Build4 Scale
U.S. Department of Energy

Design for Manufacturing, Assembly, and Testing

Module 3C Manufacturing Processes

Motivation

Why is this module important?

- Choosing an appropriate manufacturing process is perhaps the single most important decision you will make to scale up your production
- Manufacturing process selection drives:
  - —Cost and time to produce
  - —Make-or-buy decisions
  - —Capital-investment decisions
  - —Product look, quality, and reliability
  - —Adaptability to design changes

Selecting the right manufacturing process is paramount to your competitive advantage in the marketplace, so make an informed decision now!

Module Outline

- Learning objectives
- What this module addresses
- Introduction to manufacturing processes
- Process attributes
- Manufacturing cost analysis
- Manufacturing process selection
- Additional resources

Learning Objectives

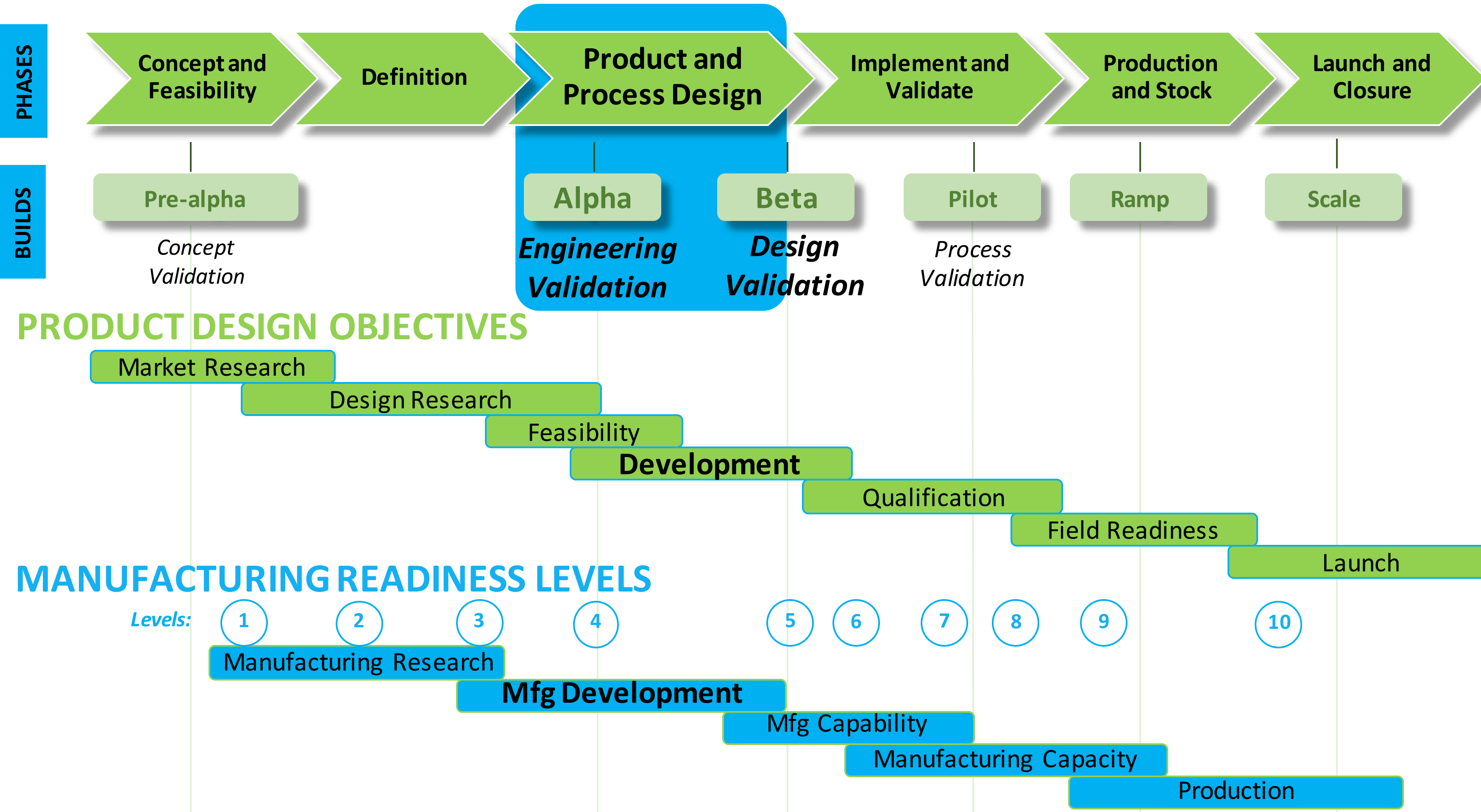
- LO1. Identify the manufacturing processes capable of producing necessary geometry
- LO2. Recommend appropriate manufacturing processes based on technical and business needs
- LO3. Estimate the capital and piece costs associated with alternative processes

What This Module Addresses

- The various types of manufacturing processes and their key attributes and cost factors
- How to select a manufacturing process based on the design requirements, material type, and process parameters
- How product geometry (such as shape and size) can limit the manufacturing-process selection decision
- Component and capital costs
- An introduction of how the manufacturing process influences product design

Selecting Manufacturing Processes

Where does this fit into the development cycle?



Manufacturing Processes

Introduction

- Manufacturing is about transforming (or converting) raw materials into finished components or products

Common manufacturing processes:

- Machining
- Press working
- Welding/fabrication
- Casting
- Powder materials
- Layered deposition
- Injection molding
- 3D Printing
- Extrusion – pipe, sheet stock, tubes
- Assembly

Manufacturing Processes

Classification

Primary shaping processes:

- These processes form the overall shape of the product, or the components that will be joined to form the final product

Secondary processes:

- The main objective of this is to provide the final shape surfaces to meet some of the product requirements such as surface finishing

Assembly/test processes:

- Assembly processes are used to join two or more components/sub-assemblies to obtain the final product while test processes are used to inspect dimensions and functionality

Adopted from ''Introduction to Manufacturing Processes and Materials" By Robert Creese

Manufacturing Process

Hierarchy

Raw Material

PRIMARY SHAPING PROCESSES

- **Casting** – Sand, die, investment casting
- **Moulding** – Injection moulding, blow moulding
- **Forming** – Forging, presswork, rolling
- **Powder** – Powder metal sintering
- **Special** – Composite lay-up
- **Additive Manufacturing** – 3D printing, fused decomposition modeling, Stereolithography

SECONDARY PROCESSES

- **Bulk Heat Treatment** – Hardening, tempering, annealing
- **Material Removal Processes** – Turning, drilling, milling, laser beam machining
- **Surface Treatment** – Plating, painting, anodizing, polishing

ASSEMBLY/ TEST PROCESSES

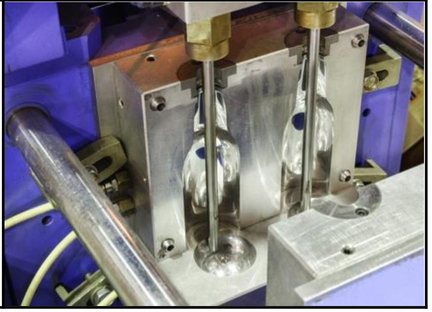
- **Joining Processes** – Bolting, riveting, welding, brazing, soldering, adhesive bonding
- **Assembly Systems** – Component feeding, orientation, robotics, placement, insertion
- **Test Processes** – Measurement, inspection, functional testing

End Product

Adapted from K.G. Swift and J.D. Booker (2013)

Primary Processes

Casting and molding

Process	Description	Common Application	Process Example
Casting	• Molten metal is poured into a mold cavity; upon solidification, metal conforms to the shape of the cavity. • Most casting processes use patterns that form the cavity of the mold made from wood, plastics, or metals.	Wind mill tower parts, generator blocks, metal blocks for machining, and other complex shapes with internal features.	
Injection Molding	• Injecting or forcing of heated molten plastic into a cavity mold, which is in the form of the product to be made. • Part is ejected from the mold after it is cooled and solidifies. • It can produce varieties of part designs in a single molding operation.	Thermoplastic components, Turbine vanes, mechanical seals, O-rings, and plastic bottles.	

Primary Processes

Shaping and forging

Process	Description	Common Application	Process Example
Roll Forming	• To form sheets of uniform cross-section. • Material is fed through multiple pairs of forming rolls countered to produce the desired cross section. • High mechanical strength, dimensional accuracy, closer tolerances, and good surface finish.	Frames of solar panel, parts of aircrafts, HVAC, rail tracks, automobile components, and other geometrically complex shapes.	
Forging	• Controlled deformation of metal into a specific shape by compressive forces. • Superior to casting because the parts formed have high strength, high resistance to wear, less porosity. • Aluminum, copper, and magnesium are preferred for forging.	Wind mill turbine disks and gear blanks, bearing housings, seals, fan cases.	

