Product Design for Manufacture and Assembly

Third Edition

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Product Design for Manufacture and Assembly

Third Edition

MANUFACTURING ENGINEERING AND MATERIALS PROCESSING

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Preface

This third edition of *Product Design for Manufacture and Assembly* includes updating of the data in all chapters of the book. In addition, a comprehensive set of problems and student assignments have been added to each chapter. This is because the book has been used in the past as the assigned text for university-level courses and the addition of these problem sets has made the new edition substantially more useful as a text book. The overall aim is to provide a text that can not only serve as a reference text for design and manufacturing engineers in industry, but will also serve as a basic text for courses in product design and design for manufacture. A comprehensive coverage of the factors that influence the ease of assembly and manufacture of products for a wide range of the basic processes used in industry is provided.

The introductory chapter has been updated to include more recent case studies of the application of design for manufacture and assembly (DFMA) techniques in industry, while still illustrating the effect that DFMA has had on U.S. industry as a whole. In Chapters 3 and 5, the extended versions of the classification schemes of the features of products that influence the difficulty of handling and insertion for manual, high-speed automatic and robot assembly have been added. This allows realistic student assignments to be added to these chapters. The chapter on printed circuit board assembly (Chapter 6) has been updated to reflect the changes in industry that have taken place since the previous edition, in particular the increased emphasis on the use of surface-mounted devices.

The remaining chapters on basic manufacturing processes have been updated with more recent data and comprehensive sets of problems and assignments added to each chapter. In Chapter 11 on design for powder metal processing, a discussion on design for powder injection molding has been added, as this technique has become more widely used in industry.

Each chapter includes some cost information on materials, labor, and machine operations. This information is representative of typical costs at the time of publication and does not necessarily indicate costs applicable at the current time. Costs obviously fluctuate over a period of time. The relative costs indicated in these data are probably suitable for a reasonable comparison between product designs and processing methods to be made.

As for the previous editions, we thank the various companies that have supported research on DFMA at the University of Rhode Island and the graduate students who have contributed to the research. The techniques developed from this research have become widely used in industry and have had a significant influence on the development of more competitive products that are both simpler in configuration and easier to manufacture with reduced overall costs.

Geoffrey Boothroyd
Peter Dewhurst
Winston A. Knight

Preface to the Second Edition

This second edition of *Product Design for Manufacture and Assembly* includes three new chapters, describing the processes of sand casting, investment casting, and hot forging. These chapters, combined with the chapters describing design for machining, injection molding, sheet metalworking, die casting, and powder metals, cover a wide range of the most basic forming processes used in industry.

In addition, substantial material has been added to the introductory chapter illustrating the effects that the application of design for manufacture and assembly (DFMA) has had on U.S. industry as a whole. Chapter 2, dealing with the selection of materials and processes for manufacture, now includes further material describing material selection specifically and the economic ranking of processes using a new software tool.

Chapter 3, dealing with product design for manual assembly, includes an updated special section dealing with the effect of design on product quality. Finally, additional material has been added to Chapter 15 discussing links between computer-aided design (CAD) solid models and design analysis tools.

As for the previous edition, we thank the various companies who have supported research on DFMA at the University of Rhode Island and the graduate students who have contributed to the research. We particularly acknowledge the help of Allyn Mackay, on whose work the new chapter on investment casting is largely based.

Finally, thanks are due to Shirley Boothroyd for typing much of the new material and to Kenneth Fournier for preparing some of the additional artwork.

Geoffrey Boothroyd
Peter Dewhurst
Winston A. Knight

Preface to the First Edition

We have been working in the area of product design for manufacture and assembly (DFMA) for over 20 years. The methods that have been developed have found wide application in industry—particularly U.S. industry. In fact, it can be said that the availability of these methods has created a revolution in the product design business and has helped to break down the barriers between design and manufacture; it has also allowed the development of concurrent or simultaneous engineering.

This book not only summarizes much of our work on DFMA, but also provides the details of DFMA methods for practicing and student engineers.

Much of the methodology involves analytical tools that allow designers and manufacturing engineers to estimate the manufacturing and assembly costs of a proposed product before detailed design has taken place. Unlike other texts on the subject, which are generally descriptive, this text provides the basic equations and data that allow manufacturing and assembly cost estimates to be made. Thus, for a limited range of materials and processes, the engineer or student can make cost estimates for real parts and assemblies and therefore, become familiar with the details of the methods employed and the assumptions made.

For practicing manufacturing engineers and designers, this book is not meant as a replacement for the DFMA software developed by Boothroyd Dewhurst, Inc., which contains more elaborate databases and algorithms, but rather provides a useful companion, allowing an understanding of the methods involved.

For engineering students, this book is suitable as a text on product design for manufacture and assembly and, in fact, is partially based on notes for a two-course sequence developed by the authors at the University of Rhode Island.

The original work on design for assembly was funded at the University of Massachusetts by the National Science Foundation. Professor K. G. Swift and Dr. A. H. Redford of the Universities of Hull and Salford, respectively, collaborated with G. Boothroyd in this early work and were supported by the British Science Research Council.

The research continued at the University of Rhode Island and was supported mainly by U.S. industry. We thank the following companies for their past and, in some cases, continuing support of the work: Allied, AMP, Digital Equipment, DuPont, EDS, Ford, General Electric, General Motors, Gillette, IBM, Instron, Loctite, Motorola, Navistar, Westinghouse, and Xerox.

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We would also like to thank our colleagues, the late Professor C. Reynolds who collaborated in the area of early cost estimating for manufactured parts, and Professor G. A. Russell who collaborated in the area of printed circuit board assembly.

Finally, thanks are due to Kenneth Fournier for preparing much of the artwork.

Geoffrey Boothroyd
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Authors

Geoffrey Boothroyd is emeritus professor of Industrial and Manufacturing Engineering at the University of Rhode Island, Kingston. Professor Boothroyd, the author or coauthor of more than 100 journal articles, is also the coauthor or coeditor of several books, including *Fundamentals of Machining and Machine Tools*, 3rd edition (with W. A. Knight) and *Automated Assembly and Product Design,* 2nd edition (published by Taylor & Francis), together with *Automatic Assembly* (with C. Poli and L. E. Murch), and *Applied Mechanics* (with C. Poli) (published by Marcel Dekker). Additionally, Professor Boothroyd has served as the coeditor of the Taylor & Francis series *Manufacturing Engineering and Materials Processing*. A Fellow of the Society of Manufacturing Engineers, he is a member of the National Academy of Engineers, among other professional societies. Professor Boothroyd received a PhD (1962) and DSc (1974) in Engineering from the University of London, England. His numerous honors and awards include the National Medal of Technology and the SME/ASME Merchant Medal.

Peter Dewhurst is a professor of Industrial Engineering and a professor of Mechanical Engineering at the University of Rhode Island, Kingston. During his career, he has made groundbreaking contributions in the areas of metal machining, metal deformation theory, design for manufacture, and the design of minimum weight structures. Since 2000, he has been the principal investigator for two research programs from the National Science Foundation, and one from Sandia National Laboratories. Awards in recognition of his work include the Sir Charles Reynold Fellowship, the F.W. Taylor Medal from the International College of Production Research, and the National Medal of Technology. He has taught senior and graduate classes in design for manufacture and assembly at URI for over two decades and was awarded the URI Carlotti Award twice for research excellence.

Winston A. Knight is emeritus professor of Industrial and Systems Engineering at the University of Rhode Island, Kingston. Dr. Knight, the author of over 120 professional papers and articles, is the coauthor of several textbooks including *Fundamentals of Machining and Machine Tools*, 3rd edition (with Geoffrey Boothroyd) published by Taylor & Francis. Dr. Knight's research interests have focused on various aspects of manufacturing engineering, including product design for manufacture, design for recycling and the environment, together with machine tool technology, group technology, and aspects of CAD/CAM. Dr. Knight is a Fellow of the Society of Manufacturing Engineers and Fellow of the International Academy of Product Research (CIRP). He received a BSc (1963) degree and PhD (1967) from the University of Birmingham, England and MA (1980) from Oxford University, England.

