard end mill sizes (e.g., 3 mm, 6 mm) to avoid custom tools. Minimum internal corner radius should be 1/3 of the feature depth.
 - *Example:* A pocket with a 4 mm radius matches a common 8 mm end mill, reducing setup time.
- **Avoid Deep Features:** Limit pocket depths to 3–4 times the tool diameter to maintain rigidity and avoid chatter.
- **Tool Access:** Ensure all surfaces are reachable without repositioning the workpiece (minimize setups), favoring 3-axis over 5-axis machining when possible.
 - *Pitfall:* A deep, narrow slot requiring a 5-axis machine increases cost versus a wider, shallower redesign.

- **Tolerances:** Specify tolerances achievable with standard machining e.g., ± 0.1 mm (± 0.004 "") unless tighter precision is critical, as ± 0.01 mm (± 0.0004 "") tolerances double costs.
- **Material Removal:** Minimize excess stock removal by starting with near-net-shape blanks (e.g., castings) rather than oversized blocks.

? Exercises

1. Research a manufacturing process (e.g., CNC machining) and create a DFM checklist for designing parts using that method.
2. Document the differences in design processes of a CNC machined part vs an injection molded part.
3. List 3 applications where you would prefer the process of EDM.

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3: Additive Manufacturing Methods

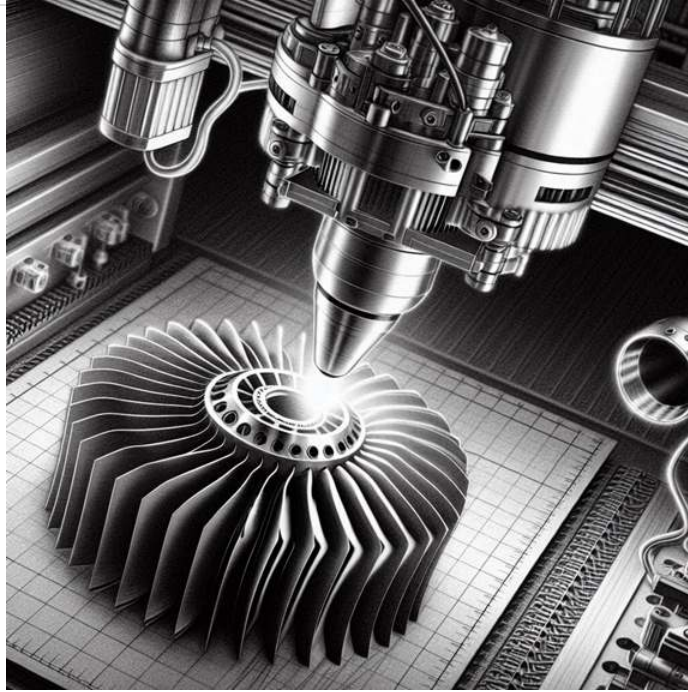


Figure 3.1: AI generated picture of a part being additively manufactured

Introduction to Additive Manufacturing

Additive manufacturing (AM), commonly referred to as 3D printing, represents a transformative approach to fabricating components by building objects layer by layer from digital models. Unlike traditional subtractive manufacturing, which removes material from a solid block, or formative methods, such as casting and forging, AM constructs parts directly from raw materials, typically in powder, liquid, or filament form. This chapter provides an overview of key AM methods, their operational principles, and the circumstances under which AM offers advantages over conventional manufacturing techniques.

Overview of Additive Manufacturing Methods

Additive manufacturing encompasses a variety of processes, each suited to specific materials and applications. The American Society for Testing and Materials (ASTM) classifies AM into seven categories, which are summarized below:

1. Vat Photopolymerization

- **Principle:** A liquid photopolymer resin is selectively cured by a light source (e.g., ultraviolet laser or digital light projection) within a vat.
- **Materials:** Photopolymer resins.
- **Applications:** High-precision components, such as dental models, jewelry molds, and prototypes.
- **Advantages:** Exceptional surface finish and fine feature resolution.
- **Limitations:** Limited material range and relatively high cost of resins.

2. Material Extrusion

- **Principle:** A thermoplastic filament is heated and extruded through a nozzle, depositing material layer by layer on a build platform.
- **Materials:** Thermoplastics (e.g., ABS, PLA, PETG).
- **Applications:** Rapid prototyping, educational models, and low-cost consumer goods.
- **Advantages:** Low equipment cost and simplicity of operation.
- **Limitations:** Lower accuracy and slower build times for complex geometries.

3. Powder Bed Fusion (PBF)

- **Principle:** A laser or electron beam selectively fuses regions of a powder bed, typically metal or polymer, to form a solid part.
- **Materials:** Metals (e.g., titanium, stainless steel), nylon polymers.
 - Stainless Steel (e.g., 316L): Corrosion-resistant, used in industrial and medical components.
 - Titanium Alloys (e.g., Ti6Al4V): Lightweight and strong, ideal for aerospace and biomedical implants.
 - Cobalt-Chromium: High wear resistance, common in turbine blades and dental prosthetics.
 - Aluminum Alloys (e.g., AlSi10Mg): Lightweight, used in automotive and aerospace parts.
 - Nickel Alloys (e.g., Inconel 718): High-temperature resistance, suited for jet engine components.
- **Applications:** Intricate designs unachievable with traditional subtractive or casting methods. Aerospace components, medical implants, and functional prototypes.
- **Advantages:** High strength and ability to produce complex internal structures.
- **Limitations:** High equipment and material costs. Slower than mass-production methods like casting or forging.
- **Subtypes:** Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Metal Laser Sintering (MLS).

4. Binder Jetting

- **Principle:** A liquid binding agent is selectively deposited onto a powder bed to bond particles, followed by post-processing (e.g., sintering).
- **Materials:** Metals, ceramics, sand.
- **Applications:** Metal parts, sand molds for casting, and full-color prototypes.
- **Advantages:** High speed and ability to process diverse materials.
- **Limitations:** Parts may require significant post-processing for strength.

5. Material Jetting

- **Principle:** Droplets of material (e.g., photopolymers or wax) are deposited and cured layer by layer using UV light.
- **Materials:** Photopolymers, waxes.
- **Applications:** Multi-material prototypes, high-detail models.
- **Advantages:** Superior surface quality and multi-material capability.
- **Limitations:** Limited mechanical properties and high operational cost.

6. Directed Energy Deposition (DED)

- **Principle:** A focused energy source (e.g., laser or electron beam) melts material (wire or powder) as it is deposited onto a substrate.
- **Materials:** Metals (e.g., titanium, aluminum).
- **Applications:** Repair of high-value parts, large-scale metal structures.
- **Advantages:** Ability to add material to existing components and handle large builds.
- **Limitations:** Lower resolution and surface finish compared to PBF.