Primary Processes

Forging and shaping (cont.)

Process	Description	Common Application	Process Example
Sheet Metal Stamping	• Stamping presses and stamping dies are tools used to produce sheet metal parts. The press machine provides the fore to close the stamping dies that shape and cut the sheet metal into finished parts • Includes processes such as punching, blanking, embossing, bending, flanging and coining.	Sheet metal parts of simple and complex geometries can be produced in high volume. Example: Automobile body parts, wind turbine casings, rolled steel sheets and many others.	

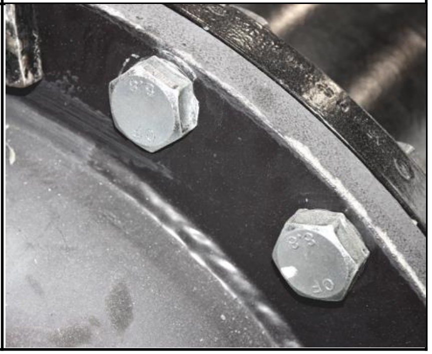
Primary Processes

Additive manufacturing

Process	Description	Common Application	Process Example
3D Printing (Rapid Prototyping)	• Produces part layer by layer from a material (both polymer and metal) based on the digital data (CAD). • Increased design freedom compared to conventional processes such as casting and machining. • No cutting tools, molds, or dies are required. • Complex parts produced in a few hours.	Prototype for manufactured objects, medical field components (e.g., stents, artificial limbs, and joints).	
Wire + Arc-AM (WAAM)	• The process uses welding wire as feedstock. • It produces very near net shape, without the need for complex tooling, moulds, dies. • WAAM hardware currently uses standard, off the shelf welding equipment: welding power source, torches and wire feeding systems. • Motion can be provided either by robotic systems or computer numerical controlled gantries.	• Suited for manufacturing of medium to large scale components. • For aerospace industries components such as cruciform, stiffened panels, wing ribs, etc. • It's also used in industries such as nuclear, oil and gas for producing round shape end caps of pressure vessels.	

Primary Processes

Additive manufacturing (cont.)

Process	Description	Common Application	Process Example
Adhesive Manufacturing	• Good alternative to welding, soldering, and brazing. Effective for joining dissimilar metal substrates with dissimilar melting points. Does not cause distortion, discoloration, or weld worms. • Holes need not be drilled into the material to accommodate fasteners. • Distributes stress load evenly over a broad area.	Typically used in applications such as thread locking; retaining rigid, cylindrical assemblies; and sealing between flanges.	

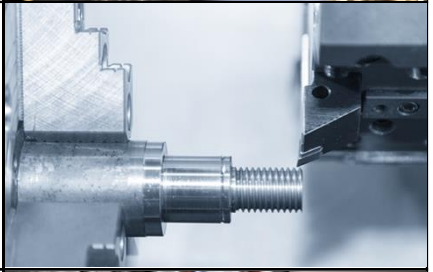
Secondary Processes

Heat treatment

Process	Description	Common Application	Process Example
Heat Treatment	• An operation, or combination of operations, which involves the heating and cooling of a solid metal or alloy for the purpose of obtaining certain desirable conditions or properties. • It is usually desired to preserve, as nearly as possible, the form, dimensions, and surface of the piece being treated.	It improves the hardness of metal for their use in applications such as certain type of bolts, mower blades, axes, saw blades, drill bits, garden tools, etc.	

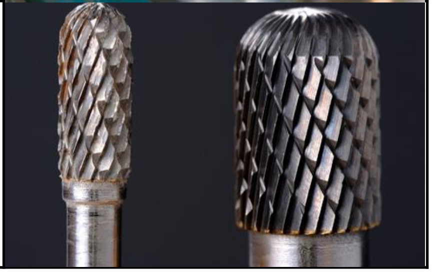
Secondary Processes

Machining

Process	Description	Common Application	Process Example
Turning	• Workpiece is rotated about its axis whereas cutting tool is fed into it. • This shears away unwanted material and creates the desired part. • Turning can be performed on both external as well as internal surfaces.	To manufacture rotating parts such as turbine shaft, axles, spindles, gear blanks, pump drives, and pinions, etc.	
Threading	• A single-point threading tool, typically with a 60-degree pointed nose, moves axially, along the side of the workpiece, cutting threads into the outer surface. • The threads can be cut to a specified length and pitch and may require multiple passes to be formed.	Application involving threads such as fasteners, connectors, worm drives, leadscrew of jack, micrometer, pipe joints and hoses.	
Milling	• It uses revolving cutters to remove material from a work piece advancing in a certain direction at an angle with the axis of the tool. • Milling can create complex shapes accurately.	Complex shapes such as blades of turbines, gearbox casings, flanges, aircraft body parts.	

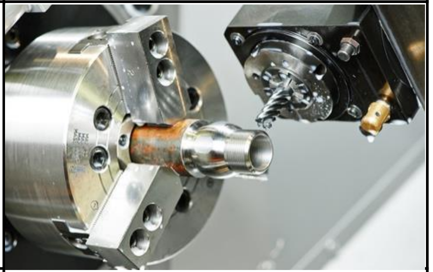
Secondary Processes

Machining (cont.)

Process	Description	Common Application	Process Example
Drilling	• To make straight cylindrical holes in solid rigid bodies and/or enlarge (coaxially) existing (pre-machined) holes. • Tool used in the process is called "Drill Bit", which is a rotary multi-point cutting tool.	Bushing, flanges, collars, and applications where it required bulk production of drilled materials in various size and shape like metal sheets, plastic, wood, glass and concrete construction applications.	
Grinding	• It is an abrasive material removal and surface generation process. • Implement to shape and finish components made of metals and other materials. • It can achieve better surface finish compared to turning or milling.	Any component requiring surface finish such as transmission shafts, camshafts, bearings, crankshafts, etc.	
Reaming	• It is used to enlarge and true a hole. • Tool used for this process are called "Reamers". • A reamer is a rotary cutting tool with one or more cutting elements used for enlarging to size and contour a previously formed hole.	Used to produce smooth and accurate holes, precision instruments, gauges, measurement tools, etc.	

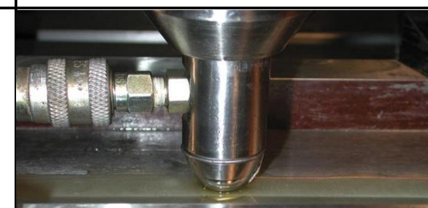
Secondary Processes

Machining (cont.)

Process	Description	Common Application	Process Example
Tapping	• A process for producing internal threads using a tool (tap) that has teeth on its periphery to cut threads in a predrilled hole. • A combined rotary and axial relative motion between tap and workpiece forms threads.	Widely used in machine tool industry to hold or fasten parts together (screws, bolts and nuts), and to transmit motion (the lead screw moves the carriage on an engine lathe.	
Boring	• Process of producing circular internal profiles on a hole made by drilling or another process. • It uses single-point cutting tool called a boring bar which can be rotated, or the workpart can be rotated.	Any component requiring a tighter surface finish such as that for transmission shaft, cam shafts, cam shafts bearing, end crank shafts.	
Counter Sinking	• It produces a larger step in a hole to allow a bolt head to be seated below the part surface, except that the step is angular to allow flat-head screws to be seated below the surface. • A countersink is an conical cutting tool with angular relief, having one or more flutes with specific size angle cutting edges.	Used to recess a flat head screw or to chamfer hole edges, especially in aviation industries.	

Secondary Processes

Machining (cont.)

Process	Description	Common Application	Process Example
Broaching	• A machining operation that uses a toothed tool called a "broach" to remove material. • Broaching can be performed either horizontally or vertically by either pushing or pulling the broaches over or inside the workpiece.	Typical use of this process includes cutting keyways on the objects such as driveshafts, gears, pulleys, etc.	
Honing	• An abrasive machining process where honing tools (honing sticks) are pressed against the rotating workpiece to obtain required material removal.	Improves the dimensional accuracy of internal surfaces of cylindrical parts such as bore of automobile gear box.	
Burnishing	• It is a process of polishing and work hardening used for a metallic surface. • It smoothens and hardens the surface, creating a finish which lasts longer.	Used mainly in clockmaking and watchmaking industries. Parts such as bearing surfaces, pivots, and, pivot holes are few examples.	
Super-finishing	• As name suggests, it's a fine material removal process. • It involves very low surface roughness values of the order of 0.012-0.025µm. • It involves relatively larger grained stone removing desired stock.	Particularly used forgiving high surface finishes to ball bearings parts such as races, etc.	

Secondary Processes

Machining (cont.)