Nomenclature

A	area contained within perimeter; length of the rectangular envelope enclosing a nonrotational machined component
A_{o}	base time allowance for trim die manufacture
A_{c}	area of cavity plate; projected area of mold base; cross-sectional area of the undeformed chip
A_{f}	cavity surface area; average fault rate of insertions
A_{H}	area of through holes in forging
A_{h}	cross-sectional area of the hole
A_{hol}	hole-modified area = $A_h/3$
A_{m}	area of the machined surface
A_{p}	projected area of one part or pattern piece
A_{pb}	trim punch block area
A_{pl}	area of the sand casting pattern plate
A_{s}	area of the sheet metal used for each part; projected shot area
A_{t}	total area enclosed for all regions at a level in a powder metal part
A_{tb}	trim die block area
A_{tp}	total projected area of all parts or pattern pieces in the mold
A_{u}	usable die set plate area
A_0	part cross-sectional area before deep drawing
A_1	part cross-sectional area after deep drawing
a_{d}	depth of the groove to be machined
a_{e}	depth of the cut in horizontal milling; width of the cut in vertical milling
a_{p}	depth of the cut in turning, vertical milling, and grinding; width of the cut in horizontal milling
a_{r}	rough grinding stock on the radius of a rotational workpiece
a_{t}	total depth of the material to be removed
B	small batch size; width of the rectangular prismatic envelope enclosing a nonrotational machined component
B_{o}	basic bench standard value for forging dies
B_{L}	batch length in furnace
B_{r}	effective blow rate of forging equipment
B_{s}	batch size of parts
b	reduction exponent; index for the cavity milling standard equation
b_{w}	width of the surface to be machined
C	thickness of the rectangular prismatic envelope enclosing a nonrotational machined component
C_1	cost of one pair of cavity and core inserts
C_{1000}	cost per operation for a 1000 lb power hammer
C_{20}	tool accessory cost for 20 ton (178 kN) press for one-level part
C_{ab}	cost of mold base with custom work
C_{ac}	cost of standard mold components or actuators
C_{af}	cost of pattern assembly fixture
C_{ap}	programming cost per part in cents
C_{AP}	press capacity

C_{b}	cost of the mold base; unit cost of the binder
C_{bo}	cost per cluster for breakout
C_{box}	cost of core box for sand casting
C_{bu}	cost to apply backup coats
C_{c}	cost of tungsten carbide per unit volume; grinding cost when recommended conditions are used; cost of the replacement component
C_{cl}	cost of a single-cavity mold
C_{cf}	operator cost per cluster for cutoff
C_{cl}	cost per cluster for cleaning or leaching; sand casting cleaning cost
C_{cn}	cost of the n-cavity mold
C_{co}	cost per cluster for cutoff
C_{core}	core processing cost
C_{csd}	cost of core sand for one casting
C_{D}	forging die cost per part
C_{d}	mold cost
C_{db}	coefficient for debinding
C_{DIE}	total forging die cost
C_{dl}	cost of single-cavity die; drilling cost per board
C_{dm}	mold-making cost
C_{dman}	forging-die manufacturing cost
C_{dmat}	material cost for forging die block
C_{dn}	cost of n-cavity die
C_{ds}	cost of the die set
C_{e}	cost of energy for melting metal
C_{en}	furnace energy cost
C_{f}	cost of feeding each part; cost of the induction melting unit; feedstock unit cost
C_{F}	cost of the feeder
C_{fk}	fixed furnace cost per weight of metal
C_{FL}	furnace operating cost per unit time
C_{fp}	cost of mold base fixed plates
C_{fs}	cost of setup for cutoff
C_{g}	production cost for a grinding operation
C_{i}	cost of automatic insertion per part; cost per unit weight of the infiltrant material
C_{ip}	process cost per pattern or core
C_{it}	insertion cost
C_{lk}	furnace labor cost per weight of metal
C_{m}	cost of polymer material per part; material cost; cost of the metal ready to pour
C_{man}	forging die manufacturing cost rate
C_{mat}	cost of the part material
C_{mf}	cost of furnace for alloy; cost of metal in finished sand casting
C_{mi}	cost of the furnace for iron
C_{min}	minimum production cost (minimum value of C_{pr})
C_{ml}	cost of labor for melting metal
C_{mp}	pouring cost; process cost for sand casting
C_{ms}	total cost of metal at the furnace spout
C_{n}	cost of n identical pairs of cavity and core inserts
C_{nh}	operator cost per cluster for a pneumatic hammer
C_{ns}	cost of setup for the pneumatic hammer
C_{o}	cost per unit volume of impregnated oil; resin or polymer

C_{op}	cost per operation of forging equipment
C_{p}	cost of powder per unit weight; grinding cost when maximum power is used; processing cost of one part; cost of electricity
C_{pca}	cost per part to assemble cluster
C_{pi}	cost of the set of pattern impressions
C_{pm}	cost of wax material; cost of pattern mounting plates
C_{po}	production cost when maximum power is used
C_{pr}	production cost per machined component; cost to apply primer coats to cluster; production cost per piece in forging; programming cost per component style
C_{pt}	cost of the sand casting pattern
C_{px}	complexity factor for sheet metal stamping
C_{r}	relative feeder cost
C_{rm}	cost of raw alloy; cost of raw material for sand casting
C_{rp}	material cost of part
C_{rs}	cost of a resink for forging dies
C_{ro}	cost per operation of forging equipment relative to 1000 lb power hammer
C_{rwc}	cost for reworking a faulty component
C_{rw}	total cost for reworking faulty components
C_{s}	setup cost per part type
C_{sb}	processing cost per board
C_{set}	setup cost per part for forging
C_{st}	setup cost for a set of parts of the same package style
C_{t}	cost of providing a new or freshly ground tool; cost of tool steel per unit weight; total handling and insertion cost per part
C_{tca}	cost to assemble one cluster
C_{tl}	cost of a single-aperture trim tool
C_{tn}	cost of a multiaperture trim tool
C_{tp}	total cost of the pattern piece
C_{tpa}	pattern assembly cost
C_{trim}	total cost of trimming tools
C_{trm}	material cost for flash trimming tools
C_{tw}	cost of cutoff tool wear per cluster
C_{vp}	cost of mold base variable plates
C_{w}	wheel wear and wheel changing costs in grinding
c	dimensionless diametral clearance between peg and hole; “individual” reduction exponent
c_{d}	average concentration of the remaining binder in the compact
c_{f}	pattern clearance factor
c_{h}	hand clearance
c_{i}	initial concentration of the binder
D	diameter of the hole; diameter of the circular cylinder enclosing a rotational machined component; part diameter; depth of the part
D_{a}	probability of a defective product
D_{bar}	equivalent bar diameter for forging
D_{bs}	binder–solvent interdiffusional coefficient
D_{c}	carbide insert diameter; cavity depth
D_{d}	die case diameter
D_{e}	equivalent part diameter
D_{eh}	equivalent hole diameter

D_h	hole diameter or circumscribing circle diameter for the hole
D_i	average probability of assembly defects per operation
D_{li}	circumscribing circle diameter for level i, $i = 1, 2, 3, \ldots$
D_o	circumscribing circle diameter for the whole part
D_{pi}	punch stock material diameter, punch $i = 1, 2, 3, \ldots$
D_{pm}	density of the pattern material
D_0	blank diameter in deep drawing
D_1	cup diameter in deep drawing
d	diameter of peg; depth
d_a	outer diameter of the surface machined by facing
d_{ave}	average cavity depth for forging
d_b	inner diameter of the surface machined by facing
d_c	cavity depth in forging
d_g	grip size
d_m	diameter of the machined surface
d_{max}	maximum section diameter
d_t	diameter of cutting tool
d_w	diameter of the work surface
E	orienting efficiency of a part
E_{ct}	cost of electricity
E_f	required energy capacity of forging equipment
E_m	overall efficiency of machine-tool motor and drive systems; minimum energy for melting a metal
E_{ma}	manual assembly efficiency
E_o	equipment factory overhead ratio
e	eccentricity of force on peg; strain in sheet metal forming
F	press force; maximum separating force
F_c	profile complexity factor
F_{fc}	fixed furnace cost per volume of metal; forging complexity factor
F_{ff}	furnace efficiency
F_{ins}	benchwork factor for forging dies
F_{lck}	trim punch lock factor
F_{lw}	plan area correction factor
F_m	maximum feed rate for standard feeder
F_{PWB}	basic cost factor for printed circuit boards
F_{trm}	load required for flash removal by trimming press
F_r	required feed rate
f	displacement of the tool relative to the workpiece, in the direction of feed motion per stroke or per revolution of the workpiece or tool; separating force on die or mold; factor increase in output; press force
f_d	die plate thickness correction factor
f_p	parting surface adjustment factor
G_f	gate factor for sand casting pattern
H	height of feature; specific heat capacity
H_b	specific heat capacity of the binder
H_f	latent heat of fusion; feedstock specific heat capacity
H_F	height of the furnace opening
H_p	specific heat capacity of powder material
H_s	specific heat

