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Design for manufacturing

Reference for designing parts and assemblies that can be manufactured reliably, at cost, at scale — with material selection, tolerance tables, cost benchmarks, and DFM rules per process.

REVISION	ISSUED	OWNER	COMPANION
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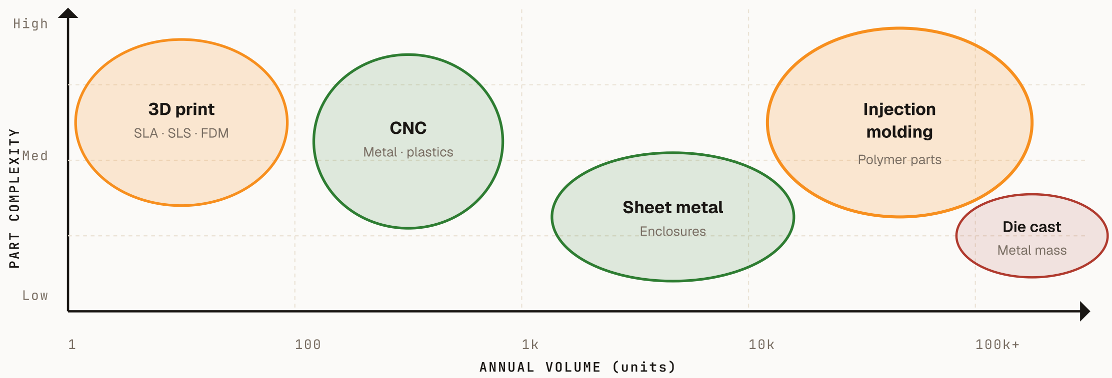
ABSTRACT

DFM (Design for Manufacturing) is the discipline of aligning design intent with manufacturing reality. Most cost overruns and yield problems originate in design decisions that surface during pilot production: wall thicknesses that won't fill, tolerances that won't hold, panelisations that can't be tested, assembly sequences that can't be balanced on the line.

Section 1 covers mechanical DFM (process selection, injection molding, sheet metal, CNC). Section 2 covers electronics DFM (PCB design rules, panelisation, design for test). Section 3 covers assembly DFM. Section 4 sets the review checkpoints from concept to pilot.

PROCESS SELECTION — VOLUME VS. COMPLEXITY



PROCESS SELECTION BY ANNUAL VOLUME AND PART COMPLEXITY. WRONG MATCH = SILENT QUOTE INFLATION BY THE SUPPLIER.

CONTENTS

1. Mechanical DFM

Mechanical decisions made in CAD determine unit cost, yield, and cosmetic quality. The expensive failures are the ones the supplier silently absorbs by quoting higher.

1.1 Process selection

Match the process to volume, complexity, and cosmetic requirement. Tooling is the dominant variable below ~50 k annual volume.

PROCESS	VOLUME SWEET SPOT	TOOLING COST (USD)	PER-PART CYCLE	BEST FOR
FDM 3D print	1–100	$0	hrs	Concept, fit-check, jigs
SLA / SLS print	1–500	$0	hrs	Cosmetic prototypes, complex
CNC machining	1–5 000	$0	mins	Metal, prototype, low volume
Sheet metal	500–50 000	$1k–10k	secs	Enclosures, brackets
Vacuum forming	1k–20k	$2k–8k	secs	Trays, covers, packaging
Injection molding	5 000+	$5k–80k	15–60 s	Polymer parts at scale
Die casting	50 000+	$20k–100k	30–90 s	Metal mass production
Sand casting	100–5 000	$200–2k per pattern	mins	One-off metal parts

> TOOLING COST BENCHMARKS (SINGLE-CAVITY, MID-TIER CHINESE SHOP)
>
> - Small simple polymer part (<50 g, no slides): **$3 000–8 000** - Medium polymer part (50–200 g, 1–2 slides): **$8 000–25 000** - Large complex polymer (>200 g, multiple slides): **$25 000–80 000** - Family mold (multiple parts in one tool): + 50–80 % vs single - Multi-cavity (2-up, 4-up, 8-up): +30 % per cavity - Tooling life: 100 k shots (P20 steel), 500 k–1 M (NAK80 / H13)

1.2 Plastic resin selection

Five resins cover ~90 % of consumer hardware. Match to use environment, not to cost.