7. Sheet Lamination

- **Principle:** Sheets of material (e.g., paper, metal, or plastic) are bonded together, typically using adhesive or ultrasonic welding, and then cut to shape.
- **Materials:** Paper, metal foils, polymers.
- **Applications:** Low-cost prototypes, architectural models.
- **Advantages:** Cost-effective for large, simple parts.
- **Limitations:** Limited structural integrity and material options.

Comparison with Traditional Manufacturing

Traditional manufacturing methods, such as machining, casting, and injection molding, have long been the cornerstone of industrial production. These processes excel in high-volume production, offering economies of scale, repeatability, and robust material properties. However, AM introduces distinct advantages that warrant its consideration under specific conditions. The decision to employ AM over traditional methods hinges on several key factors, outlined below.

When to Prefer Additive Manufacturing

Additive manufacturing is preferable to traditional manufacturing in the following scenarios:

1. Complex Geometries and Customization

- AM enables the production of intricate designs, such as lattice structures, internal channels, or organic shapes, which are impractical or impossible to achieve with subtractive or formative methods. For instance, aerospace designers utilize PBF to fabricate lightweight, topology-optimized components that reduce material use without compromising strength. Similarly, medical implants tailored to individual patient anatomies are efficiently produced using SLM or EBM.

2. Low-Volume Production and Prototyping

- Traditional methods often require expensive tooling (e.g., molds or dies), making them cost-prohibitive for small batches. AM eliminates this need, allowing rapid iteration of prototypes or production of limited-run parts. Material extrusion and vat photopolymerization are widely used in engineering design cycles to validate concepts before committing to mass production.

3. Material Efficiency

- Subtractive manufacturing generates significant waste by removing material from a larger block, whereas AM builds parts additively, minimizing scrap. This is particularly advantageous when working with costly materials, such as titanium or cobalt-chromium alloys, common in DED and PBF processes.

4. Supply Chain Simplification

- AM facilitates on-demand production, reducing the need for inventory storage and long lead times associated with traditional supply chains. For example, binder jetting can produce sand molds directly, bypassing the need for pattern-making in foundry operations.

5. Repair and Hybrid Manufacturing

- DED excels in repairing high-value components, such as turbine blades, by depositing material onto worn surfaces. This hybrid approach integrates AM with existing parts, extending service life and reducing replacement costs.

Limitations and Trade-Offs

Despite its advantages, AM is not universally superior. Traditional manufacturing remains preferable for high-volume production due to faster cycle times and lower per-unit costs. Additionally, AM parts may exhibit anisotropic properties (direction-dependent strength) and require post-processing (e.g., heat treatment, surface finishing) to meet stringent standards. Material selection in AM is also narrower compared to the extensive range available in conventional processes.

✓ Case Study: Transitioning a Precision Component from Traditional to Additive Manufacturing at Titledown Manufacturing LLC, Green Bay, WI

Background

Titledown Manufacturing LLC, a hypothetical precision metal fabrication and machining company based in Green Bay, Wisconsin, has established itself as a trusted supplier to original equipment manufacturers (OEMs) across the Midwest. Among its product portfolio, the company historically produced a critical stainless-steel valve housing for an industrial pump system used in food processing—a sector prominent in Northeast Wisconsin. Traditionally, this component was manufactured using CNC machining from a solid stainless-steel block, a subtractive process requiring multiple setups, significant material waste, and a lead time of approximately three weeks per batch.

In early 2024, Titledown faced increasing pressure from a key client to reduce costs, shorten delivery times, and accommodate design iterations for a next-generation pump system. This prompted the company to explore additive manufacturing as an alternative production method. After a feasibility study, Titledown selected powder bed fusion (PBF) using selective laser melting (SLM) to transition the valve housing production, leveraging Green Bay's growing ecosystem of advanced manufacturing support and regional expertise.

The Traditional Manufacturing Process

The valve housing, measuring approximately 150 mm x 100 mm x 80 mm with internal flow channels, was machined from 316L stainless steel billets. The process involved:

1. **Material Procurement:** Sourcing 20 kg billets, of which only 4 kg remained in the final part, resulting in 80% material waste.
2. **CNC Machining:** Multi-axis milling to create external geometry and internal channels, requiring three setups and custom fixturing.
3. **Post-Processing:** Deburring, surface finishing, and quality inspection.
4. **Production Metrics:** Each batch of 50 units took 120 labor hours, with a per-unit cost of \$180 and a three-week lead time due to tooling and machining schedules.

The subtractive process excelled in high-volume production but struggled with rapid prototyping and design flexibility, limiting responsiveness to the client's evolving needs.

Transition to Additive Manufacturing

Titletown partnered with a regional AM service provider to adopt SLM, a PBF method using a laser to fuse 316L stainless steel powder layer by layer. The transition process included:

1. **Design Optimization:** Designers redesigned the valve housing using topology optimization software, reducing weight by 15% (from 4 kg to 3.4 kg) and enhancing flow efficiency by integrating conformal internal channels—features infeasible with CNC machining.
2. **Material Shift:** Stainless steel powder was sourced, with unused powder recycled within the SLM system, reducing waste to less than 10%.
3. **Production Setup:** An SLM machine with a 250 mm x 250 mm x 300 mm build volume was utilized, allowing four housings to be printed per build cycle.
4. **Process Execution:** Printing took 18 hours per cycle, followed by heat treatment to relieve residual stresses and wire EDM to remove parts from the build plate. Surface finishing ensured compliance with food-grade standards.
5. **Production Metrics:** A batch of 50 units required 90 hours of machine time plus 20 hours of post-processing, reducing total labor to 110 hours. Per-unit cost dropped to \$150, and lead time shrank to one week.

Outcomes and Benefits

The shift to AM yielded several advantages:

- **Cost Reduction:** A 16.7% decrease in per-unit cost (\$180 to \$150) due to lower material waste and streamlined production.
- **Lead Time Improvement:** Production time reduced by 67% (three weeks to one week), enabling just-in-time delivery.
- **Design Flexibility:** The ability to produce complex internal geometries improved pump performance, increasing client satisfaction.
- **Sustainability:** Material efficiency rose from 20% to over 90%, aligning with Green Bay's emphasis on sustainable manufacturing practices.

Challenges Encountered

The transition was not without hurdles:

- **Initial Investment:** The SLM machine and training required a \$500,000 upfront cost, amortized over multiple projects.
- **Process Validation:** Ensuring mechanical properties (e.g., tensile strength, corrosion resistance) met industry standards necessitated extensive testing, delaying full-scale adoption by three months.
- **Volume Limitation:** SLM's slower build rate made it less economical for batches exceeding 200 units, prompting a hybrid approach for larger orders.

Strategic Decision and Future Implications

Titletown adopted AM for low-to-medium volume production (up to 100 units) and prototyping, retaining CNC machining for high-volume runs. This hybrid model maximized flexibility while leveraging existing infrastructure. The success of this transition positioned Titletown as a regional leader in AM adoption, attracting new clients in aerospace and medical device sectors seeking similar capabilities.