H_{st}	the maximum stack height
H_{t}	heat-transfer coefficient
h	wall thickness or gage thickness
h_{cl}	minimum clearance
h_{cm}	section thickness
h_{d}	die plate thickness; depth of the part or pattern piece
h_{f}	fill height of the powder
h_{fp}	thickness of ejector, riser, and stripper plates
$h_{\max}$	maximum wall thickness
h_{p}	combined thickness of core and cavity plates
h_{pt}	height or thickness of the mold base
K	compaction pressure correction factor; distance traveled by a point on the tool cutting edge relative to the workpiece during the machining time; coefficient for cavity milling standard equation
K_{v}	volumetric expansion factor
k	thermal conductivity
k_{b}	binder thermal conductivity
k_{f}	feedstock thermal conductivity
k_1	constant representing wheel wear and wheel-changing costs per unit metal removal rate in grinding; coefficient of machine hourly rate
k_2	constant representing rough grinding time multiplied by the metal removal rate
k_{p}	powder material thermal conductivity
k_{r}	powder compression ratio
L	length of the part or feature; length of the peg in a section in the hole; depth of insertion; length of the circular cylinder enclosing a rotational machined component
L_{blk}	length of the forging die block
L_{b}	total length of bend lines
L_{D}	total life for forging dies
L_{e}	equivalent part length
L_{FL}	furnace overall length
L_{h}	length of the hole machined by EDM
L_{HT}	sintering zone length of the furnace
L_{i}	lower punch length for punch i, $i = 1, 2, 3, \ldots$
L_{plt}	platter length for forging
L_{s}	clamp stroke
L_{tbas}	basic trimming tool life quantity
L_{trm}	trimming tool life quantity
LV	life volume
L_{w}	length of the wire
l	overall length of the part in the direction of feeding
l_{b}	printed circuit board length
l_{f}	life of a tool element
l_{p}	length of pathway between machine tools; powder loss during PM processing; printed circuit board panel length
l_{rd}	distance forklift truck travels to respond to request
l_{s}	section length
l_{t}	length of the broach
l_{w}	length of the machined surface

M	total machine tool and operator rate; equipment operating cost per unit time
M_1	manufacturing hours to make one item
$M_{1,n}$	average manufacturing hours to make each of n items
M_{bu}	machine and operator rate for backup coat application
M_{cp}	pattern or core material cost
M_{dl}	operating cost of the drilling machine in $/h
M_{ds}	equivalent manufacturing hours for die set
M_{e}	manufacturing point score or hours for the ejector pin system
M_{f}	mass of feedstock material
M_{i}	machine and operator rate
M_{m}	mass of feedstock in cavity
M_{me}	minimum melt energy
M_{n}	total manufacturing hours for making n items
M_{p}	sheet metal die manufacturing points; block area factor for trimming die
M_{pc}	manufacturing points for custom punches
M_{pn}	manufacturing die points for number and length of bends
M_{po}	basic sheet metal die manufacturing points; manufacturing hours for part or pattern piece size
M_{pr}	machine and operator rate for primer coat application
M_{ps}	manufacturing points for standard punches
M_{px}	manufacturing points for geometrical complexity
M_{r}	mass of feedstock material in runners
M_{s}	manufacturing hours for nonflat parting surface; surface patches per unit projected area for forging dies
M_{sl}	operational cost in $/h
M_{t}	manufacturing points for the trim tool
M_{to}	basic manufacturing points for the trim tool
M_{tot}	total manufacturing hours for mold making
M_{x}	manufacturing hours for geometrical complexity
m	multicavity cost index, usually 0.7
m_1	coefficient of machine hourly rate
m_{rc}	cutoff rate
N_1	normal force at point 1
N_2	normal force at point 2
N_{b}	number of bends to be formed in one die; number of blows or strokes required for a forging
N_{c}	number of contacts in a connector; number of impressions or cavities in sand casting; number of identical forgings produced per cycle
N_{d}	number of different punch shapes or sizes; number of assembly errors in one product
N_{e}	number of ejector pins
N_{fl}	number of fuller dies for a forging
N_{fw}	number of parts across furnace width
N_{h}	number of hits with turret press
N_{hd}	number of holes or depressions
N_{imp}	number of forging impressions
N_{min}	theoretical minimum number of parts
N_{mw}	number of line workers for sand casting
N_{op}	number of operations required for a forging

N_{p}	number of custom punches
N_{pi}	number of identical impressions on the pattern plate
N_{r}	number of replacement tool items
N_{tp}	number of different components of the package style
N_{rs}	number of resinks possible for forging dies
N_{sp}	number of surface patches to be machined
N_{st}	number of stitches in the lacing of a wire harness
N_{t}	number of part types
N_{w}	number of wires assembled simultaneously onto a wire harness jig
n	number of workpieces; number of cavities; Taylor tool life index (or exponent) in machining; number of assembly operations
n_{bd}	indicator for bending die required (1 or 0)
n_{bk}	indicator for blocker die required (1 or 0)
n_{c}	number of cores per pattern piece
n_{cb}	number of backup coats
n_{cl}	number of clearances required
n_{cp}	number of primer coats
n_{e}	efficiency of induction furnace
n_{edg}	indicator for edger die required (1 or 0)
n_{fin}	indicator for finishing die required (1 or 0)
n_{fl1}	indicator for first fuller die required (1 or 0)
n_{fl2}	indicator for second fuller die required (1 or 0)
n_{gp}	number of gates per casting
n_{l}	number of lifters per pattern piece; number of leads
n_{lp}	number of boards per panel length
n_{L}	number of printed circuit board layers
n_{p}	number of boards per panel
n_{pa}	number of pieces per pattern
n_{pc}	number of parts per cluster
n_{pd}	number of patterns (cavities) per mold
n_{pl}	number of core and cavity plates
n_{r}	frequency of cutting strokes
n_{ps}	number of panels per stack
n_{rs}	number of resinks required for forging dies
n_{s}	number of surface patches on the part or pattern piece
n_{sb}	indicator for scale-breaking die required (1 or 0)
n_{sf}	indicator for semifinishing die required (1 or 0)
n_{sm}	number of printed circuit board sides processed
n_{so}	number of supplemental cuts per cluster
n_{sp}	number of side pulls per pattern piece
n_{t}	rotational speed of the cutting tool
n_{ud}	number of unscrewing devices per pattern piece
n_{w}	rotational speed of the workpiece on the worktable
n_{wp}	number of boards in the printed circuit board panel width
P	compaction pressure; force on peg; perimeter length to be sheared on sheet metal part
P_{b}	payback period
P_{cm}	core production rate for sand casting
P_{e}	electrical power required for machining

P_{ff}	sand casting plant efficiency
P_{i}	recommended injection pressure; uncorrected compaction pressure
P_{j}	injection power
P_{l}	metal loss rate
P_{m}	power required in machining
P_{mp}	sand casting production rate
P_{p}	perimeter of custom punches; packing pressure
P_{psr}	pattern piece setup rate
P_{r}	perimeter of the projected area
P_{rv}	proportion of runner volume
P_{s}	specific cutting energy—power required to remove unit volume of material in unit time
P_{v}	production volume
P_{w}	perimeter of through holes in forging
Q	hole machining factor
Q	flow rate
Q_{lv}	life production volume for forgings
Q_{mx}	maximum wax injection flow rate
Q_{rb}	basic resink quantity for forging dies
Q_{rs}	resink quantity for forging dies
q_{c}	proportion by weight of the infiltrant material
q_{o}	proportion by volume of the impregnated oil
R_1	batch furnace heating rate
R_2	batch furnace cooling rate
R_{a}	arithmetical mean surface roughness
R_{cl}	worker rate for cleaning sand castings
R_{co}	operator rate for cutoff
R_{ds}	mold-making rate
R_{f}	cost of using feeding equipment
R_{i}	cost of using an automatic workhead per part
R_{mp}	worker rate for the sand casting line
R_{nh}	operator rate for breakout
R_{p}	production rate (parts per unit time); number of repeats
R_{t}	tool making rate for sand casting
r	inside bend radius; tool profile radius; average time for a factor increase in output divided by the time for the first output expressed as a percentage
r_{c}	cutting tool corner radius
S	profile cutting speed
S_{a}	volume shrinkage for metal
S_{bw}	bench standard for forging dies
S_{c}	cavity standard for forging dies
S_{ca}	setup time for cluster assembly
S_{co}	setup time for cutoff
S_{d}	cavity spacing in forging
S_{ds}	time to set up the mold on the injection machine
S_{e}	cavity edge distance in forging
S_{lk}	die lock standard for forging dies
S_{g}	percentage of scrap for sand castings
S_{m}	scrap rate for sand casting

S_{ml}	milling standard for forging dies
S_{n}	number of shifts worked per day
S_{nh}	setup time for the pneumatic hammer
S_{pa}	setup time for pattern assembly
S_{sl}	scale loss in forging (%)
S_{z}	capacity of the furnace
s_{b}	spacing between boards in a printed circuit board panel
s_{e}	edge spacing in printed circuit board panel
T	part thickness; die thickness; temperature
T_{1}	time of production for the first unit
$T_{1,100}$	assumed basic DFA time value
$T_{1,\mathrm{B}}$	adjusted DFA time for batch size B
$T_{1,\mathrm{x}}$	average time of production for x units
T_{B}	burn-off time
T_{blk}	thickness of the forging die block
T_{bt}	base time for forging die block preparation time
T_{bw}	bench-working time for forging dies
T_{cav}	cavity time for forging dies
T_{cl}	sand casting cleaning time
T_{dl}	dowel machining time for forging dies
T_{edg}	edger machining time for forging dies
T_{f}	flash land thickness in hot forging
T_{fl}	flash gutter time for forging dies
T_{int}	initial time allowance for trim die manufacture
T_{i}	injection temperature; insertion time per part
T_{lay}	forging die layout time
T_{lk}	additional time for trimming die manufacture for locked dies
T_{lp}	time to load and unload each panel
T_{m}	mold temperature
T_{mill}	cavity milling time for forging dies
T_{pl}	block planning time for forging dies
T_{pol}	cavity polishing time for forging dies
T_{prep}	forging die block preparation time
T_{rm}	unsoldering or removal time
T_{rs}	time to solder the replacement component
T_{s}	sintering time
T_{set}	setup time for forging equipment
T_{sm}	processing time per board side in seconds
T_{tp}	time to manufacture a flash trimming punch
T_{trd}	manufacturing time for a flash trimming die
T_{w}	web thickness in forging
T_{x}	ejection temperature; time to produce the xth unit
t	machine cycle time; part thickness; tool life (machining time between regrinds or between cutting edge replacements); binder extraction time
t_{a}	basic assembly time for one part
t_{b}	basic time to insert a peg through the stack of parts; board thickness.
t_{c}	nonproductive time in grinding including wheel dressing time and time to load and unload the workpiece; tool life giving minimum cost machining; cooling time