Process	Description	Common Application	Process Example
Shaping	• Tool is reciprocating horizontally and the work piece is fed in to the cutting tool. • Tool used for shaping is called shaper. • Feed and depth of cut are provided by moving the work piece.	Used for machining flat surfaces on small sized jobs. Work piece is held on a fixed bed to be usually rectangular in shape.	
Plaining	• Work piece is reciprocating and the tool is fed in. • Produces flat surfaces in different planes. • Much larger and more rugged with longer length and heavy cuts compared to shaping machines.	Used if the size of the job requiring longer and faster stroke, e.g. large stamp dies and plastic injection molds. Other uses contains any task where large block of metals have to be squared.	
Slotting	• Tool is reciprocating vertically and the work piece is fed in to the cutting tool. • Can be considered as vertical shaping machines. • Length and position of stroke can be adjusted.	Used to machine internal surfaces (flat, formed grooves and cylindrical). Work piece is held on a fixed bed to be usually circular in shape.	

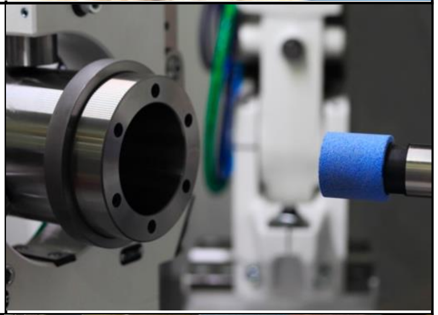
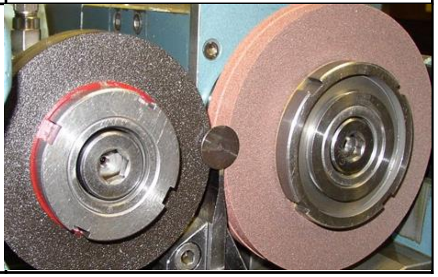
Secondary Processes

Machining (cont.)

Process	Description	Common Application	Process Example
Electrical Discharge Machining (EDM)	• Removes metal by means of electric spark erosion. • Electric spark is used as a cutting tool to cut (erode) the work piece. • Pulsating (on/off) electric charge of high-frequency current is supplied through the electrode to the work piece. • Removing very tiny pieces of metal from the work piece at a controlled rate.	The most common use of EDM is in die making. It can produce very small and accurate parts as well as large items like automotive stamping dies and aircraft body components.	

Secondary Processes

Types of grinding

Process	Description	Common Application	Process Example
Surface Grinding	• It is used for grinding plain flat surfaces. • Either periphery of the grinding wheel (horizontally) or the flat face of the wheel (vertically) is used to perform this operation.	Used for grinding of special contoured surfaces and has high metal removal rates.	
Cylindrical Grinding	There are two sub types: • External or center-type: similar to turning operation, work-piece is rotated between centers and the grinding wheel is fed against it. • Internal: similar to boring operation, work-piece is held in chuck (rotated at a very high speed) against the rotating grinder.	External: crankshafts, axles, spindles, rolls for rolling mills. Internal: to grind rotational parts such as the hardened inside surfaces of bearing races and bushing surfaces.	
Centerless Grinding	• Workpiece is not held between centers. • Workpiece is supported by a rest blade and fed through between the two wheels. • Sometimes, two support rolls are used instead of rest blade to maintain the position of the work.	Used for grinding external and internal cylindrical surfaces. This is specifically used to ground bar stock and chromed bar stock.	

Source: Fundamentals of Modern Manufacturing Materials, Processes, and Systems – Groover, Mikell P., John Wiley & Sons, 2010, 4th edition, PP. 616-617

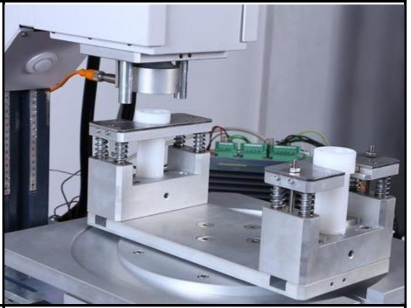
Assembly Processes

Joining

Process	Description	Common Application	Process Example
Welding	• It is a materials joining process wherein two or more parts are coalesced at their contacting surfaces by a suitable application of heat and/or pressure. • Most of the welding processes are accomplished by heat alone, with no pressure applied; others by a combination of heat and pressure; and still others by pressure alone, with no external heat supplied.	Common application includes (but not limited to) construction, such as buildings and bridges, pressure vessels, boilers, piping, and storage tanks, shipbuilding, aircraft, aerospace, and automotive and railroad.	
Brazing	• A joining process wherein a filler metal is melted and distributed by capillary action between the faying surfaces of the metal parts being joined. • No melting of the base metals occurs in brazing; only the filler melts.	It can be used to join any metals including dissimilar metals. It can be used in application where welding cannot be performed, e.g. thin wall plates	
Pressure Welding	• External pressure is applied to produce welded joints either at temperatures below the melting point, which is solid state welding, or at a temperature above the melting point, which is fusion state welding.	Used for metals that are highly ductile or whose ductility increases with increasing temperatures. Applications include joining sheets, wires, and electric components.	

Assembly Processes

Joining (cont.)

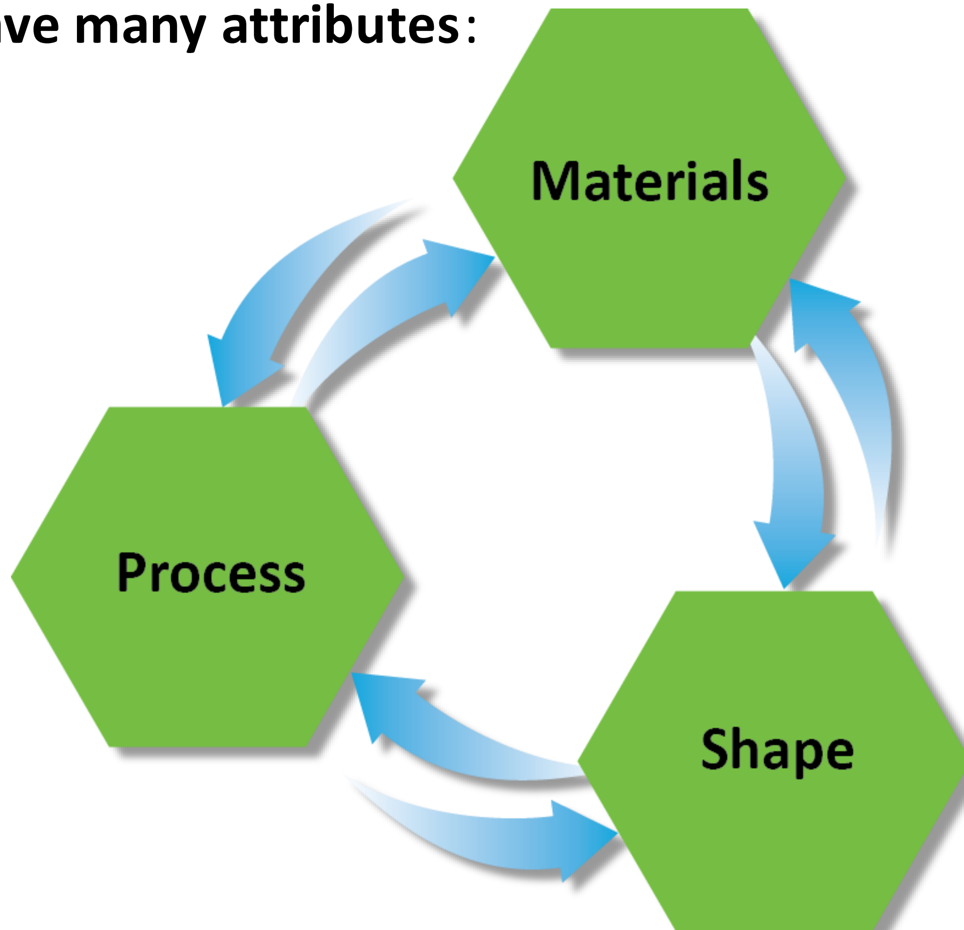
Process	Description	Common Application	Process Example
Spin Welding	• It uses heat generated by rotational friction at the joint line to weld thermoplastic parts with rotationally symmetric joints. • The spin welding machine applies pressure axially while rotating one part against its stationary mate, and the resulting friction generates heat that melts the parts together.	Most efficient method of joining circular parts that require high quality permanent joints. Note: Only applicable for thermoplastic parts.	
Electric Resistance Welding	• It includes the spot, seam, and projection welding processes. • Spot welding occurs when the work is squeezed between two copper electrodes which have an electric current flowing between them. • In seam welding, the electrodes are in the form of opposing wheels which effect a continuous fused joint or seam. • In projection welding, fusion occurs at predetermined locations characterized by embossments, projections, or joint intersections.	This is a widely used welding method to join any carbon steel parts. These welding methods are widely used in automobile final assembly plants to weld the car bodies.	