Looking forward, Titletown plans to invest in multi-material AM systems to further enhance component functionality, capitalizing on Green Bay's manufacturing talent pool and proximity to technical colleges like Northeast Wisconsin Technical College (NWTC) for workforce development.

This case study demonstrates how a Green Bay-based manufacturer successfully transitioned a traditionally machined component to additive manufacturing, achieving cost savings, faster delivery, and design innovation. It underscores AM's value in low-volume, high-complexity applications, offering a blueprint for other regional firms navigating the shift from traditional methods.

✓ Case Study, Real-World Example: General Electric's LEAP Engine Fuel Nozzle Transition to Additive Manufacturing

Background

General Electric (GE) Aviation, a global leader in aerospace manufacturing, historically produced fuel nozzles for its jet engines using traditional manufacturing methods. One such component, the fuel nozzle for the LEAP (Leading Edge Aviation Propulsion) engine, developed in collaboration with CFM International, was originally fabricated through a complex subtractive and assembly process. In 2012, GE began exploring additive manufacturing to enhance performance, reduce costs, and streamline production, culminating in the successful transition of this component to AM by 2016. This case is widely regarded as a landmark in the adoption of AM for production parts.

The Traditional Manufacturing Process

The original LEAP engine fuel nozzle was a precision component made from a cobalt-chromium alloy, designed to inject fuel into the combustion chamber with high efficiency. Traditionally, it was manufactured as follows:

1. **Casting and Machining:** The nozzle comprised 20 individual parts, cast separately using investment casting, followed by CNC machining to achieve precise tolerances.
2. **Assembly:** These parts were brazed and welded together, requiring skilled labor and extensive quality control to ensure structural integrity and leak prevention.
3. **Production Metrics:** Each nozzle required approximately 40 hours of manufacturing and assembly time. For a batch of 100 units, the process generated significant scrap (up to 30% material waste) and cost \$250 per unit, with a lead time of four weeks due to tooling and assembly schedules.

This method, while effective for high-volume production, limited design flexibility and resulted in a heavier component, impacting engine efficiency.

Transition to Additive Manufacturing

GE adopted Direct Metal Laser Melting (DMLM), a subtype of powder bed fusion, to redesign and produce the fuel nozzle as a single, integrated part. The transition involved:

1. **Design Optimization:** Using generative design software, designers consolidated the 20-part assembly into a single geometry, reducing weight by 25% (from 0.9 kg to 0.67 kg) and improving fuel flow dynamics with intricate internal channels—features unachievable with casting or machining.
2. **Material and Process:** The nozzle was printed using cobalt-chromium powder in a DMLM system with a build volume of 250 mm x 250 mm x 300 mm. Each print cycle produced two nozzles in 24 hours, followed by heat treatment to relieve stresses and minimal surface finishing.
3. **Production Metrics:** A batch of 100 units required 1,200 machine hours (50 print cycles) plus 100 hours of post-processing, totaling 1,300 hours. Per-unit cost dropped to \$200, and lead time was reduced to two weeks, as no tooling was required.

Outcomes and Benefits

The shift to AM delivered substantial improvements:

- **Performance Enhancement:** The redesigned nozzle improved fuel efficiency by 15%, contributing to the LEAP engine's superior thrust-to-weight ratio, a critical factor in aerospace applications.
- **Cost and Time Savings:** Per-unit cost decreased by 20% (\$250 to \$200), and lead time was halved, enabling faster delivery to customers like Airbus and Boeing.
- **Material Efficiency:** Waste was reduced to less than 10%, as AM used only the material needed for the part, with excess powder recycled.
- **Production Scalability:** By 2020, GE was producing over 100,000 nozzles annually at its Auburn, Alabama facility, demonstrating AM's viability for serial production.

Challenges Encountered

The transition faced several obstacles:

- **Certification:** The Federal Aviation Administration (FAA) required rigorous testing to certify the AM nozzle for flight, delaying initial deployment by 18 months.
- **Equipment Investment:** DMLM machines cost upwards of \$1 million each, necessitating significant capital expenditure, though offset by long-term savings.
- **Process Refinement:** Early builds exhibited porosity issues, requiring optimization of laser parameters and powder quality, adding six months to development.

Strategic Impact and Broader Implications

GE's adoption of AM for the LEAP fuel nozzle marked a paradigm shift in aerospace manufacturing. The company integrated AM into its supply chain, reducing reliance on external vendors and enabling on-demand production. This success spurred further AM investments, such as the 2021 development of AM-produced turbine blades, and inspired competitors like Rolls-Royce and Pratt & Whitney to accelerate their own AM programs.

This example highlights AM's ability to replace traditional manufacturing for high-value, complex components, offering superior performance, reduced lead times, and material efficiency. It remains a benchmark for industries transitioning to AM worldwide.

This case study is grounded in documented industry developments, drawing from GE Aviation's widely publicized adoption of AM for the LEAP engine, as reported in engineering and aerospace literature. It provides a concrete, real-world illustration of AM replacing traditional methods.

Conclusion

Additive manufacturing offers a versatile suite of methods that complement, rather than replace, traditional manufacturing. Designers must evaluate project requirements—geometry complexity, production volume, material properties, and cost constraints—to determine the optimal approach. As AM technologies advance, their adoption will likely expand, reshaping design and production paradigms across industries.

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4: AI and AM Generative Design



Figure 4.1: AI Generated picture of a generative design motorcycle

Introduction to Generative Design

Generative design is an advanced computational approach that leverages algorithms and artificial intelligence (AI) to explore a vast array of design solutions based on user-defined constraints and objectives. Unlike traditional design methods, where designers manually iterate on a single concept, generative design automates the creation of optimized geometries, often producing organic, lightweight structures that maximize performance. In manufacturing, this technology enhances efficiency, reduces material usage, and enables innovation. Particularly when paired with additive manufacturing (AM). This chapter focuses on implementing generative design within SolidWorks, a widely used computer-aided design (CAD) software, and its applications in modern engineering workflows.

Fundamentals of Generative Design

Generative design operates by defining a design space, specifying boundary conditions, and employing optimization algorithms to generate multiple viable solutions. Key elements include:

- **Design Goals:** Objectives such as minimizing weight, maximizing stiffness, or reducing cost.
- **Constraints:** Physical limits, such as load conditions, mounting points, or manufacturing methods.
- **Materials:** Material properties (e.g., density, yield strength) that influence the outcome.
- **Manufacturing Method:** Specifies whether the part will be produced via AM, machining, or casting, affecting geometric feasibility.

The process typically integrates topology optimization, a subset of generative design, which removes unnecessary material while preserving structural integrity, and more advanced AI-driven exploration for broader design possibilities.