t_{cl}	time for applying the first primer coat
t_{ca}	time for assembling the cluster
t_{cb}	time for applying one backup coat
t_{cg}	time for cutting through a single gate
t_{cl}	time for loading the cluster for cutoff
t_{co}	time for cutting off all parts from the cluster
t_{cp}	time for applying each subsequent primer coat
t_{ct}	tool changing time
t_{d}	time to dress a wire; dry cycle time
t_{dc}	solvent debinding time
t_{enl}	entry film layer thickness for hole drilling
t_{enl}	exit film layer thickness for hole drilling
t_{f}	mold fill time; transportation time for a roundtrip by a forklift truck
t_{FB}	batch furnace batch sintering time
t_{FL}	furnace throughput time per part
t_{gc}	grinding time for recommended conditions
t_{gf}	finish grinding time
t_{gp}	grinding time when maximum power is used; time to reposition the cluster from one gate to next
t'_{gp}	corrected value of t_{gp} to allow for wheel costs
t_{gr}	time for rough grinding
t_{h}	basic time for handling a "light" part
t_{i}	manual insertion time for a peg into the hole; average assembly time per operation; injection time
t_{l}	nonproductive time incurred each time the workpiece is clamped and undamped or loaded and unloaded in the machine tool
t_{m}	machining time—time between engagement and disengagement of feed motion; time to assemble N_{w} wires attached to a connector onto a wire harness jig
t_{ma}	total assembly time for the product
t_{mc}	machining time when cutting speed for minimum cost is used
t_{mp}	machining time when maximum power is used
t_{n}	time for assembling N_{w} wires simultaneously onto a wire harness jig
t_{nh}	breakout cycle time for the pneumatic hammer
t_{oc}	open and close time
t_{p}	time penalty for insertion of a peg through the stack of parts; time for assembling wires with crimped contacts into a connector; packing time
t_{pa}	time for pattern assembly
t_{pw}	additional part handling time due to weight
t_{r}	total reset time; tool life for a cutting speed of v_r
t_{s}	spark-out time in grinding; time for assembling a connector having soldered contacts
t_{sc}	time for supplemental cut through runner or sprue
t_{so}	time for repositioning cluster for supplemental cuts
t_{st}	time for lacing a wire harness
t_{t}	total cycle time
t_{tr}	transportation time per workpiece
t_0	minimum debinding cycle time
U	ultimate tensile strength
U_{i}	upper punch length; punch i, $i = 1, 2, 3, \ldots$

V	part volume; required production volume
V_c	cavity volume
V_{fc}	volume of metal in finished casting
V_{fl}	volume of flash per unit length of the flash line
V_m	volume of material to be removed by machining
V_p	part volume
V_r	volume of material in runners
V_s	shot size
V_{sc}	value of scrap
V_{trd}	material volume for the flash trimming die
V_{trp}	material volume for the flash trimming punch
υ	cutting speed—relative velocity of the tool relative to the workpiece
υ_{av}	average cutting speed
υ_c	cutting speed giving minimum cost machining; press closing speed
υ_f	feed speed in milling
υ_F	belt or feed speed for furnace
υ_{max}	maximum cutting speed
υ_o	press opening speed
υ_{po}	cutting speed giving maximum power
υ_r	cutting speed for a tool life of t_r
υ_{trav}	traverse speed in grinding
W	weight of the part; width of the part or feature
$\dot{W}$	heat flow rate
W_a	manual operator rate
W_{blk}	width of forging die block
W_c	workhead cost
W_f	width of the flash land in hot forging
W_{max}	maximum weight per unit area for the furnace
W_p	poured weight of casting
W_{pa}	operator rate for pattern assembly
W_{plt}	platter width for hot forging
W_{pr}	weight of material poured into a single mold
W_r	relative workhead cost
W_{sm}	dry weight of the shell mold
W	thickness of the gate
w_1	width of the chamfer on the peg
w_2	width of the chamfer on the hole
w_b	printed circuit board width
w_p	printed circuit board panel width
w_F	belt or feeder width for furnace
w_s	section width
w_t	width of the grinding wheel
X_i	inner complexity value
X_o	outer complexity value
x	number of identical units
Y_1	yield stress after 1.0 percent strain
Y_d	casting yield
X_p	profile complexity value
Y_s	equivalent shear yield stress of the material

Y_{sm}	shell mold yield
Z_{pw}	metal removal rate when maximum power is used in grinding
Z_w	metal removal rate
Z_{wc}	metal removal rate for recommended conditions in grinding
Z_{wmax}	maximum metal removal rate
α	thermal diffusivity; alpha symmetry of a part
α_m	material load factor for hot forging
α_s	shape load factor for forging
β	beta symmetry of a part; limiting deep-drawing ratio
β_m	material die life factor for hot forging
β_s	shape die life factor for hot forging
θ	angle of force on the peg; angle of bend of the sheet metal part
θ_b	burn-off temperature
θ_s	sintering temperature
θ_1	semiconical angle of chamfer on the peg
θ_2	semiconical angle of chamfer on the hole
μ	coefficient of friction
ρ	part density
ρ_a	density of alloy; powder apparent density
ρ_f	feedstock theoretic density
ρ_i	density of iron; infiltrant material wrought density
ρ_o	density of the impregnated oil
ρ_p	part density, including infiltrant
ρ_t	density of the tool steel
ρ_w	equivalent wrought density of the material
Φ_c	critical solids loading of feedstock
Φ_m	mass-based solids loading
Φ_v	volumetric powder loading
Ψ_{fl}	angle of fuller dies on the die block

1

Introduction

1.1 What Is Design for Manufacture and Assembly?

In this chapter we shall assume that "to manufacture" refers to the manufacturing of the individual component parts of a product or assembly and "to assemble" refers to the addition or joining of parts to form the completed product. Hence, the term "design for manufacture" (or DFM) means the design for the ease of manufacture of the collection of parts that form the product after assembly and "design for assembly" (or DFA) means the design of the product for the ease of assembly. Design for manufacture and assembly (DFMA) is a combination of DFA and DFM.

DFMA is used for three main activities:

1. As the basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure to reduce manufacturing and assembly costs, and to quantify the improvements.
2. As a benchmarking tool to study competitors' products and quantify manufacturing and assembly difficulties.
3. As a should-cost tool to help control costs and to help negotiate suppliers contracts.

1.2 History

For many years, "design for ease of manufacture," also referred to as "manufacturability" or "producibility," has been considered important. However, until the 1970s no quantitative measures of the manufacturability of a product and its component parts were readily available to the designer without waiting for supplier estimates.

That designers should give more attention to possible manufacturing problems has been advocated for many years. A competent designer should be familiar with manufacturing processes to avoid adding unnecessarily to manufacturing costs during design. Traditionally, it was expected that engineering students should take "shop" courses which gave some familiarity with manufacturing processes. Unfortunately, in the 1960s, shop courses disappeared from university curricula in the United States; they were not considered suitable for academic credit. Now, engineering graduates joining design departments often have little knowledge of manufacturing processes.