Process Attributes

Basics

Manufacturing processes have many attributes:

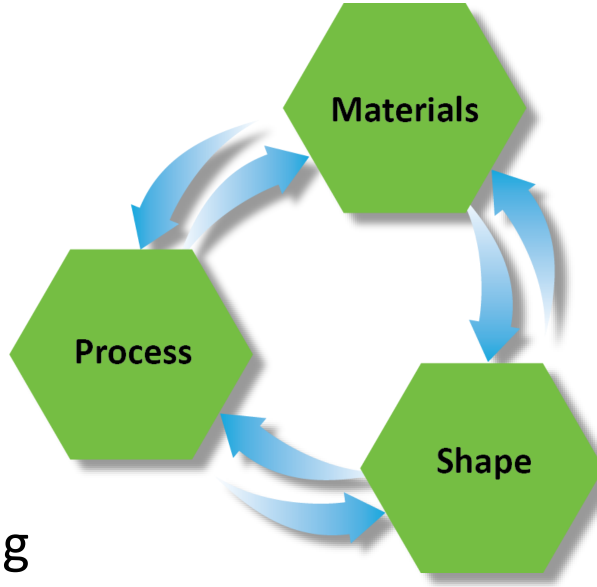
- Tolerance
- Surface roughness
- Mass range
- Size range
- Economic batch size
- Capital costs
- Production rate



Process Attributes

Basics (cont.)

- Only specific materials can be shaped or formed by specific processes
- Specific designs can be achieved with specific processes and materials
- Process-attribute tables provide detailed information on the above-mentioned attributes, thereby helping decision makers in choosing the right manufacturing processes for their design and material requirements



Process Attributes

Machining

Attributes of Machining Processes									
Process	Material	Size Range	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Turning	All except some ceramics	<ϕ3000 mm	±0.05	0.025-25	High	Low	Medium	1+	1-50
Milling	All except some ceramics	<1000 mm^2	±0.1	0.2-25	Medium-high	Medium	Medium-high	1+	1-100
Drilling	All except some ceramics	<ϕ250 mm	±0.05	0.8-12.5	Low-medium	Low	Low-medium	1+	10-500
Grinding	All metals	<ϕ0.5 mm - 2 m 6 m long	±0.005	0.025-6.3	Low-high	Medium	Medium-high	1+	1-100
Threading	All metals	0.1 m – 0.8 m	±0.05	0.2-25	Low-high	Low-high	Medium	1+	1-50

Process Attributes

Machining (cont.)

Attributes of Machining Processes									
Process	Material	Size Range	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Broaching	All metals	25 mm – 3m long	±0.005	0.4-6.3	Low-high	High	Low-Medium	1+	1-400
Honing	All including some ceramics and plastics	Ø6-750 mm 12 m long	±0.005	0.025-1.6	Medium	Low-high	Medium	1+	10-1000
Lapping	All hard materials	500 mm	±0.005	0.012-0.8	Low-high	Low-high	Medium	1+	10-3000
Shaping	All metals	2 m long	±0.05	0.4-25.0	Medium-high	Low	Medium-high	1+	1-50
Planning	All metals	25 m long	±0.05	0.4-25.0	Medium-high	Low	Medium-high	1+	1-50

Process Attributes

Shaping and forging

Attributes of Shaping/Forming Processes									
Process	Material	Weight (kg)/size	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Shape Rolling	Most Metals	10-1000	±0.5	0.8-25	Low-medium	Medium-high	Medium-high	50 000 m	20-500 m/hr
Shape drawing	Steel or Al and/or Cu alloys	10-1000	±0.1	0.2-0.8	Low-medium	Medium-high	Medium	1000 m	10-2000 m/hr
Cold forging and extrusion	Most metals	0.001-50	±0.1	0.4-3.2	Low-medium	Medium-high	High	1000	10-10000
Hot extrusion	Most metals	1-5000	±0.1	1.0-25.0	Medium	High	Medium	1-10	10-100
Hot forging (open die)	Most metals	0.1-200000	±0.5	1.0-25.0	High	Medium	Low	1-100	1-50

Process Attributes

Shaping and forging (cont.)

Attributes of Shaping/Forming Processes									
Process	Material	Weight (kg)/size	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Hot forging (impression)	Most metals	0.01-100	±0.5	1.0-25.0	Medium	High	Medium	100-1000	10-300
Bending	Steel or Al and/or Cu alloys	Any	±0.2	0.2-0.8	Low-medium	Medium	Medium	100-10000	100-100000
Deep Drawing	Steel or Al and/or Cu alloys	Any	±0.1	0.2-0.8	Low-medium	Medium-high	High	>1000	10-10000
Vacuum forming	Thermoplastics	20 m^2	±0.25	Good	Low-medium	Low-Medium	Low-Medium	10-1000	50-350
Blow molding	Thermoplastics	3 m^2	±0.5	Good	Low	Medium-high	Medium-high	1000-1 x 10^6	100-2500
Contact molding	Glass reinforced fibers, thermosetting liquid resins	0.01 – 500 m^2	±0.03-20	Good	High	Low	Low	1-500	1-10

Process Attributes

Casting

Attributes of Casting Processes									
Process	Material	Weight (kg)	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Sand casting	Any, but steel difficult	0.05-No limit	±0.5	3.2-25	Low-medium	Low	Low	<100	1-60
Shell casting	Most metals except (Pb, Zn, Mg, titanium alloys, refractory and zirconium alloys)	0.05-100	±0.2	0.8-6.3	Low-medium	Medium-high	Low-medium	>100	5-200
Plaster casting	Non-ferrous metals (Al, Mg, Zn, Cu)	0.025-25	±0.05	0.8-3.2	High	Medium	Low-medium	10-100	1-10
Investment casting	Any metal	0.005-100	±0.05	0.4-3.2	High	Low-medium	Medium-high	10-1000	1000
Die casting	Non-ferrous metals (Al, Mg, Zn, Cu)	0.05-300	±0.05	0.4-3.2	Low-medium	High	High	500-1000	5-200
Centrifugal casting	Any metal and some ceramics	1-5000	±0.2	1.6-12.5	Low-medium	Medium-high	Medium	<1000	50

Process Attributes

Casting (cont.)

Attributes of Casting Processes

Process	Material	Weight (kg)	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Injection molding	Most thermoplastics, some thermosets, composites and elastomers	6-25	±0.05-8.0	0.2-0.8	Low	Medium-high	High	>10000	60-360
Reaction injection molding	Most thermoplastics, some thermosets, composites and elastomers	6-25	±0.05-8.0	0.2-0.8	Low	Medium-high	High	>1000	60-360
Compression molding	Most thermoplastics, some thermosets, composites and elastomers	0.05-15	±0.05-9.0	0.2-0.8	Low	Medium-high	High	>1000	5-200

Process Attributes

Additive manufacturing

Attributes of Additive Manufacturing								
Process	Material	Part Dimensions	Part Complexity	Dimensional Accuracy	Deposition Rate	Build-Up On	Surface Roughness (µm)	Layer Thickness
LMD (Laser Metal Deposition)	Large materials diversity	Limited by the handling system	Limited	≥0.1 mm	3 – 10 mm^3/s	3D surface and on existing parts	60-100	≥ 0.03 – 1mm
SLM (Selective Laser Melting)	Limited and lower materials diversity	Limited by the process chamber (ϕ 250mm, height: 160 mm)	Nearly unlimited	≥0.1 mm	1 – 3 mm^3/s	Flat surface and flat performs	30-50	≥ 0.03 – 0.1mm

Source: Introduction to Additive Manufacturing Technology – A guide for design engineers, European Powder Metallurgy Association, 2015, 1st edition, pp. 14.

Manufacturing Cost Estimation

Basics

Cost estimations are critical for:

- Determining whether to make an investment to produce a product or part, or to buy it from a vendor (outsourcing decision)
- Deciding if a company should provide a quote on a product for sale to another company
- Also called a **make-versus-buy analysis**

Manufacturing Cost Estimation

Purpose

- Establish the bid price, specifications, quality, and engineering requirements of a product for a quotation or contract
- Verify quotations submitted by suppliers – typically three quotes if possible
- Ascertain whether a proposed product can be manufactured and marketed profitably
- Provide data for make-versus-buy decisions

Manufacturing Cost Estimation

Purpose (cont.)

- Help determine the most economical method, process, and material for manufacturing a product
- Provide a temporary standard for production efficiency and guide operating costs at the beginning of a project
- Support evaluation of design proposals
- Compare different concepts of product designs and manufacturing processes

Manufacturing Cost Drivers

Sample list

Variable costs:

- Materials: raw materials, any other process consumables
- Energy: to run the machines
- Labor: direct labor that goes into your process

Fixed costs:

- Main machine and additional equipment: the main machine(s) for your process
- Tooling: the dedicated tooling or fixtures that are required for your process
- Building: the cost of the space that houses your operations
- Maintenance: the cost of keeping equipment running

Overhead Cost Drivers

Sample list (cont.)