Generative Design in SolidWorks

SolidWorks, offers generative design capabilities through its integration with tools like SolidWorks Simulation and cloud-based platforms such as 3DEXPERIENCE Works. As of 2025, SolidWorks provides a streamlined workflow for generative design via its Topology Optimization Module, accessible within the SolidWorks Simulation add-in. This section outlines the process and tools available.

Workflow in SolidWorks

1. Model Setup:

- Create a 3D model in SolidWorks, defining the initial design space (the maximum volume the part can occupy).
- Specify preserved regions (e.g., mounting holes, interfaces) that must remain unchanged.

2. Simulation Setup:

- Access SolidWorks Simulation and define material properties (e.g., aluminum 6061, stainless steel 316L).
- Apply boundary conditions: forces, pressures, or displacements based on real-world use cases.
- Set constraints, such as symmetry or minimum thickness, to align with manufacturing capabilities.

3. Topology Optimization:

- Select the “Topology Study” tool within SolidWorks Simulation.
- Define the optimization goal (e.g., minimize mass with a stiffness constraint).
- Run the solver, which uses finite element analysis (FEA) to iteratively redistribute material, producing an optimized shape.

4. Result Evaluation:

- Review the generated design, presented as a mesh or smoothed geometry.
- Validate performance through additional FEA to ensure compliance with engineering requirements.

5. Refinement and Manufacturing:

- Export the optimized geometry to SolidWorks for final detailing (e.g., adding fillets or adjusting tolerances).
- Prepare the model for manufacturing, typically AM, using SolidWorks’ export tools (e.g., STL or 3MF formats).

Key Features in SolidWorks

- **Integration with FEA:** Seamlessly combines design and analysis, reducing workflow interruptions.
- **Manufacturing Constraints:** Allows users to specify AM overhang angles or machining tool access, ensuring producibility.
- **Cloud Connectivity:** Via 3DEXPERIENCE Works, users can access advanced AI-driven generative design tools beyond basic topology optimization, exploring a broader design space.

Applications in Manufacturing

Generative design in SolidWorks finds applications across industries, particularly when paired with AM:

1. **Aerospace:** Lightweight brackets and structural components (e.g., reducing mass by 30% while maintaining load capacity).
2. **Automotive:** Optimized suspension arms or engine mounts, balancing strength and weight.
3. **Medical Devices:** Custom implants with porous structures for bone integration, tailored to patient anatomy.
4. **Consumer Products:** Ergonomic tools or housings with minimal material use.

For example, an aerospace designer might use SolidWorks to design a turbine blade mount, specifying a 50 kN load and a 20% mass reduction goal. The resulting organic geometry, validated through FEA, can be 3D printed using metal laser sintering, achieving performance unattainable with traditional methods.

Advantages of Generative Design in SolidWorks

- **Efficiency:** Automates design exploration, reducing manual iteration time from weeks to hours.
- **Optimization:** Produces lightweight, high-strength parts, critical for cost-sensitive industries.
- **Integration:** Leverages SolidWorks’ robust CAD ecosystem, minimizing software transitions.
- **Sustainability:** Reduces material waste, aligning with eco-friendly manufacturing trends.

Limitations and Challenges

While powerful, generative design in SolidWorks has constraints:

- **Computational Demand:** Requires significant processing power, often necessitating high-end workstations or cloud resources.
- **Learning Curve:** Designers must understand FEA and optimization principles to effectively use the tools.
- **Manufacturing Dependency:** Optimized designs often require AM, which may not suit high-volume production due to cost and speed limitations.

✓ Case Study: Optimizing a Structural Bracket

Consider a structural bracket for an industrial machine, traditionally machined from steel with a mass of 2 kg. Using SolidWorks:

- **Setup:** The designer defines a 10 kN vertical load, fixes two bolt holes, and selects steel (density: 7850 kg/m³).
- **Optimization:** A topology study targets a 40% mass reduction while maintaining a factor of safety of 2.
- **Outcome:** The solver generates a lattice-like structure weighing 1.2 kg, validated via FEA to withstand the load. The design is 3D printed using selective laser melting, reducing material costs by 35% and lead time from two weeks to three days compared to machining.

This example illustrates how SolidWorks bridges generative design and manufacturing, enhancing efficiency and performance

Future Directions

As generative design evolves, SolidWorks is expected to integrate more AI-driven features, such as real-time multi-objective optimization and broader material libraries. Advances in AM technology will further complement these tools, enabling designers to push design boundaries. For students and professionals, mastering generative design in SolidWorks offers a competitive edge in innovative manufacturing.

Conclusion

Generative design in SolidWorks transforms traditional engineering by automating optimization and enabling complex, efficient designs. Its integration with simulation and manufacturing workflows positions it as a vital tool for modern designers.

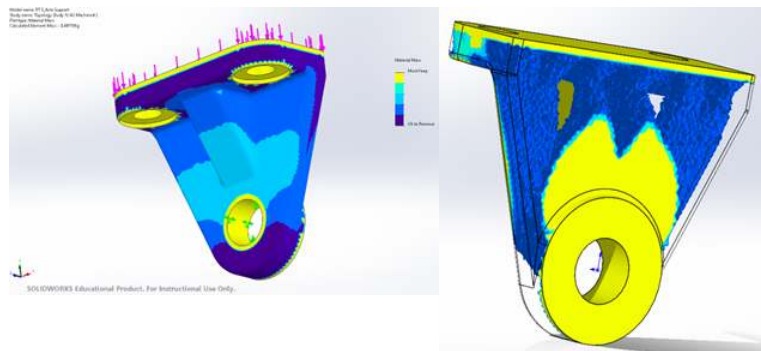


Figure 4.2: Pictures of SolidWorks Pre-Generative and Generative Designed Bracket

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5: Cost Analysis of Traditional Manufacturing vs. Additive Manufacturing Methods



Figure 5.1: AI generated picture of money on table in an AM generative design warehouse

Introduction

Manufacturing costs are a pivotal factor in selecting production processes, balancing efficiency, scalability, and design requirements. Traditional manufacturing methods—such as machining, casting, injection molding, and welding—have been optimized for high-volume production. Additive manufacturing (AM), including techniques like powder bed fusion and material extrusion, offers advantages in low-volume, complex, or customized applications. This chapter analyzes the cost structures of these methods, incorporating material, labor, equipment, tooling, and overhead expenses. By comparing traditional and AM approaches, engineers can optimize decision-making for specific manufacturing scenarios.

Cost Components in Manufacturing

Manufacturing costs are categorized as follows:

1. **Material Costs:** Raw materials consumed in production.
2. **Labor Costs:** Operator time and expertise required.
3. **Equipment Costs:** Initial investment, maintenance, and depreciation of machinery.
4. **Tooling Costs:** Design and fabrication of molds, dies, fixtures, or jigs.
5. **Overhead Costs:** Facility expenses, energy consumption, and post-processing.

These elements vary across methods, influenced by production volume, part complexity, and process characteristics.