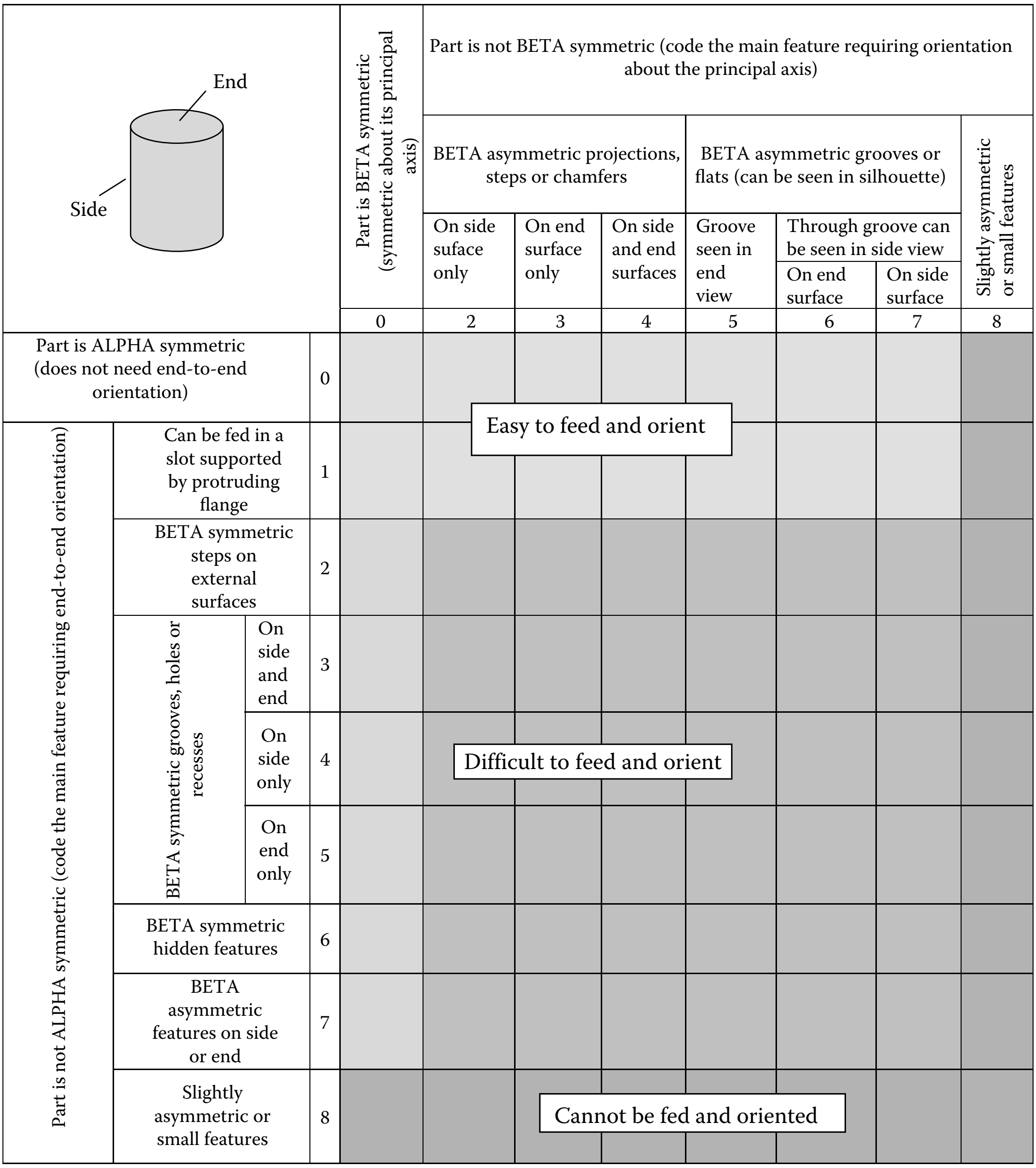


FIGURE 1.1
Coding system for the automatic feeding and orienting of small rotational parts. (Adapted from Boothroyd, G. *Assembly Automation and Product Design*, 2nd Ed., CRC Press, Boca Raton, FL, 2005.)

The development of DFMA started with research into automatic assembly. In the early 1970s, a handbook [1], which catalogs feeding and orienting techniques for small parts, was published at the University of Massachusetts (UMass). This handbook was the culmination of research started at Salford University in England in 1963 by Geoff Boothroyd and his graduate student Alan Redford and further pursued at UMass by Geoff Boothroyd and his colleagues Corrado Poli and Laurence Murch. A part coding system based on group technology was devised for the handbook in order to catalog the various solutions to feeding and orienting techniques (Figure 1.1) of which one of Boothroyd's graduate students, C. Ho was the primary contributor [2]. The numerical codes not only showed which pages in the handbook illustrated automatic feeding solutions but also showed which parts would be easy to feed and orient, which parts would be relatively difficult to feed and orient, and which parts could not normally be fed and oriented automatically.

It seemed that product designers might use the coding system to avoid part shapes that were difficult to feed and orient or to provide part features that facilitated feeding and orienting. Using a combination of the coding system and the data developed in the research, a systematic method was devised to provide designers with a technique to quantify product designs for the ease of automatic assembly.

Thus, the efforts of numerous undergraduate and graduate students, visiting scholars, and summer exchange students who built and tested some 140 feeding and orienting systems led to the development of the Design for Automatic Assembly methodology.

Later, Boothroyd and his colleague at UMass, Bill Wilson, believed that they could make a significant contribution to the broader subject of Product Design for Ease of Manufacture. Boothroyd and Wilson visited the NSF to present a proposal and received funding in 1978 for a 3-year research program to study Design for Manufacturability [3].

As his responsibility in the research program, Boothroyd pursued his interest in DFA based on the results of the feeding and orienting studies. For the automatic insertion of parts, he collaborated with his colleagues in England, Alan Redford and Ken Swift who had obtained a grant for a study of product design for automatic assembly. As part of the study in England, various designs of domestic gas flow meters were compared. These meters all worked on the same principle and had the same basic components. However, it was found that their manufacturability varied widely and that the least manufacturable design had six times the labor content of the best design.

Figure 1.2 shows five different solutions for the same attachment problem taken from the gas flow meters studied. It can be seen that, on the left, the simplest method for securing a housing consisted of a simple snap fit. In the examples on the right, not only does the assembly time increase, but also both the number and cost of parts increases. This illustrates the two basic principles of design for the ease of assembly of a product: reduce the number of assembly operations by reducing the number of parts and make the assembly operations easier to perform.

Boothroyd and his students developed the analysis method for Design for Manual Assembly in order that manufacturing engineers could make justifications for automation proposals.

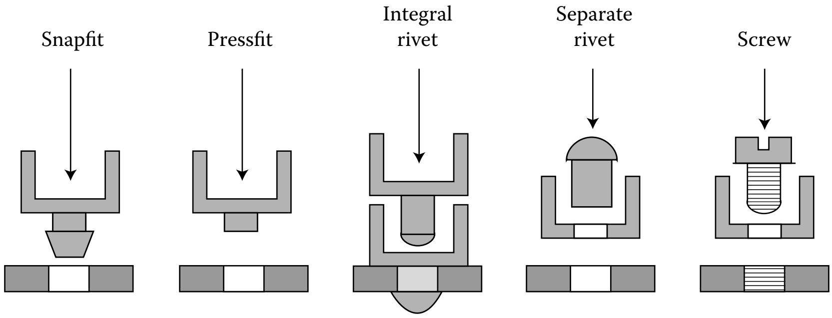


FIGURE 1.2
Examples of design features affecting assembly.

Bill Wilson's contribution to the research program was his study of the initial Selection of Materials and Processes for the manufacture of parts which dealt with important decisions made by designers in the initial stages of product design [4].

The third area of research was DFM of the parts. In this, we were fortunate to have Winston Knight from Oxford University spend his sabbatical at UMass working with Poli on the research program. Knight's contributions, specifically in the area of Design for Forging, continued as he spent subsequent summers at UMass.

Thus, DFA and DFM were born, later to become DFMA.

The original objectives of the entire research program were to develop analytical methods to guide designers in their work. The general idea was to design products for the ease of assembly and to design their component parts for the ease of manufacture (often referred to as producibility). However, these objectives were soon found to be conflicting. Producibility rules have led to suggestions that component parts be divided into simple shapes. However, as will be illustrated, this is rarely a good idea. In fact, *reduction* of the number of separate component parts in a product not only reduces the cost of assembly but generally reduces the total cost of the parts.

In the work on DFA, three simple criteria were developed to determine whether a component part should be considered for elimination. It was the application of these criteria that held the key to simplification of the product structure with the resulting cost benefits [5].

The DFA methodology for both automatic and manual assembly was published at UMass in the form of a loose-leaf handbook [6] made available to industry for a small subscription. Over a period of only 4 years, 2000 subscriptions were obtained and used to supplement the work on DFA.

Soon after the DFA Handbook was made available, several studies were undertaken at the Diablo Printer Division of the Xerox Corporation. These studies, of small electromechanical assemblies, generated redesigns of assemblies where significant savings were made in the total manufacturing cost, most of which arose from a reduction in the number of separate parts.

Major companies, such as Xerox, General Electric, Westinghouse Electric, IBM, and Digital Equipment, were quick to implement DFA in order to simplify product designs. As an example, it was estimated by Sydney Liebson of Xerox, that full implementation of the DFA methodology would result in annual savings for the Company in hundreds of millions of dollars [5]. Sydney Liebson, who was the corporate manager of manufacturing at Xerox, was an enthusiastic supporter of the original NSF proposal on Design for Manufacturability.

The results of all of the research on automatic assembly and on DFA are presented in detail in the companion text "Automatic Assembly and Design for Assembly" [7].

1.3 Implementation of Design for Assembly

The objective of DFMA was to produce tools which could be used by product designers. These tools guide the designers or design team to where the problems in a proposed design lie. However, it is one thing to develop design tools but quite another to get designers to use them.