Fixed Costs: (cont.)

- Fixed overhead: non-process-specific operating costs (e.g., management, administration)

Production management:

- Plant supervisor
- Plant administrator
- Plant engineer
- Quality control
- Production control

Other units and administrators:

- Laboratory
- Health and work-safety departments
- Maintenance
- Plant security

Total Cost Calculations

Basics

- **Total cost (TC) = Total fixed cost (FC) + Total variable cost (VC)**
- Average costs:

$$AFC = \frac{\text{Fixed cost}}{\text{Quantity}} = \frac{FC}{Q} \qquad ATC = \frac{\text{Total cost}}{\text{Quantity}} = \frac{TC}{Q}$$

$$AVC = \frac{\text{Variable cost}}{\text{Quantity}} = \frac{VC}{Q}$$

- Average cost is the per-unit cost of a component (this is a good metric to compare between different process options)

See Module 3A for a more detailed cost analysis

Cost Analysis

Example – Plastic bottles

- Plastic bottles are products in wide use on a daily basis—Let's analyze the costs involved in their manufacturing process
- The production process involves the following steps:

Injection Molding

Stretch Blow Molding

Initial Data Collection

Example – Plastic bottles (cont.)

All calculations from here on are based on the following assumptions:

- Monthly rent of production facility = $8,000
- Monthly production capacity = 400,000 bottles
- Average lifetime of machines = 10 years
- Average lifetime of tools = 2 years
- Production period = 1 month
- Production quantity = 400,000 units

Note: Average lifetimes source: Nevada Dept. of Taxation, Personal Property Manual 2011–2012. Actual machine lifetimes are less than stated above due to continuous technological advancements

Depreciation Cost Calculations

Example – Plastic bottles (cont.)

Injection Mold Machine:

- Total Cost (TC) = $13,000
- Salvation Cost = $1,000
- Depreciable Cost = TC – Salvation cost = $12,000
- Expected Lifetime = 10 years
- Monthly Depreciation Percent = 100% of its value/number of months in life (in this case 10 years X 12 months or 120 months.

Calculation: 100%/120 months = 0.8334% depreciation per month

- Monthly Depreciation Value = Depreciation Costs x Depreciation Percent

Calculation: $12,000 x 0.0834% = $100

Depreciation Cost Calculations

Example – Plastic bottles (cont.)

Injection Molds:

- Total Cost (TC) = $8,000
- Salvation cost = $200
- Depreciable Costs = TC – Salvation cost = $7,800
- Expected Lifetime = 2 years
- Monthly Depreciation Percent = 100% of its value/number of months in life (in this case 2 years X 12 months or 24 months.

Calculation: 100%/24 months = 04.167% depreciation per month

- Monthly Depreciation Value = Depreciation Costs x Depreciation Percent

Calculation: $7,800 x 4.167% = $325

Depreciation Cost Calculations

Example – Plastic bottles (cont.)

Blow Molding Machine:

- Total Cost (TC) = $34,000
- Salvation cost = $4,000
- Depreciable Costs = TC – Salvation cost = $30,000
- Expected Lifetime = 10 years
- Monthly Depreciation Percent = 100% of its value/number of months in life (in this case 2 years X 12 months or 24 months.

Calculation: 100%/24 months = 4.167% depreciation per month

- Monthly Depreciation Value = Depreciation Costs x Depreciation Percent

Calculation: $30,000 x 0.834% = $250

Depreciation Cost Calculations

Example – Plastic bottles (cont.)

Blow Molding Molds:

- Total Cost (TC) = $4,000
- Salvation cost = $280
- Depreciable Costs = TC – Salvation cost = $3,720
- Expected Lifetime = 2 years
- Monthly Depreciation Percent = 100% of its value/number of months in life (in this case 2 years X 12 months or 24 months.

Calculation: 100%/24 months = 4.167% depreciation per month

- Monthly Depreciation Value = Depreciation Costs x Depreciation Percent

Calculation: $3,720 x 4.167% = $155

Cost Analysis

Example – Plastic bottles (cont.)

Fixed Cost Type	Total Cost (A)	% Applicable for This Job (B)	Net Fixed Cost for This Job (A*B/100)
Equipment			
Injection molding Machine	$100	60%	$60
Stretch Blow Molding Machine	$250	100%	$250
Equipment Subtotal			$310
Tooling			
Injection Molds	$325	100%	$325
Blow Molding Dies	$155	100%	$155
Tooling Subtotal	$480		$480
Building	$8,000	20%	$1,600
Maintenance	$3,000	20%	$600
Management and Administrative Overheads	$4,000	20%	$800
Total Fixed Cost for This job			$3,790

Note: The building may be used to house other manufacturing processes and office uses, therefore, can't be charged 100% just for this job. Same concept may be applicable to other cost categories as well.

Cost Analysis

Example – Plastic bottles (cont.)

Variable Cost Type	Per Unit Cost (A)	Quantity Produced (B)	Net Variable Cost for This Job (A*B)
Material			
Raw Materials	$0.03	40,000	$1,200
Consumables	$0.06	40,000	$2,400
Materials Subtotal			$3,600
Labor	$0.10	40,000	$4,000
Energy	$0.05	40,000	$2,000
Total Variable Cost	$0.24		$9,600

Marginal Costs

Example – Plastic bottles (cont.)

- **Marginal cost** (MC) is the increase in TC that arises from an extra unit of production
- MC helps answer the following question: How much does it cost to produce an additional unit of output?

$$\textbf{Marginal Cost (MC)} = \frac{\textbf{Change in Total Cost (TC)}}{\textbf{Change in production quantity}}$$

Marginal Costs

Example – Plastic bottles (cont.)

MC calculations are based on the following assumptions (any changes in these assumptions would require new calculations):

- Production capacity of machines for current utilization rate (60% of injection molding machine and 100% of blow molding machine) is 40,000 units/month
- FC remains the same until the 40,000 units/month because it is within the current capacity
  - If production quantity is more than the current capacity, new machines need to be purchased, which would require accounting for that additional investment in your FC
- The newly bought machines and their tooling would be used 100% for this product only
- The per unit rate for VC remains the same regardless of product quantity

Marginal Costs

Example – Plastic bottles (cont.)

- The calculated TC for 40,000 bottles/month was $13,390 (row 1)
- When this quantity is increased from 40,000 to 45,000 units, it requires purchasing new machines; therefore, MC increases
- However, when change is from 45,000 to 80,000 units, the additional FC is offset with the additional production volume (The MC then reduces even further to $0.11/unit)

Quantity	FC	VVC	TC	Average TC	MC
40,000	$3,790	$9,600	$13,390	$0.33	$0.24
45,000	$4,620*	$10,800	$15,420	$0.35	$0.41
80,000	$4,620*	$19,200	$23,820	$0.30	$0.11

Note: The FC calculation table for more than 40,000 production units is provided at the end of this module

Break-Even Analysis

Basics

- The break-even point is the minimum quantity required to make a profit from manufacturing
- It is the point at which the burden of fixed costs (FC) is made equal to the profit made from selling a product

Formulation:

- Total Revenue = selling price x total quantity sold
- TC = total FC + total VC

At the break-even point:

- Total Revenue = TC
- SP x Q = FC + VC x Q
- Q = FC/(SP-VC)

Break-Even Analysis

Basics

- The break-even point is the minimum quantity required to make a profit from manufacturing
- It is the point at which the burden of fixed costs (FC) is made equal to the profit made from selling a product

Formulation:

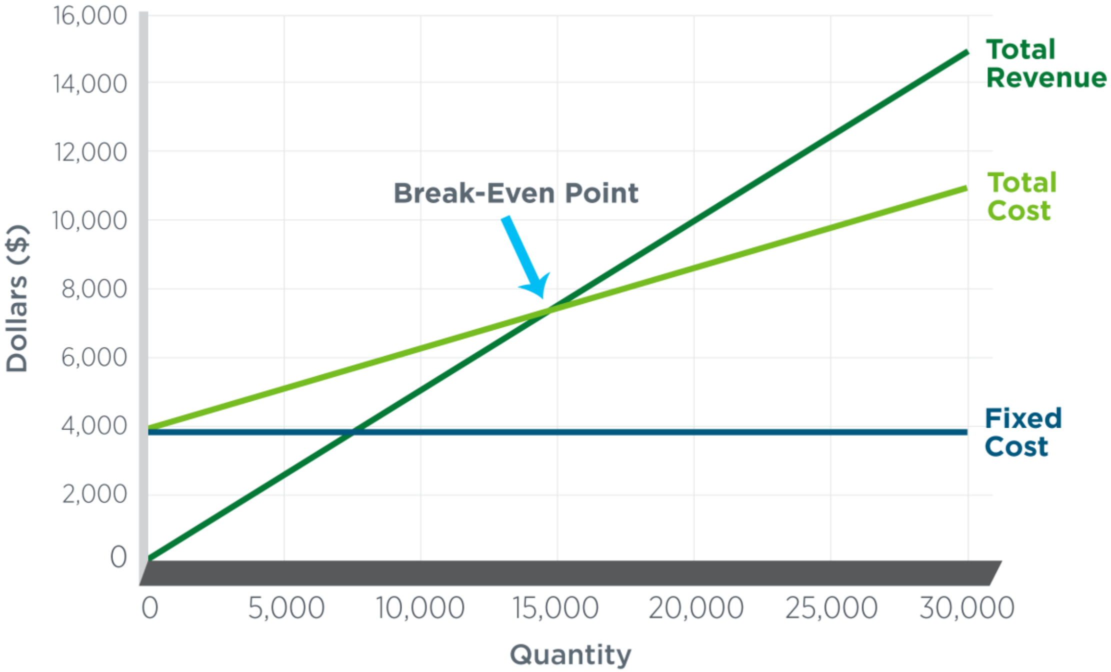
- Total Revenue = selling price x total quantity sold
- Total Cost (TC) = total Fixed Cost (FC) + total Variable Cost (VC)

At the Break-Even (BE) point:

- Total Revenue = TC
- BE is when Sale Price (SP) x Quantity (Q) = FC + VC x Q
- Break Even Quantitate = FC/(SP-VC)

Break-Even Analysis

Example



Quantity	FC ($)	VC ($)	TC ($)	Total Revenue ($)	Profit ($)
0	$3,790	$0	$3,790	$0	$-3,790
1,000	$3,790	$240	$4,030	$500	$-3,520
10,000	$3,790	$2,400	$6,190	$5,000	$-1,190
20,000	$3,790	$4,800	$8,590	$10,000	$1,410
30,000	$3,790	$7,200	$10,990	$15,000	$4,010

- If SP = $0.50,
- Total Revenue
  = SP x Q = $0.50 x Q
- **Break-Even Point**
  = 0.5 x Q
  = 3,790 + 0.24 x Q
  Q = 3,790/(0.5 – 0.24)
  Q≈14577
- TC = FC + VC x Q
  = 3,790 + 0.24 x Q

Manufacturing Process Selection

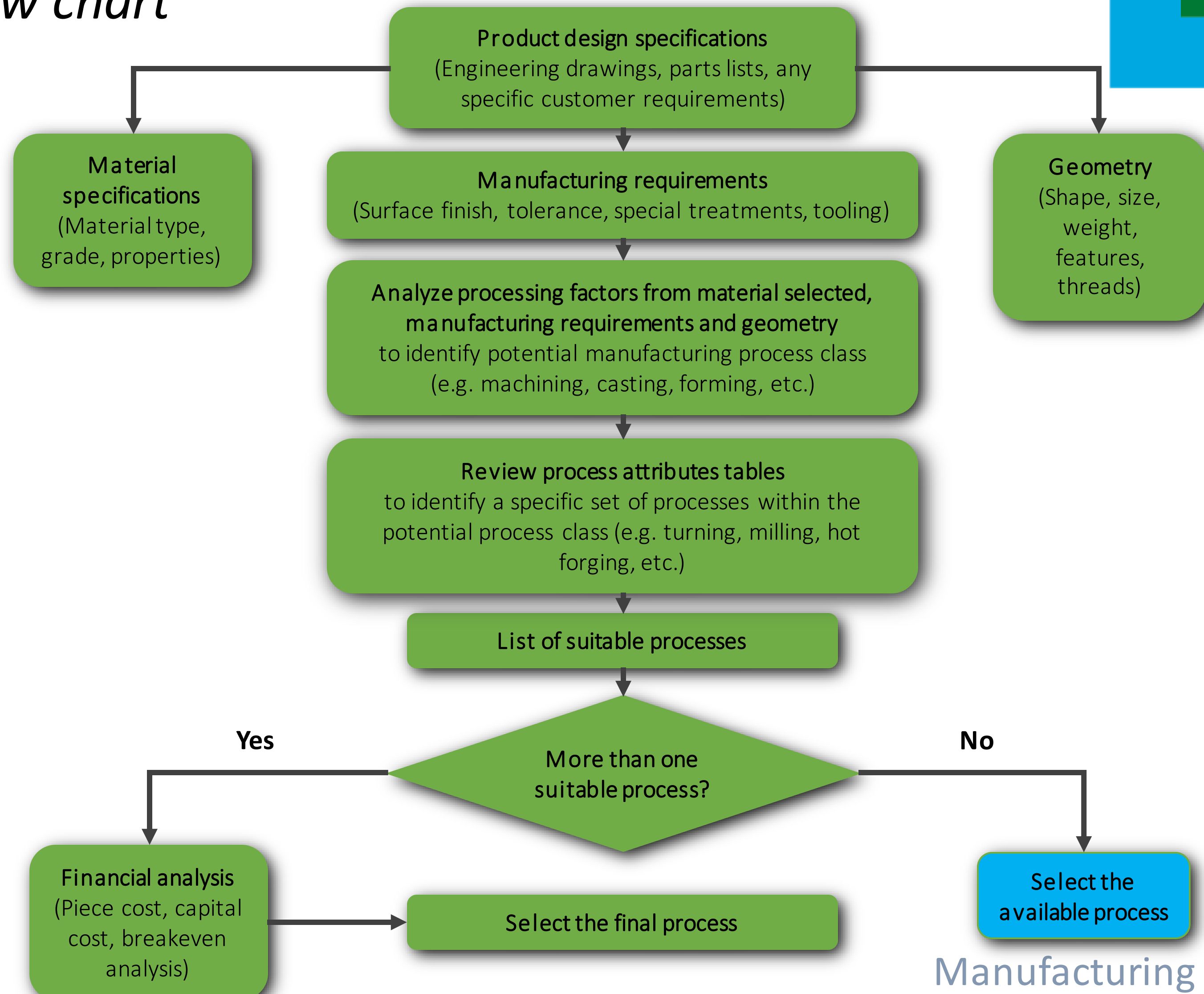
Factors

Selecting the best manufacturing process for a given component depends on several factors such as the following:

- Material selection
- Final shape and appearance
- Desired tolerance and surface finish
- Design requirements
- Tooling cost
- Product market price (if it is a commodity product)
- Safety and environmental concerns

Manufacturing Process Selection

Flow chart



Manufacturing Process Selection

Key steps

- Understand customer (or design) requirements
  - Conduct materials analysis
  - Conduct component geometry analysis (shape, size, features like threading, holes, etc.)
  - Process parameters or manufacturing information analysis (tolerance, surface finish, volume needed, etc.)
- Analyze critical processing factors
  - Determine critical processing factors based on component geometry, materials selection, and manufacturing information
- Review process attributes
  - Compare the candidate processes with respect to processing factors by using process attributes tables
- Identify a suitable process
  - Financial analysis: compare average cost per unit for various process options