Traditional Manufacturing Methods and Costs

Traditional manufacturing encompasses subtractive, formative, and joining processes. Below are cost profiles for key manufacturing methods.

CNC Machining

- **Process:** Material is removed from a solid block using computer-controlled tools (e.g., milling, turning).
- **Cost Breakdown:**
 - **Material:** High waste (30–70% removed), e.g., \$50/kg for titanium.
 - **Labor:** Skilled operators; \$20–\$40/hour, 2–5 hours per part for complex shapes.
 - **Equipment:** CNC machines cost \$50,000–\$500,000; maintenance is 5–10% annually.
 - **Tooling:** Cutting tools (\$50–\$200 each) require replacement.
 - **Overhead:** Moderate energy (5–15 kW); facility costs vary.
- **Cost per Part:** \$100–\$300 for a 1 kg steel bracket in a batch of 50, dropping to \$50–\$100 at 1,000 units.

Die Casting

- **Process:** Molten metal is injected into a mold under pressure, cooled, and ejected.
- **Cost Breakdown:**
 - **Material:** Efficient (5–15% waste); aluminum at \$2–\$5/kg.
 - **Labor:** Semi-automated; \$15–\$25/hour, 0.5–1 hour per batch setup.
 - **Equipment:** Machines range from \$100,000–\$1 million.
 - **Tooling:** High cost (\$10,000–\$100,000 per die), amortized over large volumes.
 - **Overhead:** High energy (20–50 kW) for melting.
- **Cost per Part:** \$5–\$15 for a 0.5 kg part at 10,000 units, \$50–\$100 at 100 units.

Injection Molding

- **Process:** Molten plastic is injected into a mold, cooled, and ejected.
- **Cost Breakdown:**
 - **Material:** Low waste (5–10%); polymers at \$1–\$5/kg.
 - **Labor:** Minimal; \$15–\$25/hour for setup.
 - **Equipment:** Machines cost \$50,000–\$200,000.
 - **Tooling:** Molds range from \$5,000–\$50,000.
 - **Overhead:** Moderate energy (10–20 kW).
- **Cost per Part:** \$0.50–\$2 for a 0.1 kg part at 10,000 units, \$20–\$50 at 100 units.

Welding

- **Process:** Metal parts are joined by melting and fusing them, often with a filler material (e.g., MIG, TIG, or arc welding).
- **Cost Breakdown:**
 - **Material:** Base metals (e.g., steel at \$1–\$5/kg) plus filler rods/wire (\$5–\$20/kg); waste is minimal (5–10%) but includes scrap from fit-up.
 - **Labor:** Highly skilled welders; \$25–\$50/hour, 1–3 hours per assembly depending on complexity (e.g., 2 hours for a 1 kg steel frame).
 - **Equipment:** Welding machines cost \$1,000–\$50,000 (e.g., MIG welder at \$5,000); maintenance is 5–10% annually.
 - **Tooling:** Fixtures or jigs (\$500–\$5,000) needed for alignment, reusable across batches.
 - **Overhead:** Moderate energy (5–15 kW) plus shielding gas (e.g., argon at \$20–\$50 per tank).
- **Cost per Part:** \$50–\$150 for a 1 kg welded steel assembly in a batch of 50, dropping to \$30–\$80 at 1,000 units with fixture amortization.

Additive Manufacturing Methods and Costs

AM constructs parts layer by layer, reducing tooling needs but introducing distinct cost factors. Key methods are outlined below.

Powder Bed Fusion (PBF) - Selective Laser Melting (SLM)

- **Process:** A laser fuses metal powder (e.g., titanium, steel) in a bed.
- **Cost Breakdown:**
 - **Material:** High cost (\$50–\$150/kg); low waste (5–10%, recyclable).
 - **Labor:** \$20–\$40/hour for setup and post-processing (2–3 hours per build).
 - **Equipment:** SLM machines cost \$500,000–\$1.5 million; maintenance is 5–10% annually.
 - **Tooling:** None required.
 - **Overhead:** High energy (10–20 kW) and inert gas (\$50–\$100 per build).
- **Cost per Part:** \$150–\$300 for a 1 kg titanium bracket in a batch of 50, stable across low volumes.

Material Extrusion (FDM)

- **Process:** Thermoplastic filament is extruded (e.g., ABS, PLA).
- **Cost Breakdown:**

- **Material:** \$20–\$50/kg; minimal waste (5–10%).
- **Labor:** \$15–\$25/hour for setup (1–2 hours per build).
- **Equipment:** FDM printers range from \$2,000–\$50,000.
- **Tooling:** None required.
- **Overhead:** Low energy (1–5 kW).
- **Cost per Part:** \$5–\$20 for a 0.1 kg part in a batch of 50.

Vat Photopolymerization (SLA)

- **Process:** A UV laser cures liquid resin.
- **Cost Breakdown:**
 - **Material:** \$100–\$200/kg; low waste (5–10%).
 - **Labor:** \$20–\$40/hour for setup and cleaning (1–2 hours).
 - **Equipment:** SLA printers cost \$5,000–\$100,000.
 - **Tooling:** None required.
 - **Overhead:** Moderate energy (5–10 kW).
- **Cost per Part:** \$20–\$50 for a 0.1 kg part in a batch of 50.

Comparative Cost Analysis

Cost-effectiveness depends on volume, complexity, and material:

- **Low Volume (1–100 units):**
 - **Traditional:** High tooling or labor costs dominate (e.g., \$50–\$150 for welding, \$50–\$100 for die casting).
 - **AM:** Lower costs (e.g., \$150–\$300 for SLM) due to no tooling, ideal for prototypes.
- **Medium Volume (100–1,000 units):**
 - **Traditional:** Costs decrease with amortization (e.g., \$30–\$80 for welding, \$15–\$50 for CNC).
 - **AM:** Stable costs (e.g., \$150–\$300 for SLM), less competitive unless complexity is high.
- **High Volume (1,000+ units):**
 - **Traditional:** Highly efficient (e.g., \$5–\$15 for die casting, \$30–\$80 for welding).
 - **AM:** Rarely viable due to slow build rates and material costs.

Welding's labor-intensive nature makes it costly for small batches, while AM eliminates assembly costs for complex parts (e.g., a welded 5-part frame at \$200 vs. a single SLM part at \$250). Material efficiency favors AM for costly alloys (e.g., 70% waste in CNC vs. 10% in SLM).

✓ Case Study: Motorcycle Swingarm

A 2 kg aluminum swingarm:

- **CNC Machining:** \$250/part at 50 units (80% waste, 5 hours labor, \$10,000 tooling).
- **Die Casting:** \$100/part at 50 units (\$50,000 tooling), \$10/part at 10,000 units.
- **Welding:** \$120/part at 50 units (5 subparts, 3 hours labor at \$40/hour, \$2,000 jig), \$80/part at 1,000 units.
- **SLM:** \$200/part at 50 units (10% waste, no tooling, 20-hour build).
 - **Outcome:** SLM is cheapest at 50 units (\$10,000 total vs. \$12,500 for CNC, \$52,000 for casting, \$6,000 for welding + jig), but casting excels at high volume.