RESIN	TYPICAL USE	COST ($/KG)	STRENGTHS	WEAKNESSES
ABS	Enclosures, toys	2–3	Toughness, easy mold	UV-yellows, low chem
PC	Lenses, safety	4–6	Optical clarity, impact	Scratches, stress-crack
PC + ABS	Premium enclosures	3–5	Toughness + finish	Higher cost
PP	Living hinges, food	2–3	Chemical resistant	Low stiffness
TPU	Cables, grips	4–8	Elastic, durable	Slow cycle
Nylon (PA66)	Gears, structural	4–6	High strength	Moisture absorbs
POM (Acetal)	Bearings, snaps	4–7	Self-lubricating	Adhesion poor
PMMA	Display covers	3–5	Optical, weatherable	Brittle

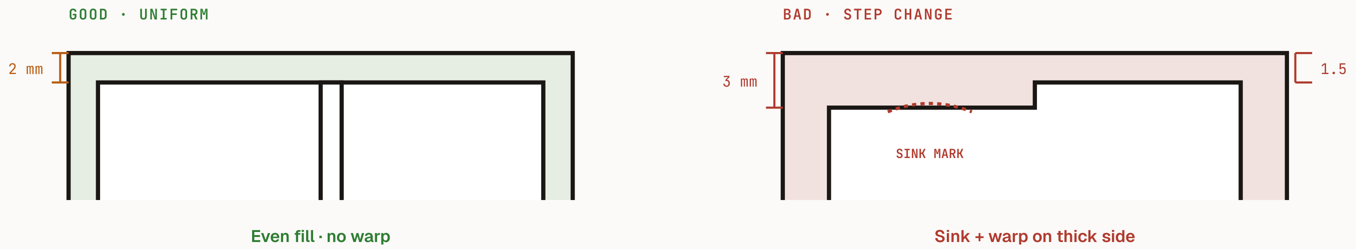
1.3 Tolerance grades

ISO 2768 covers general tolerances when none are specified on the drawing. Specify tighter only where it matters.

GRADE	LINEAR ±0.5–3 MM	LINEAR 50–120 MM	ANGLE ±10 MM	TYPICAL USE
f (fine)	±0.05	±0.15	±10'	Mating surfaces, bearings, optics
m (medium)	±0.1	±0.3	±30'	Visible mechanical features
c (coarse)	±0.2	±0.8	±1°	Non-fitting features
v (very coarse)	±0.5	±2.0	±2°	Cosmetic, rough castings

1.4 Injection molding rules

WALL THICKNESS — UNIFORM VS. STEP CHANGE



RULE Keep wall thickness uniform within ±50 %. Add ribs (0.5–0.7× wall) instead of thickening.

FIG 1.1 WALL THICKNESS MUST STAY UNIFORM WITHIN ±50 %. STEP CHANGES CAUSE SINK MARKS (VISIBLE DEPRESSION) ON THE THICK SIDE. ADD RIBS INSTEAD OF THICKENING.

- **Wall thickness**
  Nominal **1.5–3.0 mm** for most polymers. Uniform within ±50 %. Below 1.2 mm risks short shots; above 3.5 mm risks sinks and 2× cycle time.
- **Radii**
  Internal corners ≥ **0.5× wall** thickness. Sharp corners concentrate stress and slow fill; molded radii at 0.5R minimum survive ejection.
- **Ribs**
  Height **2–3× wall**, base thickness **0.5–0.7× wall**, draft **0.5°+**. Higher than 3× wall buckles; thicker than 0.7× wall causes sinks on the show surface.
- **Bosses**
  Outer Ø **2× screw diameter**, base radius **0.25× wall**. Self-tapping screws need 2.0–2.2× screw OD; heli-coil inserts: 2.5×.
- **Gate location**
  Discuss with the moulder before CAD lock. Pin-point (small parts), fan/edge (cosmetic), submarine (auto-trim), hot-runner (multi-cavity).
- **Cooling time**
  Approx `t = wall² × 0.5` seconds for ABS. A 3 mm wall = 4.5 s cooling; 2× wall = 4× cooling.
- **Mold draft**
  0.5°–2° minimum on vertical faces. 3°–5° on textured surfaces (VDI 27+ requires 3°+).