Manufacturing Options

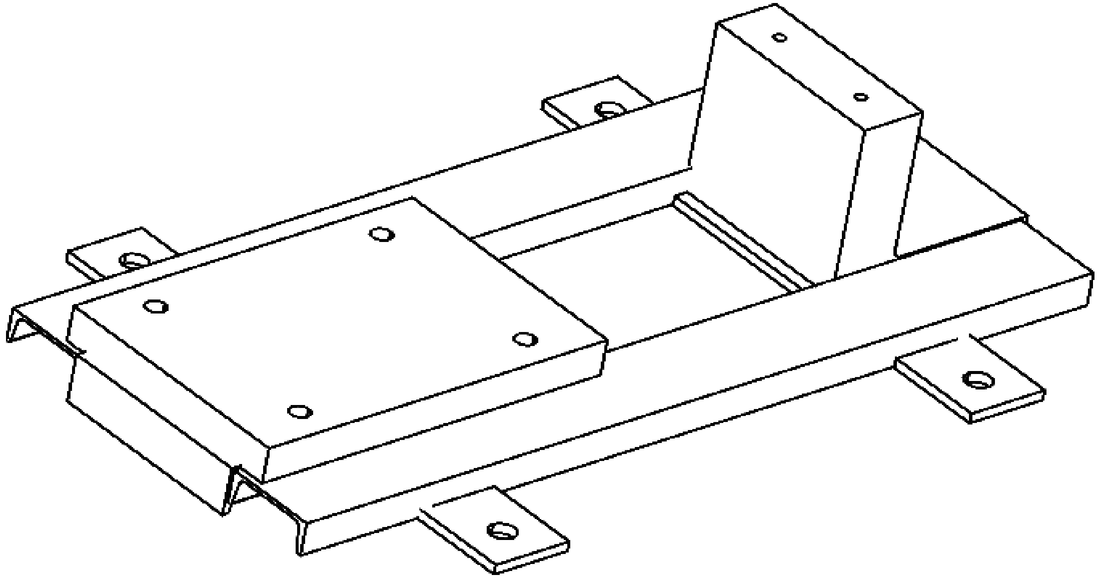
Part geometry

Shape/ Features	Production Method
Flat surfaces	Rolling, planning, broaching, milling, shaping, grinding
Parts with cavities	End milling. Electrical-discharge machining, electrochemical machining, ultrasonic machining, cast-in cavity
Parts with sharp features	Permanent-mold casting, machining, grinding, fabricating
Thin hollow shapes	Slush casting, electroforming, fabricating
Shaping of tubular parts	Rubber forming, expanding with hydraulic pressure, explosive forming, spinning
Curvature on thin sheets	Stretch forming, peen forming, fabricating
Openings in thin sheets	Blanking, chemical blanking, photochemical blanking
Reducing cross-sections	Drawing, extruding, shaving, turning, centerless grinding
Producing Square edges	Fine blanking, machining, shaving, belt grinding
Producing small holes	Laser, electrical-discharge machining, electrochemical machining
Producing surface textures	Knurling, wire brushing, grinding, belt grinding, shot blasting, etching
Detailed surface features	Coining, investment casting, permanent mold casting
Threaded parts	Thread cutting, thread rolling, thread grinding, chasing
Very large parts	Casting, Forging, fabricating
Very small parts	Investment casting, machining
Parts with holes, and/or threads	Drilling, Reaming, Boring, Tapping, Countersinking

Source: Adapted from Swift and Booker (2015)

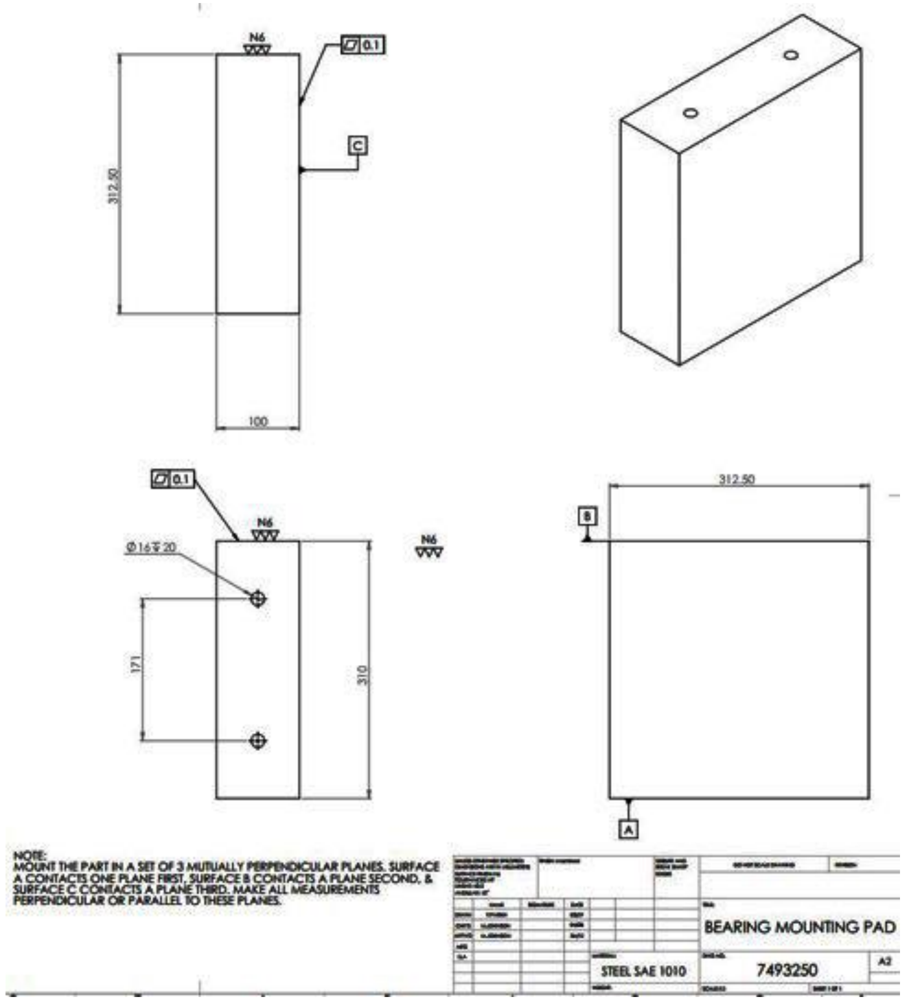
Schematic

Case study – Baseplate assembly for electric motor



Engineering Drawing

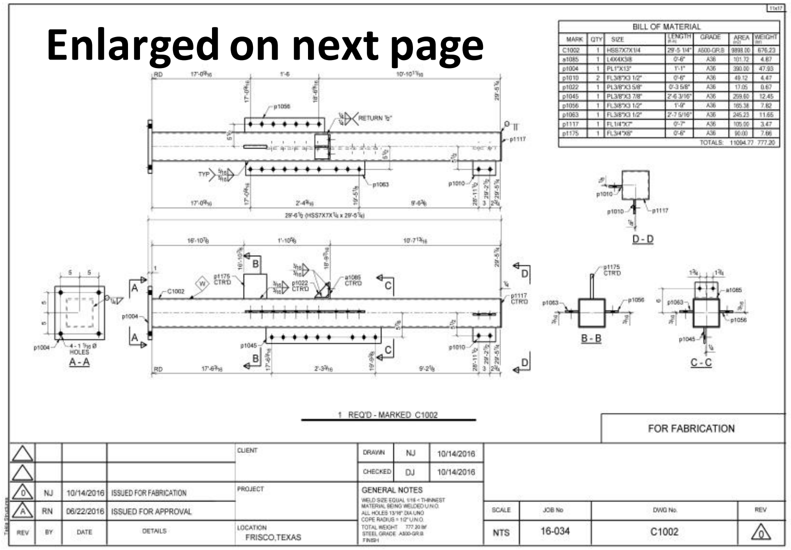
Case study – Baseplate assembly for electric motor (cont.)



Engineering Drawing

Example

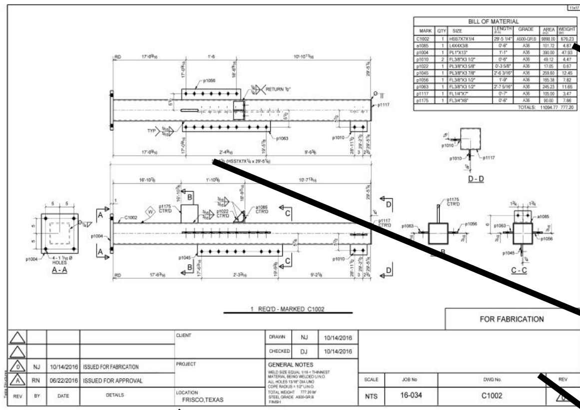
- An engineering drawing should accurately state the geometric features of a product or its components.
- The goal is to clearly define requirements in accordance with conventions for layout nomenclature, size, etc. to enable its production.
- This can include (not limited to):
  - Bill of material
  - General notes
  - Material specifications
  - Drawing origin and version
  - Multiple view
  - Hole specifications



Source: Diagram: Copyright c 2010 paradigm IT Private Limited

Engineering Drawing

Example: Enlarged view of sections



BILL OF MATERIAL						
MARK	QTY	SIZE	LENGTH (ft-in)	GRADE	AREA (in2)	WEIGHT (lbf)
C1002	1	HSS7X7X1/4	29'-5 1/4"	A500-GR.B	9898.00	676.23
a1085	1	L4X4X3/8	0'-6"	A36	101.72	4.87
p1004	1	PL1"X13"	1'-1"	A36	390.00	47.93

Multiple views of product and sections of product.

DRAWN	NJ	10/14/2016
CHECKED	DJ	10/14/2016

GENERAL NOTES

WELD SIZE EQUAL 1/16 < THINNEST
MATERIAL BEING WELDED U.N.O.
ALL HOLES 13/16" DIA UNO
COPE RADIUS = 1/2" U.N.O.
TOTAL WEIGHT 777.20 lbf
STEEL GRADE A500-GR.B
FINISH

SCALE	JOB No	DWG No.	REV
NTS	16-034	C1002	0

REV	BY	DATE	DETAILS
0	NJ	10/14/2016	ISSUED FOR FABRICATION
A	RN	06/22/2016	ISSUED FOR APPROVAL

PROJECT

LOCATION
FRISCO,TEXAS

Source: Diagram: Copyright c 2010 paradigm IT Private Limited

Engineering Specifications

Case study – Baseplate assembly for electric motor (cont.)