Peter Dewhurst joined Boothroyd in 1980 at UMass. They quickly collaborated in developing a computer version of the DFA handbook [8]. They used the latest personal computer

(PC), the Apple II Plus, and released a software package "Design for Automatic and Manual Assembly." It appeared that, unlike their European or Japanese counterparts, the U.S. designers preferred to use the new computers rather than perform hand calculations to analyze their designs for ease of assembly. Both IBM and Digital Equipment funded translation efforts so that the code would run on their own computers—in the case of IBM on their new PC. It is clear that the availability of computer software for DFA analysis contributed significantly to successful implementation in U.S. industry.

This work led to the incorporation of Boothroyd Dewhurst Inc. in 1981. The company has continued to develop software for DFA and for the estimation of manufacturing costs for a variety of processes (DFM Concurrent Costing).

A major breakthrough in DFA implementation was made in 1988 when Ford Motor Company reported that DFA software had helped them save billions of dollars on their Taurus line of automobiles. Later, General Motors (GM) made comparisons between its assembly plant at Fairfax, Kansas, which made the Pontiac Grand Prix, and Ford's assembly plant for its Taurus and Mercury Sable models near Atlanta [9]. GM found a large productivity gap and concluded that 41% of the gap could be traced to the manufacturability of the two designs. For example, the Ford car had fewer parts—10 in its front bumper compared with 100 in the GM Pontiac—and the Ford parts fit together more easily.

1.4 Design for Manufacture

Research on early cost estimating for a variety of manufacturing processes was pursued at UMass and then, from 1985 to 1996 at the University of Rhode Island (URI) by Geoff Boothroyd, Peter Dewhurst, and Winston Knight. Knight joined Boothroyd and Dewhurst on the faculty at URI in 1986. The present text describes much of this work.

It should be pointed out that the commercial software developments were all based on the research. Much of the support for this research came from industrial gifts which were mainly used to fund graduate students—many of whom went on to apply the results in the supporter companies. The results of the research were made freely available to industry in the form of 22 research reports from UMass and over 100 research reports from URI.

1.5 Producibility Guidelines

In the 1960s, there was much talk about designing products so they could be manufactured more easily. Recommendations commonly known as producibility guidelines were developed. Figure 1.3 shows a typical design guideline published in 1971 that emphasized simplifying the individual parts [10]. The authors of this guideline mistakenly assumed that several simple-shaped parts are inherently less expensive to manufacture than a single complex part and that any assembly cost is more than offset by the savings in part costs. They were wrong on both counts, as the results in Table 1.1 show. Even ignoring assembly costs, the two parts in the "right" design are significantly more expensive than the single part in the "wrong" design—even the piece part costs (neglecting tooling costs) are more expensive. Taking assembly costs into account and ignoring

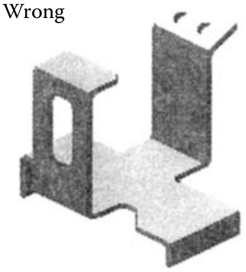
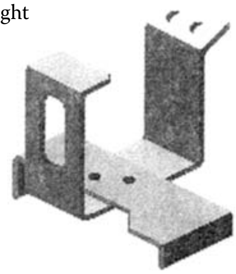
Guideline	Wrong	Right
Avoid complex bent parts (material waste); rather split and join		

FIGURE 1.3
Misleading producibility guideline for the design of sheet metal parts. (From Pahl, G. and Beitz, W. *Engineering Design*, English Edition, The Design Council, London, 1984. With permission.)

storage, handling, quality, and paperwork costs, the "right" design is 50% more costly than the "wrong" design!

Once methods for analyzing assembly difficulties were developed in the 1970s, it became recognized that there was a conflict between producibility and assembly. It was found that the simplification of products by reducing the number of separate parts through DFA—on the order of 50% on average—could easily achieve substantial reductions in assembly costs. Much more important, however, was the fact that even greater savings could be achieved in the cost of the parts. The ability to estimate both assembly and part manufacturing costs at the earliest stages of product design is the essence of DFMA. The authors of this text have carried out numerous research programs over the past two decades on the subject of DFMA. A primary objective of this work has been to develop economic models of manufacturing processes, based on product design information, and which require a minimum of manufacturing knowledge [11–13].

The simple example in Figure 1.3 and Table 1.1 illustrates this. If the "right" design were subject to a DFA analysis, the designer would be challenged as to why the subassembly could not be manufactured as a single part, thereby eliminating an assembly cost of $0.20. Further analysis would show an additional saving of $0.17 in part costs.

Of course, the word "design" has many different meanings. To some it means the esthetic design of a product such as the external shape of a car or the color, texture, and shape of the casing of a can opener. In fact, in some university curricula this is what would be meant by a course in "product design." On the other hand, design can mean establishing

TABLE 1.1

Estimated Costs in Dollars for the Two Examples in Figure 1.3 if 100,000 are Made

	Wrong	Right
Setup	0.015	0.023
Process	0.535	0.683
Material	0.036	0.025
Piece part	0.586	0.731
Tooling	0.092	0.119
Total manufacture	0.678	0.850
Assembly	0.000	0.200
Total	0.678	1.050

the basic parameters of a system. For example, before considering any detail, the design of a power plant might mean establishing the characteristics of the various units such as generators, pumps, boilers, connecting pipes, and so on.

Yet another interpretation of the word "design" would be detailing of the materials, shapes, and tolerance of the individual parts of a product. This is the aspect of product design mainly considered in this text. It is an activity that starts with sketches of parts and assemblies; it then progresses to the computer-aided design (CAD) workstation, where assembly drawings and detailed part drawings are produced. These drawings are then passed to the manufacturing and assembly engineers whose job it is to optimize the processes used to produce the final product. Frequently, it is at this stage that manufacturing and assembly problems are encountered and requests are made for design changes. Sometimes these design changes are large in number and result in considerable delay in the final product release. In addition, the later in the product design and development cycle changes occur, the more expensive they become. Therefore, not only is it important to take manufacture and assembly into account during product design, but also these considerations must occur as early as possible in the design cycle.

This is illustrated qualitatively by the chart in Figure 1.4 showing that extra time spent early in the design process is more than compensated for by savings in time when prototyping takes place. Thus, in addition to reducing product costs, the application of DFMA shortens the time to bring the product to market. As an example, Ingersoll–Rand Company reported [14] that the use of DFMA software from Boothroyd Dewhurst, Inc., slashed product development time from two years to one. In addition, the simultaneous engineering team reduced the number of parts in a portable compressor radiator and oil-cooler assembly from 80 to 29, decreased the number of fasteners from 38 to 20, trimmed the number of assembly operations from 159 to 40, and reduced assembly time from 18.5 to 6.5 min. Developed in June 1989, the new design went into full production in February 1990.

Another reason why careful consideration of manufacture and assembly should be taken into account early in the design cycle is because it is now widely accepted that over 70% of the final product costs are determined during design [15]. This is illustrated in Figure 1.5.

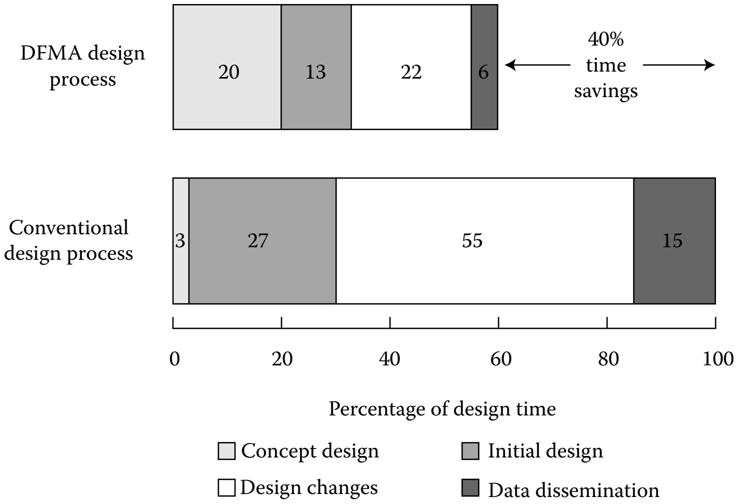


FIGURE 1.4
DFMA shortens the design process. (Adapted from Bauer, L. *Team Design Cuts Time, Cost, Welding Design Fabrication,* September, 1990, p. 35.)

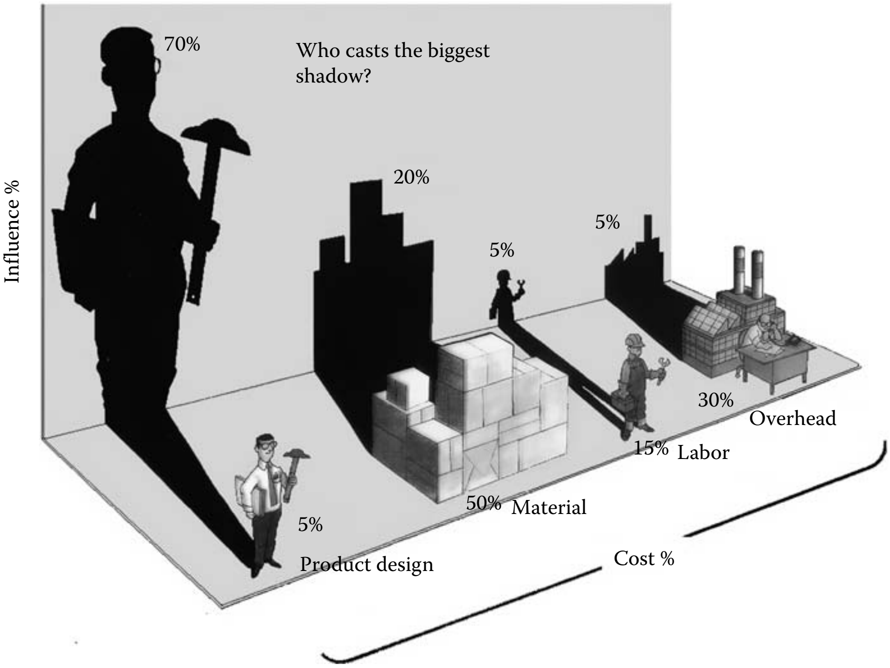


FIGURE 1.5
Who casts the biggest shadow? (Adapted from Munro and Associates, Inc.)