DRAFT ANGLE — MOLD RELEASE GEOMETRY

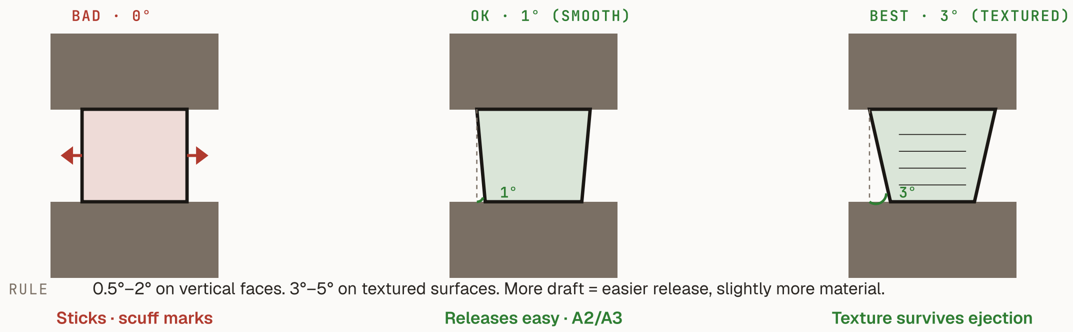


FIG 1.2 DRAFT ANGLE = MOLD RELEASE GEOMETRY. 0° CAUSES SCUFF MARKS DURING EJECTION; 1–2° RELEASES CLEANLY ON POLISHED SURFACES; 3°+ REQUIRED ON TEXTURED.

1.5 Sheet metal rules

FEATURE	RULE	NOTE
Bend radius (inside)	≥ material thickness	1.5× safer; tighter cracks
Hole-to-bend distance	≥ 2.5× material thickness	Closer warps the hole
Hole edge spacing	≥ 2× material thickness	Avoids tear-out
Slot length	≤ 6× width	Longer needs reinforcement
Hem allowance (open)	0.5 mm gap min	Closed hem: contact
Tab/slot tolerance	±0.1 mm typical	Punch wear loosens over time
Min bend leg	4× material thickness + bend radius	Shorter loses grip in press brake
Material thicknesses	0.5 / 0.8 / 1.0 / 1.2 / 1.5 / 2.0 / 3.0 mm	Standard stock

1.6 CNC machining rules

Geometry

- **Pocket depth-to-width ≤ 3:1**
- **Internal radius ≥ end-mill radius (3 mm typical, 1 mm with smaller)**
- **Thin walls ≥ 0.5 mm aluminium, 0.8 mm steel**
- **Threaded holes: M2 min in aluminium, M1.6 with care**
- **Boss height ≤ 4× diameter to avoid chatter**
- **Deep slots ≤ 4× width (chip evacuation)**

Surface finish

- **Ra 6.3 µm**
  milled, no finish pass
- **Ra 1.6 µm**
  standard finish (2 passes)
- **Ra 0.8 µm**
  fine finish (extra passes, +20 % cost)
- **Ra 0.4 µm**
  polish required, +50 % cost
- **Anodise Type II (decorative): adds 0.025 mm per side**
- **Anodise Type III (hard): adds 0.05–0.1 mm per side**

WATCH OUT — SILENT QUOTE INFLATION

Most "DFM issues" surface as the supplier silently quoting a longer cycle time, looser tolerance, or higher reject rate. A DFM review with the supplier before quoting often saves 15–30 % on unit cost and catches the issues that would otherwise show up at first samples. Budget 1–3 days of engineering time per part.