Strategic Considerations

- **Break-Even Point:** AM suits low volumes or complex designs; traditional methods (e.g., welding, casting) dominate mass production.
- **Hidden Costs:** AM requires post-processing (\$20–\$50/part for SLM); welding involves inspection (e.g., \$10–\$20/part for NDT).
- **Future Trends:** Decreasing AM equipment costs may shift economics, while welding automation could reduce labor expenses.

Conclusion

Traditional methods like welding, machining, and casting offer cost advantages in high-volume production, while AM excels in low-volume, complex scenarios. Welding's reliance on skilled labor contrasts with AM's tooling-free flexibility, highlighting trade-offs designers must evaluate based on volume, complexity, and material costs.

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6: Differences in 3D Models and Detail Prints for Various Manufacturing Methods

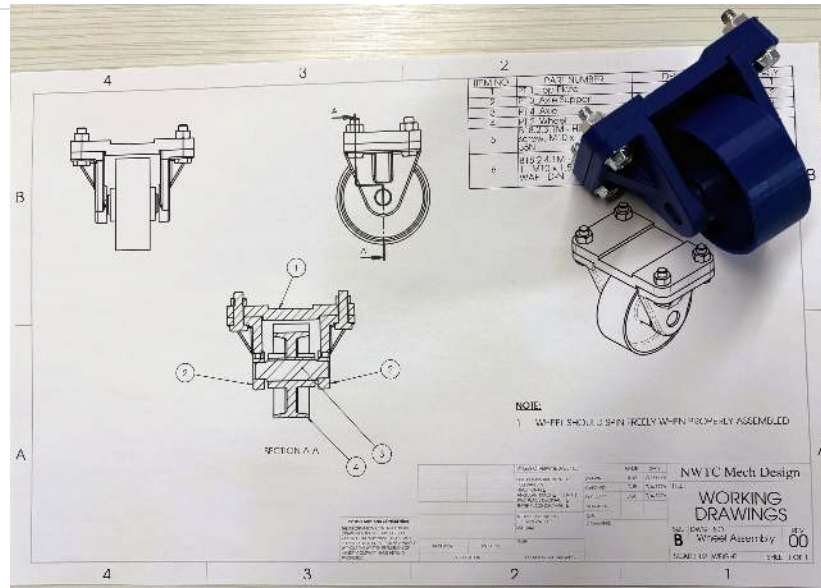


Figure 6.1: Picture of 3D Printed Wheel and Assembly Drawing of Wheel

Introduction

In mechanical design, the design process hinges on two critical deliverables: the 3D model, which defines the part's geometry in a digital environment, and the detail print (or engineering drawing), which communicates precise specifications for manufacturing. These deliverables are not static; they must adapt to the chosen manufacturing method, as each process—whether injection molding, casting, or additive manufacturing—imposes unique constraints and opportunities. Tooling differences further shape the final design, influencing tolerances, features, and material use. This chapter explores how 3D models and detail prints differ across seven common manufacturing methods, how tooling impacts design, and how process shifts necessitate design adjustments, supported by case studies of real-world examples.

Overview of Manufacturing Methods and Their Design Implications

Each manufacturing method has distinct characteristics that affect the 3D model's geometry and the detail print's annotations. Below, we outline these methods and their implications.

Injection Molding

- **3D Model:** Requires draft angles (1–2°) on vertical surfaces for mold release, uniform wall thickness (typically 1–3 mm) to prevent sink marks, and rounded corners to reduce stress concentrations. Features like ribs or bosses may be added for strength.
- **Detail Print:** Specifies parting line location, gate positions, and ejection pin marks. Tolerances are tight (e.g., ± 0.05 mm), reflecting mold precision.
- **Tooling Influence:** Designs must accommodate a two-part mold (core and cavity), often requiring complex slides or inserts for undercuts, increasing tooling costs.

Casting (e.g., Sand or Die Casting)

- **3D Model:** Incorporates draft angles (2–5° for sand, 1–3° for die) and generous fillets to aid molten metal flow. Sand casting allows thicker sections; die casting favors thinner, uniform walls.
- **Detail Print:** Includes allowances for shrinkage (e.g., 1–2% for steel) and machining stock (2–5 mm). Sand casting prints note rougher surface finishes (Ra 12–25 μ m).
- **Tooling Influence:** Sand casting uses disposable patterns, permitting complex shapes, while die casting's steel molds limit geometry but enhance repeatability.

Sheet Metal Fabrication

- **3D Model:** Designs flat patterns that fold into 3D shapes, requiring bend radii (e.g., 1x material thickness) and relief cuts to prevent tearing. Features like hems or flanges are common.
- **Detail Print:** Details bend lines, K-factors (neutral axis shift), and hole-to-edge distances (min. 2x thickness). Tolerances are moderate (e.g., ± 0.1 mm).
- **Tooling Influence:** Press brakes and punches dictate minimum bend radii and hole sizes, constraining design flexibility.

Welding

- **3D Model:** Comprises assemblies of simpler parts, with chamfers or grooves for weld preparation. Avoids tight fits to accommodate thermal distortion.
- **Detail Print:** Specifies weld symbols (e.g., fillet, butt), joint types, and post-weld machining needs. Tolerances are looser (e.g., ± 1 mm) due to variability.
- **Tooling Influence:** Minimal tooling (e.g., jigs, fixtures) allows complex assemblies but requires design for accessibility.

EDM Machining (Electrical Discharge Machining)

- **3D Model:** Focuses on intricate features (e.g., sharp corners, deep cavities) unachievable by traditional cutting. No draft angles needed.
- **Detail Print:** Notes electrode geometry and surface finish (Ra 0.1–1.6 μm). Tolerances are extremely tight (e.g., ± 0.005 mm).
- **Tooling Influence:** Custom electrodes shape the design, adding cost but enabling precision in hard materials.

CNC Machining

- **3D Model:** Avoids undercuts unless multi-axis machines are used. Includes larger radii (e.g., 0.5 mm min.) for tool access and chamfers to reduce burrs.
- **Detail Print:** Specifies tool paths, fixturing points, and tight tolerances (e.g., ± 0.01 mm). Surface finish (Ra 0.8–3.2 μm) is detailed.
- **Tooling Influence:** Tool size and reach limit internal features, often requiring multiple setups.

Additive Manufacturing (3D Printing)

- **3D Model:** Permits complex, organic geometries (e.g., lattices, internal channels) without draft angles. Support structures may be modeled for overhangs ($>45^\circ$).
- **Detail Print:** Notes build orientation, layer thickness (e.g., 0.1–0.3 mm), and post-processing (e.g., support removal). Tolerances vary (e.g., ± 0.1 –0.5 mm).
- **Tooling Influence:** No traditional tooling; design freedom is high, but surface finish and strength depend on process (e.g., FDM vs. SLM).