Part Number	Part Name	Description	Dimensions (mm) (L x B X H)	Tolerance	Surface Finish (µm)	Quantity	Any Special Features?
UCP211-AST	PILLOW BLOCK BEARING	AST - METRIC SERIES	219 x 60 x 125	8 – 28 µm	0.8	1	N.A.
3GAA103001-BSE	ELECTRIC MOTOR	ABB - M2AA100L 6 1.5 KW	351 x 200 x 237	±0.5 mm	0.8	1	N.A.
91292A241	SOCKET HEAD SCREWS	MCMASTER-CARR	M16 x 2 mm Thread, 45 mm long	--	--	2	N.A.
91292A274	SOCKET HEAD SCREWS	MCMASTER-CARR	M20 x 2.5 mm Thread, 45 mm long	--	--	4	N.A.
7493250	BEARING MOUNTING PAD	MACHINED AND FABRICATED	312.5 x 100 x 312.5	±0.015 mm	0.8	1	2 Holes with Ø16 dia 20 mm deep
7493251	BASE FRAME	MACHINED AND FABRICATED	400 x 300 x 50	±0.25 mm	0.8 – 12.5	1	N.A.
7493252	MOTOR SHAFT	MACHINED AND FABRICATED	Ø55 diam 770 length	±0.015 mm	0.8	1	N.A.

Manufacturing Process Selection

Step-by-step – How to select a suitable option

1. Understand design requirements
2. Analyze critical processing factors
3. Review relevant process-attributes tables
4. Identify suitable processes

Manufacturing Process Selection

Step 1 - Understand design requirements

- There are three parts that need to be machined or fabricated, which include bearing mounting pad, base frame, and motor shaft
- Component materials: all low-carbon steel
- Component shapes:
  - Mounting pad and base frame have flat surfaces with rectangular shapes
  - Motor shaft has round surface
- Special manufacturing features: two holes on bearing mounting pad
- Manufacturing requirements:
  - Design tolerances range from 8–28 micrometers, and surface finish is also in the range of 8–12.5 micrometers for all parts including holes
  - Motor shaft needs to be hardened to withstand the torsional stress

Manufacturing Process Selection

Step 2 - Analyze critical processing factors

Based on the geometry, material, and manufacturing requirements mentioned in Step 1, the initial process required must satisfy the following criteria:

- Be suitable to machine low-carbon steel
- Be able to produce a flat surface and rectangular shapes
- Be able to produce a round surface with a diameter of 55 mm
- Be able to meet the general dimensional tolerance of +/-8 micrometers (µm)
- Be able to meet the surface finish requirements of 12.5 µm
- Be able to produce holes with the above-mentioned tolerance of +/-8 µm

Manufacturing Process Selection

Step 2 - Analyze critical processing factors (cont.)

Based on the geometry, material, and manufacturing requirements mentioned in Step 1, the initial process required must satisfy the following criteria: (cont.)

- Be able to economically produce in batches of 100 (assumed) (It is also assumed that the shape of the raw material will be flat)
- Be able to meet the specific dimensional and geometric tolerances stated on the drawing
- Be able to improve the hardness of motor shaft

Based on these requirements, the initial candidate processes are broaching or milling for flat surface of mounting pad and base frame, turning for the motor shaft, and drilling a hole on the mounting pad

Manufacturing Process Selection

Step 3 - Review relevant process-attributes tables

- Reviewing the machining process attributes tables (S27-28; see relevant rows below), all four processes can meet general tolerance and surface-finish requirements

Process	Material	Size Range	Tolerance (mm)	Surface Finish (µm)	Costs			EOQ	Production rate per hour
					Labor	Equipment	Tooling		
Turning	All except some ceramics	<ϕ3000 mm	±0.05	0.025-25	High	Low	Medium	1+	1-50
Milling	All except some ceramics	<1000 mm^2	±0.1	0.2-25	Medium-high	Medium	Medium-high	1+	1-100
Drilling	All except some ceramics	<ϕ250 mm	±0.05	0.8-12.5	Low-medium	Low	Low-medium	1+	10-500
Broaching	All metals	25 mm – 3m long	±0.005	0.4-6.3	Low-high	High	Low-Medium	1+	1-400
Grinding	All metals	<ϕ0.5 mm - 2 m 6 m long	±0.005	0.025-6.3	Low-high	Medium	Medium-high	1+	1-100

Note: Although broaching and milling can produce flat surfaces, their production rates and cost structures are different (Broaching has a higher production rate and can achieve tighter tolerances than milling, but it is also more expensive than the milling operation)

Manufacturing Process Selection

Step 4 - Identify suitable processes

Based on the review of the process-attributes table, the following processes are recommended for the given jobs:

- Bearing mounting pad: Milling for flat surface, drilling for hole
- Base frame: Milling for flat surface
- Motor shaft: Turning for diameter or round surface, surface hardening and grinding to meet the hardness and tolerance requirements respectively.

Note: Although broaching offers a greater production rate and can produce tighter tolerance, the desired production quantity can be achieved along with the required tolerance and surface-finish specifications with lower investments. Therefore, milling is recommended over broaching for producing the flat surfaces. However, if there are more options with less obvious choices, one can calculate the average TC for the option using the methods described previously to determine the lowest cost option.

Resources

- Turning
  https://v.ftcdn.net/01/07/59/25/700_F_107592507_IsVzgls5saZIPa1AeP6EuM3yWQLEx5N5_ST.mp4
- Milling
  https://v.ftcdn.net/01/34/51/13/700_F_134511365_G546DqFEsvnob4P5lGUbBkLdrSgNjNWp_ST.mp4
- Drilling
  https://v.ftcdn.net/01/27/58/86/700_F_127588642_XTAt07UoBr1tvEuhD6lRE5WqhAkwXExu_ST.mp4
- Grinding
  https://v.ftcdn.net/00/36/97/31/700_F_36973197_XNCHEwNjD1WtIhTYRLr0PDfhwd2CGvqd_ST.mp4
- 3D printing
  https://v.ftcdn.net/01/44/42/33/700_F_144423391_TXIBLUFKu2fN2mfuRRAtkonzN8HCdlGw_ST.mp4

Resources

(cont.)

- Casting https://www.youtube.com/watch?v=LmjAQGvSrF0
- Roll forming https://www.youtube.com/watch?v=uGEYZHriKZk
- Injection molding https://www.youtube.com/watch?v=b1U9W4iNDiQ
- Forging https://www.youtube.com/watch?v=hSUp-e7zu0g
- Threading https://www.youtube.com/watch?v=9IvWuXjCVbg
- Reaming https://v.ftcdn.net/00/79/23/02/700_F_79230212_xsxgXmVD3ORY5eL0igojeUhqpYb5OloC_ST.mp4
- Boring https://v.ftcdn.net/01/07/57/45/700_F_107574502_9ADKfORVouLtVKOLtV3V62rTDDsFlXhl_ST.mp4
- Drilling boring reaming https://www.youtube.com/watch?v=ZGU1zP7KPbY

Resources

(cont.)

- Counter sinking https://www.youtube.com/watch?v=kLbX8ISF5UA
- Electrical discharge machining https://www.youtube.com/watch?v=kSIFiWSRpBw
- Sheet metal stamping https://www.youtube.com/watch?v=Fid1r3tG538
- Wire+ arc Am https://youtu.be/_WrhWf9XLHM
- Shaping https://youtu.be/Omsyy-RiaqU
- Planing https://www.youtube.com/watch?v=W8-_9ziKiao
- Slotting https://www.youtube.com/watch?v=hE2aKmINlU4

Appendix – Slide 51 Follow-Up

Fixed cost for production over 40000 units

Fixed Cost Type	Total Cost (A)	% Applicable for This Job (B)	Net Fixed Cost for This Job (A*B/100)
Equipment			
Injection Molding Machine 1	$100	60%	$60
Stretch Blow Molding Machine 1	$250	100%	$250
Injection molding Machine 2	$100	100%	$100
Stretch Blow Molding Machine 2	$250	100%	$250
Equipment Subtotal			$660
Tooling			
Injection Molds 1	$325	100%	$325
Blow Molding Dies 1	$155	100%	$155
Injection Molds 2	$325	100%	$325
Blow Molding Dies 2	$155	100%	$155
Tooling Subtotal			
Building	$8,000	20%	$1,600
Maintenance	$3,000	20%	$600
Management and Administrative Overheads	$4,000	20%	$800
Total Fixed Cost for This job			$4,620