2. Electronics DFM

PCB design intent is communicated through Gerbers, drill files, and assembly drawings. DFM at the PCB and assembly level is the difference between 95 % first-pass yield and 75 %.

2.1 PCB design rules

FEATURE	STANDARD (8/8)	ADVANCED (5/5)	HDI (3/3)
Trace / space (mil)	8 / 8	5 / 5	3 / 3
Trace / space (mm)	0.20 / 0.20	0.125 / 0.125	0.075 / 0.075
Annular ring	0.20 mm	0.15 mm	0.10 mm
Drill (mech via)	0.30 mm	0.20 mm	0.15 mm
Drill (laser via)	n/a	0.15 mm	0.10 mm
Aspect ratio (depth/Ø)	8:1	10:1	12:1
Soldermask dam	0.10 mm	0.075 mm	0.05 mm
Silkscreen line	0.15 mm	0.10 mm	0.10 mm
Min text height	0.8 mm	0.6 mm	0.5 mm
Edge-to-copper	0.20 mm	0.20 mm	0.20 mm

2.2 Standard layer stacks

STACK	COPPER WEIGHT	DIELECTRIC	USE
2L FR-4	1 oz / 1 oz	1.6 mm total	Simple logic, prototype
4L FR-4	1/H/H/1	1.6 mm total	Most consumer electronics
6L FR-4	1/H/H/H/H/1	1.6 mm	RF, high-speed digital
8L+ FR-4	mix	1.6–2.4 mm	Complex SoC, BGA
4L impedance-controlled	1/H/H/1	50 Ω SE / 100 Ω diff	USB, MIPI, Ethernet

Standard impedance reference (50 Ω single-ended, FR-4, 4-layer):

- **Trace width: 0.30 mm over 0.20 mm dielectric**
- **Trace width: 0.10 mm for HDI 4-layer 0.05 mm dielectric**
- **Verify with manufacturer's impedance calculator (Polar Si9000, supplier's tool).**

2.3 Component placement

- **Component-to-component spacing**
  Minimum 0.5 mm SMD, 1 mm for hand-rework accessibility.
- **Orientation consistency**
  Group similar components in same orientation to reduce machine-vision verification time and AOI false-positives.
- **Polarity markings**
  Capacitors, diodes, ICs clearly marked on silkscreen.
- **Fiducial marks**
  Three global fiducials (preferred) or two diagonal. Local fiducials for 0402 + finer or BGA.

- **Test points**
  1.0 mm diameter pads, 2.54 mm spacing for ICT. At least one per net.
- **Keep-out zones**
  1 mm around connectors, 2 mm around antennas, 3 mm around shielding cans.

2.4 Panelisation

- **Panel size**
  Match supplier standard. Common: **18" × 24"** (457 × 610 mm) or **250 × 350 mm**.
- **Routing vs. V-scoring**
  V-scoring for simple rectangles (cheaper, faster). Routing for complex outlines, internal cutouts, or PCBs <1 mm thick.
- **Tabs and mouse-bites**
  1.5–2 mm tabs, 4–6 mouse-bites per tab (0.5 mm hole × 0.7 mm spacing).
- **Edge rails**
  5–10 mm wide with global fiducials and tooling holes (3.175 mm typical).
- **Panel utilisation**
  Target 70 %+ for cost; below 50 % drives per-board cost up sharply.

2.5 Design for test (DFT)

- **Test points on every net**
  Especially power rails, signals, programming interfaces. ICT coverage target: 85 %+ of nets.
- **Programming interface**
  JTAG, SWD (Cortex), UART, or ISP. Pin header or pogo pad (0.65 mm pitch typical).
- **Boundary scan**
  IEEE 1149.1 for complex digital boards (>50 nets).
- **Manufacturing test mode**
  Firmware support for self-test (LEDs, sensors, comms, RF self-check).
- **Functional test fixtures**
  Design alongside the product, not after. Budget 2–4 weeks NRE + $3 k–15 k per fixture.