Tooling Differences and Their Impact on Final Design

Tooling—the molds, dies, fixtures, or electrodes used in manufacturing—directly influences part design. For injection molding, a split mold necessitates draft angles and restricts undercuts, whereas CNC machining’s rotating tools limit internal feature depth. Additive manufacturing eliminates tooling, enabling intricate designs but requiring support structures that affect surface quality. These constraints shape the 3D model’s geometry (e.g., adding fillets in casting) and the detail print’s specifications (e.g., noting mold parting lines).

Process Effects on 3D Models and Detail Prints

Manufacturing processes dictate design adjustments:

- **Material Flow:** Injection molding and casting require smooth transitions (fillets, tapers) in the 3D model to ensure fill, reflected in the print’s draft annotations.
- **Subtractive vs. Additive:** CNC machining simplifies geometry for tool access, while additive manufacturing embraces complexity, altering model topology and print callouts.
- **Assembly:** Welding’s 3D model splits a part into sub-components, with the print detailing weld joints, unlike sheet metal’s single-part approach with bend notations.

✓ Case Studies: Design Transitions Across Manufacturing Methods

Case Study 1: Automotive Bracket (Casting to CNC Machining)

- **Original Method:** Sand casting produced a steel bracket with a 3D model featuring 3° draft angles and 5 mm machining allowance. The detail print specified shrinkage (1.5%) and a rough finish (Ra 25 μm).
- **New Method:** Switching to CNC machining for prototyping eliminated draft angles and reduced wall thickness from 8 mm to 6 mm for weight savings. The 3D model added chamfers for tool clearance, and the print tightened tolerances (± 0.01 mm) and specified a smoother finish (Ra 1.6 μm).
- **Reason for Change:** Faster prototyping and tighter tolerances were needed for testing.
- **Impact:** Simplified tooling (no mold) but increased machining time and cost.

Case Study 2: Pump Housing (Injection Molding to Additive Manufacturing)

- **Original Method:** Injection-molded ABS housing had a 3D model with 2° draft angles, uniform 2 mm walls, and ribs for stiffness. The detail print noted gate locations and ± 0.05 mm tolerances.
- **New Method:** Transition to 3D printing (SLA) for low-volume production removed draft angles and integrated internal channels for fluid flow. The 3D model included support structures, and the print specified build orientation and ± 0.2 mm tolerances.
- **Reason for Change:** Small batch size (50 units) made molding uneconomical.
- **Impact:** Greater design freedom but coarser finish and higher per-unit cost.

Best Practices for Adapting Designs

- **Start with Process in Mind:** Design the 3D model with the intended method's constraints (e.g., draft for molding, tool access for CNC).
- **Iterate Across Methods:** Use parametric modeling to adjust features (e.g., wall thickness) when switching processes.
- **Update Prints Rigorously:** Reflect process-specific details (e.g., weld symbols, support removal) to avoid miscommunication.

Conclusion

The interplay between manufacturing methods, tooling, and design deliverables is a cornerstone of mechanical design. Injection molding demands draft and uniformity, while additive manufacturing offers geometric freedom; CNC machining excels in precision, but welding suits assemblies. These differences ripple through 3D models and detail prints, requiring engineers to tailor their approach. By understanding process constraints and tooling impacts—illustrated through case studies—students can design adaptable, manufacturable parts that meet performance and cost goals.

? Exercises

1. Create a 3D model sketch and detail print excerpt for a simple flange using injection molding, then adapt them for CNC machining. Note changes.
2. Research a part made by sheet metal fabrication and propose how its design would change for additive manufacturing.
3. Analyze the Case Study 1 transition. Suggest a third manufacturing method and predict design adjustments.

Further Reading

- Boothroyd, G., Dewhurst, P., & Knight, W. A. (2010). *Product Design for Manufacture and Assembly*. CRC Press.
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7: Justify Your Design Decision

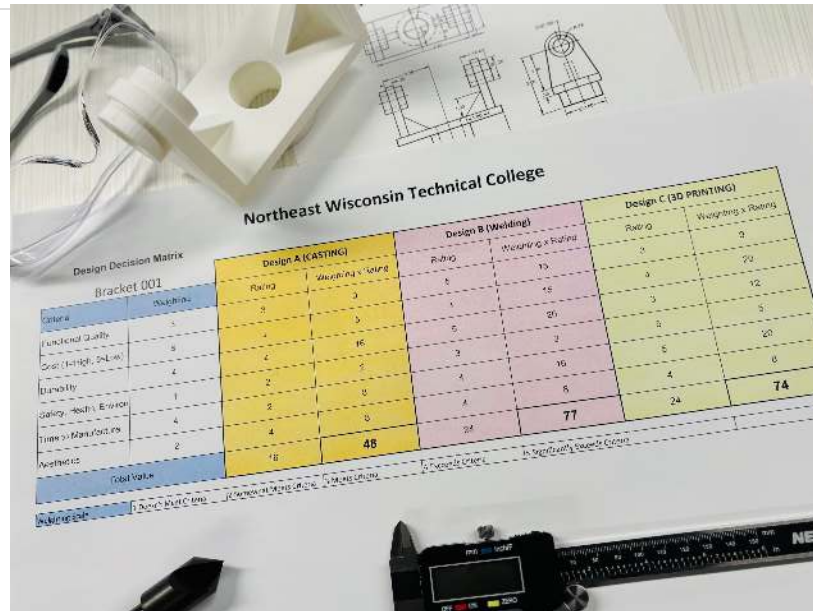


Figure 7.1: Picture of Decision Matrix and 3D Printed Bracket and Tools

Introduction

In mechanical design, design decisions are rarely made in isolation or based solely on intuition. Designers must justify their choices with a structured, evidence-based approach that balances technical feasibility, cost, performance, and manufacturability. Whether designing a component for an automotive suspension system or a structural element for a bridge, the ability to defend your decision is as critical as the design itself. This chapter explores how to justify mechanical design decisions, focusing on the use of decision matrices to evaluate manufacturing options, strategies for arguing the benefits of your selected design, presenting tangible evidence to instill confidence, and leveraging historical data from similar applications.

Developing and Preparing a Decision Matrix

A decision matrix is a quantitative tool that allows engineers to systematically compare multiple design or manufacturing options against a set of weighted criteria. It transforms subjective preferences into an objective evaluation framework, ensuring decisions are defensible and transparent.