3. Assembly DFM

Assembly is where part count, sequence, and fixturing decisions surface as cost on the production line.

3–8s	50–100k	95 %
PER SCREW	UNITS	TARGET
typical fastener cycle time	typical jig refresh cycle	first-pass yield at full ramp

3.1 Part-count reduction

- **Combine features**
  Snap-fit replacing screw + nut; live hinge replacing pin + clip; overmolded grip replacing separate elastomer.
- **Eliminate fasteners**
  Each screw is **3–8 s of cycle time**. At 10 k units, that's 8–20 hours of line time. At 100 k, that's 80–200 hours.
- **Standardise fasteners**
  One screw type per assembly. Three variants doubles the operator pick-time and inventory.

3.2 Assembly sequence

- **Linear stack**
  Components added from one direction. Simpler line, fewer flips, faster cycle.
- **Self-aligning features**
  Asymmetric mating prevents mis-orientation. Pin-and-slot beats two-bolt symmetric.
- **Visual confirmation**
  Each step has a clear visual cue for the operator. Coloured connectors, asymmetric profiles.
- **Test gates**
  Functional test at each major sub-assembly stage, not just at end of line. Catches 60–80 % of issues earlier.

3.3 Line balance + cycle time

Cycle time per station should match. Bottleneck station = UPH (units per hour) ceiling.

STATION	TYPICAL CYCLE	NOTES
SMT placement	0.05–0.2 s/part	Machine-rate-limited
Through-hole insertion	5–15 s	Manual unless wave/selective solder
Reflow	4–8 min total	Conveyor speed sets throughput
Hand assembly (per screw)	3–8 s	Skill + tool dependent
Functional test	30–120 s	Test coverage trade-off
Cosmetic inspection	5–15 s	Operator fatigue limit
Pack	10–30 s	Per unit + master carton

3.4 Tolerance stack-up example

A 4-part assembly with critical clearance:

- **Part A (PC injection): nominal 25.0 mm ± 0.2 mm (process capability ±2σ)**
- **Part B (sheet metal): nominal 24.5 mm ± 0.1 mm**
- **Part C (gasket, foam): nominal 0.3 mm ± 0.05 mm**

- **Part D (PCB thickness): 1.6 mm ± 0.16 mm**
- **Linear stack: total ±(0.2 + 0.1 + 0.05 + 0.16) = ±0.51 mm**
- **RSS stack (statistical): $\sqrt{(0.2^2 + 0.1^2 + 0.05^2 + 0.16^2)}$ = ±0.28 mm**

Linear stack is conservative (worst case); RSS assumes independent normal distributions. Use RSS for ±3σ design, linear for safety-critical clearances.

4. Review checkpoints

DFM is a discipline, not a single review meeting. Apply at four checkpoints.

#	CHECKPOINT	WHEN	DELIVERABLE	OWNER
1	Concept review	Pre-CAD	Process + material short-list	ME + supplier
2	Detailed design	Mid-CAD (50 %)	Per-part DFM walk-through	ME + EE + supplier
3	Pre-tooling	CAD locked (100 %)	DFM sign-off, tolerance stack	ME + supplier + QC
4	Pilot production	First off-tool samples	Cp/Cpk, yield baseline	ME + QC + production

COST OF LATE CATCHES — THE 1-10-100 RULE

Catching a DFM issue at concept review costs ~1 unit of engineering time. Catching the same issue at detailed design costs ~10 units (CAD rework, BoM update, supplier re-quote). Catching it at pilot production costs ~100 units (tooling rework, sample iteration, schedule slip).

Front-load the discipline. Three days of supplier DFM review in week 6 saves three weeks of tooling rework in month 4.

FINAL NOTE. the goal of DFM is not to constrain creativity, but to surface the manufacturing implications of design decisions while the cost of changing them is still low. Every dimension on every part is also a tolerance, a process choice, and a cost.