Steps to Develop a Decision Matrix

- 1. Identify Design or Manufacturing Options:** Begin by listing all viable alternatives. For example, when selecting a manufacturing process for a steel bracket, options might include casting, forging, or additive manufacturing.
- 2. Define Evaluation Criteria:** Select criteria relevant to the project's goals. Common criteria include cost, production time, material strength, dimensional accuracy, scalability, and environmental impact. Ensure these align with stakeholder priorities (e.g., client requirements, regulatory standards).
- 3. Assign Weights to Criteria:** Not all criteria are equally important. Assign a weight (e.g., 1–10 scale) to each based on its relative significance. For instance, if cost is a primary concern, it might receive a weight of 8, while environmental impact might be weighted at 3.
- 4. Score Each Option:** Rate each option's performance against each criterion on a consistent scale (e.g., 1–5, where 5 is best). Use data from material specifications, process capabilities, or preliminary analyses to inform scores.
- 5. Calculate Weighted Scores:** Multiply each score by its criterion's weight and sum the results for each option. The option with the highest total score is the strongest candidate.
- 6. Review and Refine:** Validate the matrix by discussing results with team members or stakeholders. Adjust weights or scores if new information emerges.

✓ Example: Manufacturing a Gearbox Housing

Consider a gearbox housing with three manufacturing options: sand casting, die casting, and CNC machining. The criteria are cost (weight: 8), lead time (weight: 6), and surface finish (weight: 4). Scores are assigned as follows:

Option	Cost (8)	Lead Time (6)	Surface Finish (4)	Weighted Score
Sand Casting	4 (32)	3 (18)	2 (8)	58
Die Casting	3 (24)	4 (24)	4 (16)	64
CNC Machining	2 (16)	2 (12)	5 (20)	48

Die casting scores highest (64), suggesting it as the preferred method. However, the matrix is a starting point—qualitative factors like equipment availability or expertise may also influence the final decision.

Arguing the Benefits of Your Selected Design Decision

Once a decision is made, designers must convincingly articulate its advantages to stakeholders, such as project managers, clients, or peers. This requires a clear, logical argument supported by data and aligned with project objectives.

Key Strategies

- **Link to Project Goals:** Emphasize how the decision supports overarching priorities. For example, “Die casting was selected because its superior surface finish reduces post-processing costs, aligning with the project’s budget constraints.”
- **Highlight Trade-offs:** Acknowledge limitations but frame them as acceptable compromises. “While die casting has a higher initial tooling cost than sand casting, its shorter lead time and scalability offset this expense for high-volume production.”
- **Use Comparative Analysis:** Contrast your choice with alternatives to underscore its strengths. “Unlike CNC machining, die casting achieves tighter tolerances at a lower per-unit cost, making it ideal for this application.”
- **Address Stakeholder Concerns:** Anticipate questions or objections. If environmental impact is a concern, note, “Die casting’s energy efficiency and material recyclability mitigate its ecological footprint compared to sand casting.”

A compelling argument blends technical rigor with persuasive communication, ensuring stakeholders trust your judgment.

Presenting Tangible Evidence to Convey Confidence

Confidence in a design decision stems from empirical evidence, not assertions. Tangible evidence—data, simulations, prototypes, or industry benchmarks—grounds your justification in reality and reassures stakeholders.

Types of Evidence

- **Material and Process Data:** Provide specifications, such as yield strength for a forged part or cycle time for a manufacturing process, sourced from supplier datasheets or standards (e.g., ASME, ISO).
- **Simulation Results:** Use finite element analysis (FEA) or computational fluid dynamics (CFD) to demonstrate performance under load or flow conditions. For example, “FEA shows the die-cast housing withstands 150% of the design load with a safety factor of 2.”
- **Prototyping and Testing:** Physical prototypes or small-batch trials offer concrete proof. “A prototype die-cast housing passed 10,000 fatigue cycles, exceeding the target lifespan by 20%.”
- **Cost-Benefit Analysis:** Quantify savings or efficiencies. “Die casting reduces per-unit cost by \$2.50 compared to CNC machining over 10,000 units, yielding \$25,000 in savings.”

Presentation Tips

- Use visuals like charts, graphs, or 3D renderings to make data accessible.
- Cite credible sources (e.g., peer-reviewed journals, manufacturer documentation).
- Keep explanations concise but detailed enough to preempt skepticism.

Evidence transforms a subjective preference into an objective conclusion, bolstering your credibility.

Incorporating the History of Similar Parts in Similar Applications

Historical context provides a powerful lens for justifying decisions. By referencing similar parts in comparable applications, you can demonstrate precedent, identify lessons learned, and avoid past pitfalls.

How to Integrate Historical Data

- **Research Precedents:** Investigate how similar components were manufactured in the past. For instance, “Gearbox housings in automotive applications have historically favored die casting for its balance of strength and cost, as seen in models X and Y.”
- **Analyze Successes and Failures:** Highlight what worked and why, or explain how your design avoids previous failures. “Sand-cast housings in model Z exhibited porosity issues, which die casting mitigates through higher pressure and better material flow.”
- **Leverage Industry Standards:** Reference established practices. “The aerospace sector’s adoption of forging for high-stress components informs our choice for this load-bearing bracket.”
- **Quantify Performance:** Use data from past applications. “Die-cast housings in a similar gearbox application achieved a 15-year service life, supporting our reliability projections.”

Sources of Historical Data

- Technical literature (e.g., journals, conference papers).
- Manufacturer case studies or white papers.
- Company archives or tribal knowledge from experienced engineers.

By grounding your decision in history, you show due diligence and reinforce its practicality.

✓ Putting It All Together: A Case Study

Imagine you’re tasked with designing a pump impeller for a wastewater treatment system. Manufacturing options include sand casting, investment casting, and 3D printing. After constructing a decision matrix (criteria: cost, precision, lead time), investment casting emerges as the top choice. You argue its benefits: “Investment casting delivers the tight tolerances needed for impeller efficiency while keeping costs lower than 3D printing for this batch size.” Evidence includes FEA results showing stress distribution and a cost analysis projecting 18% savings over 5,000 units. Historical data reveals that investment-cast impellers in similar pumps have a proven track record of durability in corrosive environments. Presented to stakeholders with clear visuals and concise explanations, your justification earns approval.

Conclusion

Justifying a mechanical design decision is a multifaceted process requiring analytical tools, persuasive communication, and robust evidence. The decision matrix provides a structured comparison of options, while a well-crafted argument aligns your choice with project goals. Tangible evidence—simulations, tests, or cost analyses—builds confidence, and historical context ties your decision to proven practices. Together, these elements equip mechanical designers to defend their designs with clarity and authority, ensuring technical excellence and stakeholder buy-in.

? Exercises

1. Create a decision matrix to compare three manufacturing methods for a bicycle frame (e.g., welding, brazing, carbon fiber molding). Assign weights and justify your scoring.
2. Draft a 200-word argument defending your chosen method from Exercise 1, addressing cost, strength, and production speed as the top design considerations.
3. Research a historical example of a mechanical component failure (e.g., Tacoma Narrows Bridge). Explain how the lessons could inform a modern design decision.

Further Reading

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- Ulrich, K. T., & Eppinger, S. D. (2015). *Product Design and Development*. McGraw-Hill.

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