Traditionally, the attitude of designers has been "we design it, you build it." This has now been termed the "over-the-wall approach" where the designer sits on one side of the wall and throws designs over the wall (Figure 1.6) to the manufacturing engineers, who then have to deal with the various manufacturing problems arising because they were not involved in the design effort. One means of overcoming this problem is to consult the manufacturing engineers at the design stage. The resulting teamwork avoids many problems. However, these teams, now called simultaneous engineering or concurrent engineering teams, require analysis tools to help them study proposed designs and evaluate them from the point of view of manufacturing difficulty and cost.

By way of illustration we see that DFMA efforts at Hewlett Packard Loveland [16] started in the mid-1980s with the redesign of existing products and continued with application to new product design. During these studies, which proved increasingly successful, product development involved one to three manufacturing engineers interacting frequently with the R&D team members. Eventually, by 1992, HP Loveland had incorporated DFMA into a formal concurrent engineering approach. The gradual improvements in their product manufacturing and assembly costs are shown in Figure 1.7.

1.6 How Does DFMA Work?

Let us follow an example from the conceptual design stage. Figure 1.8 shows the original design of a motor drive assembly that is required to sense and control its position on two

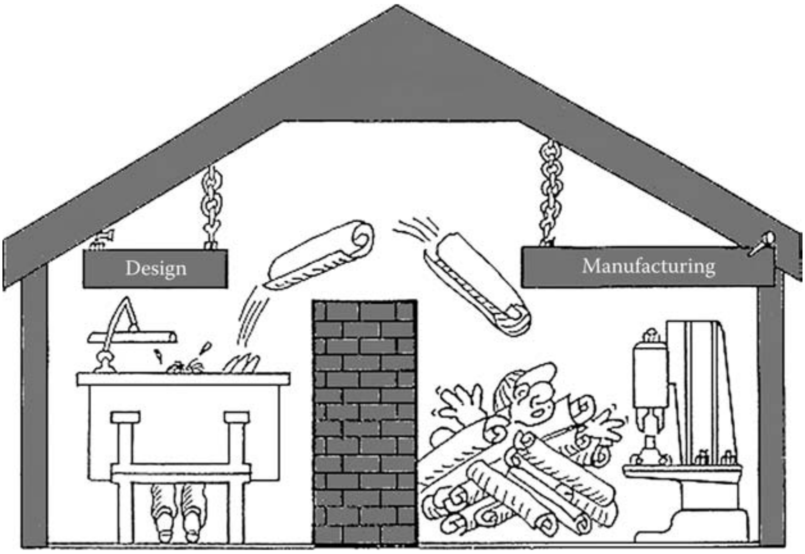


FIGURE 1.6
"Over-the-wall" design, historically the way of doing business. (Adapted from Munro and Associates, Inc.)

steel guide rails. The motor must be fully enclosed for esthetic reasons and have a removable cover to provide access to adjustment of the position sensor. The principle requirements are a rigid base designed to slide up and down the guide rails and both support the motor and locate the sensor. The motor and sensor have wires connecting to a power supply and control unit, respectively.

The base is provided with two bushings to provide suitable friction and wear characteristics. The motor is secured to the base with two screws; a hole accepts the cylindrical

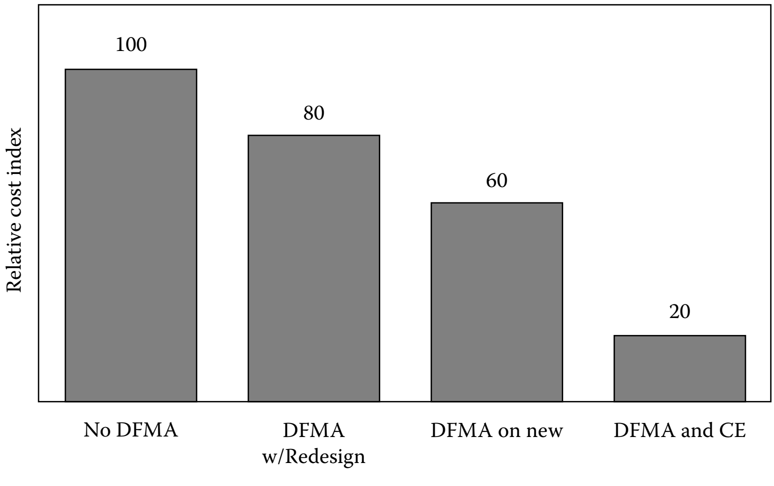


FIGURE 1.7
Effects of DFMA and CE on product cost at Hewlett Packard. (Adapted from Williams, R.A. *Successful Implementation of Engineering Products and Processes*. Van Nostrand, New York, 1994.)

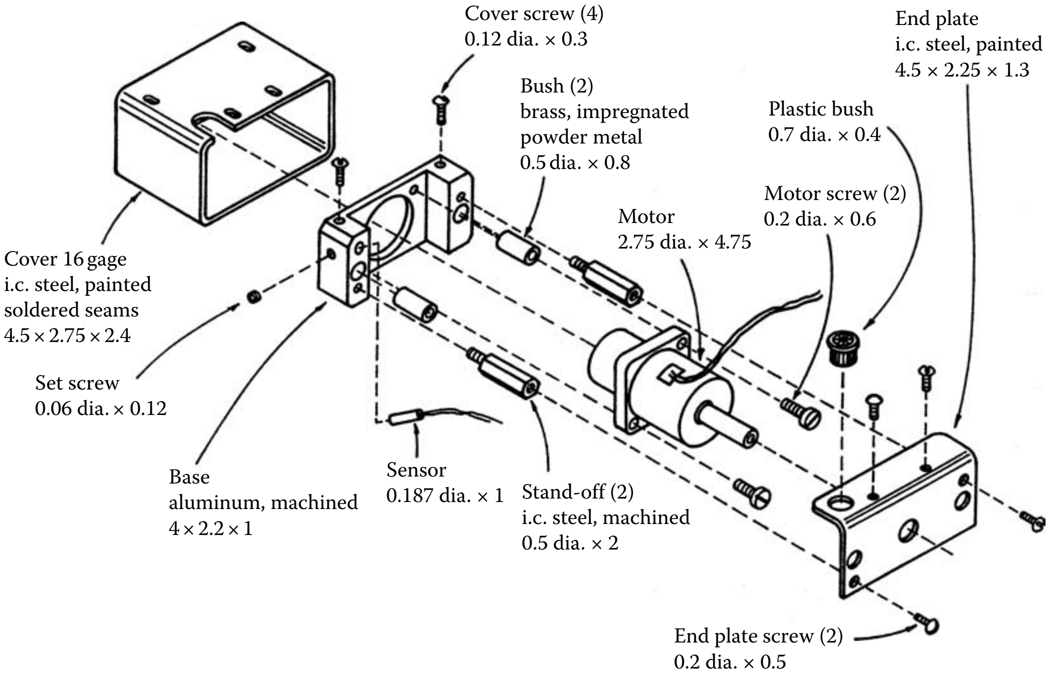


FIGURE 1.8
Original design of the motor drive assembly (dimensions in inches).

sensor, which is held in place with a set screw. The motor base and sensor are the only items necessary for the operation of the device. To provide the required covers, an end plate is screwed to two standoffs which are screwed into the base. This end plate is fitted with a plastic bushing through which the connecting wires pass. Finally, a box-shaped cover slides over the whole assembly from below the base and is held in place by four screws, two passing into the base and two into the end cover.

There are two subassemblies, the motor and the sensor, which are required items, and, in this initial design, there are eight additional main parts and nine screws making a total of nineteen items to be assembled.

When DFA began to be taken seriously in the early 1980s and the consequent benefits were appreciated, it became apparent that the greatest improvements arose from simplification of the product by reducing the number of separate parts. In order to give guidance to the designer in reducing the part count, the DFA methodology [5] provides three criteria against which each part must be examined as it is added to the product during assembly.

1. During operation of the product, does the part move relative to all other parts already assembled. Only gross motion should be considered—small motions that can be accommodated by integral elastic elements, for example, are not sufficient for a positive answer.
2. Must the part be of a different material or be isolated from all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.

3. Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible.

Application of these criteria to the original design (Figure 1.8) during assembly would proceed as follows:

1. *Base:* Since this is the first part to be assembled, there are no other parts with which it can be combined, and so it is a theoretically necessary part.
2. *Bushings (2):* These do not satisfy the criteria because, theoretically, the base and bushings could be of the same material.
3. *Motor:* The motor is a standard subassembly of parts that, in this case, is purchased from a supplier. Thus, the criteria cannot be applied and the motor is a necessary separate item.
4. *Motor screws (2):* Invariably, separate fasteners do not meet the criteria, because an integral fastening arrangement is always theoretically possible.
5. *Sensor:* This is another standard subassembly and will be considered as a necessary separate item.
6. *Set screw:* Theoretically not necessary.
7. *Standoffs (2):* These do not meet the criteria; they could be incorporated into the base.
8. *End plate:* Must be separate for reasons of assembly of necessary items.
9. *End plate screws (2):* Theoretically not necessary.
10. *Plastic bushing:* Could be of the same material as, and therefore combined with, the end plate.
11. *Cover:* Could be combined with the end plate.
12. *Cover screws (4):* Theoretically not necessary.

From this analysis, it can be seen that if the motor and sensor subassemblies could be arranged to snap or screw into the base and a plastic cover designed to snap on, only four separate items would be needed instead of 19. These four items represent the theoretical minimum number needed to satisfy the requirements of the product design without considering practical limitations.

It is now necessary for the designer or design team to justify the existence of those parts that did not satisfy the criteria. Justification may arise from practical or technical considerations or from economic considerations. In this example, it could be argued that two screws are needed to secure the motor and one set screw is needed to hold the sensor, because any alternative would be impractical for a low-volume product such as this. However, the design of these screws could be improved by providing them with pilot points to facilitate assembly.

It could be argued that the two powder metal bushings are unnecessary, because the part could be machined from an alternative material, such as nylon, having the necessary frictional characteristics. Finally, it is difficult to justify the separate standoffs, end plate, cover, plastic bushing, and six screws.

Now, before an alternative design can be considered, it is necessary to have estimates of the assembly times and costs so that any possible savings can be taken into account when considering design alternatives. Using the techniques described in this text, it is possible

TABLE 1.2

Results of DFA Analysis for the Motor Drive Assembly Original Design (Figure 1.8)

	No.	Theoretical Part Count	Assembly Time (s)	Assembly Cost (¢)[a]
Base	1	1	3.5	2.9
Bushing	2	0	12.3	10.2
Motor subassembly	1	1	9.5	7.9
Motor screw	2	0	21.0	17.5
Sensor subassembly	1	1	8.5	7.1
Set screw	1	0	10.6	8.8
Standoff	2	0	16.0	13.3
End plate	1	1	8.4	7.0
End plate screw	2	0	16.6	13.8
Plastic bushing	1	0	3.5	2.9
Thread leads	—	—	5.0	4.2
Reorient	—	—	4.5	3.8
Cover	1	0	9.4	7.9
Cover screw	4	0	31.2	26.0
Totals	19	4	160.0	133

$$\text{Assembly index} = \frac{4\times3}{160} = 7.5\%$$

[a] For a labor rate of $30 per h.

to make estimates of assembly costs, and later estimate the cost of the parts and associated tooling, without having final detail drawings of the part available.

Table 1.2 presents the results of an assembly analysis for the original motor drive assembly where it can be seen that an assembly index of 7.5% is given. This figure is obtained by comparing the estimated assembly time of 160 s with a theoretical minimum time obtained by multiplying the theoretical minimum part count of four by a minimum time of assembly for each part of 3 s. It should be noted that for this analysis, standard subassemblies are counted as parts.

Considering first the parts with zeros in the theoretical part count column, it can be seen that those parts that did not meet the criteria for minimum part count involved a total assembly time of 120.6 s. This figure should be compared with the total assembly time for all 19 parts of 160 s. It can also be seen that parts involving screw-fastening operations resulted in the largest assembly times. It has already been suggested that the elimination of the motor screws and the set screw would probably be impractical. However, elimination of the remaining parts not meeting the criteria would result in the redesign concept shown in Figure 1.9 where the bushings are combined with the base and the standoffs, end plate, cover, plastic bushing, and six screws are replaced by one snap-on plastic cover. The eliminated items involved an assembly time of 97.4 s. The new cover would take only 4 s to assemble and would avoid the need for a reorientation. In addition, screws with pilot points would be used and the base redesigned so that the motor is self-aligning.

Table 1.3 presents the results of an assembly analysis of the new design where it can be seen that the new assembly time is only 46 s—less than one-third of the original assembly time. The assembly index is now 26%, a figure that approaches the range found from the experience to be the representative of good designs of small electromechanical devices produced in a relatively low volume.

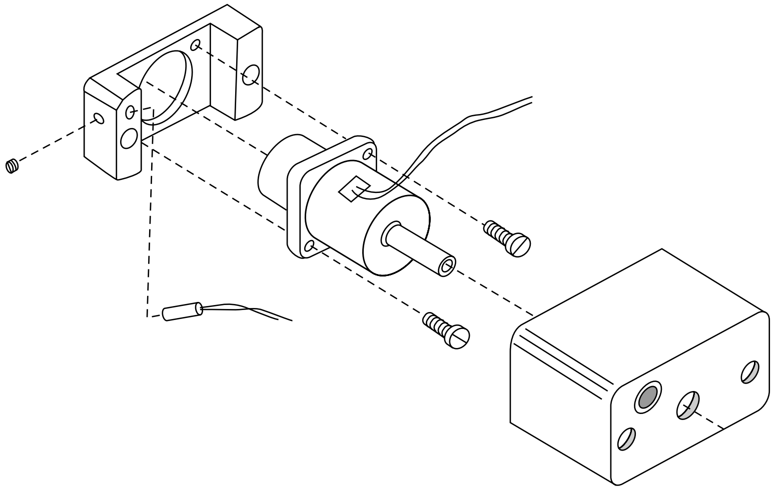


FIGURE 1.9
Redesign of the motor drive assembly following DFA analysis.

Table 1.4 compares the cost of the parts for the two designs showing a savings of $15 in parts cost. However, the tooling for the new cover is estimated to be $6307—an investment that would have to be made at the outset. The parts' cost and tooling cost estimates were made using the techniques described in this text.

Thus, the outcome of this study is a second design concept representing a total savings of $15.95, of which only 95 cents represents the savings in assembly time. In addition, the assembly index has been improved by about 250%.

It is interesting to note that the redesign suggestions arose through the application of the minimum part count criteria during the DFA analysis—the final cost comparison being made after assembly cost and parts cost estimates were considered.

The second step in an analysis is DFM. This means estimating the cost of the manufactured parts in order to quantify the effects of any design improvements suggested by the initial DFA analysis. In the present example, the DFM analysis of the base revealed the cost of providing each set of features by machining. Interestingly, it was found that elimination

TABLE 1.3
Results of DFA Analysis for the Motor Drive Assembly Redesign (Figure 1.9)

	No.	Theoretical Part Count	Assembly Time (s)	Assembly Cost (¢)[a]
Base	1	1	3.5	2.9
Motor subassembly	1	1	4.5	3.8
Motor screw	2	0	12.0	10.0
Sensor subassembly	1	1	8.5	7.1
Set screw	1	0	8.5	7.1
Thread leads	—	—	5.0	4.2
Plastic cover	1	1	4.0	3.3
Totals	6	4	46.0	38.4

$$\text{Assembly index} = \frac{4 \times 3}{46.0} = 26\%$$

[a] For a labor rate of $30 per h.

TABLE 1.4

Comparison of Parts Cost for the Motor Drive Assembly Original Design and Redesign (Purchased Motor and Sensor Subassemblies not Included)

(a) Original Design		(b) Redesign	
Item	**Cost ($)**	**Item**	**Cost ($)**
Base (aluminum)	12.91	Base (nylon)	13.43
Ushing (2)	2.40[a]	Motor screw (2)	0.20[a]
Motor screw (2)	0.20[a]	Set screw	0.10[a]
Set screw	0.10[a]	Plastic cover	6.71
Standoff (2)	5.19	(includes tooling)	
End plate	5.89		
End plate screw (2)	0.20[a]	Total	20.44
Plastic bushing	0.10[a]		
Cover	8.05	Tooling cost for plastic cover, $6307	
Cover screw (4)	0.40[a]		
Total	35.44		

[a] Purchased in quantity.

of the two drilled and tapped screw holes in the side of the base and the two drilled and tapped holes provided for the standoffs would reduce the total machining cost by $1.14. Thus, these changes would save more than the total possible savings in an assembly cost of 95 cents. This is an indication that it is important not only to know the total estimated manufacturing cost of an item but, more importantly, to know the cost of providing the various features. This case study is typical in the sense that although DFA means design for assembly, the results of improving assemblability usually manifest themselves in significant reductions in part manufacturing costs.

Figure 1.10 summarizes the steps taken when using DFMA during design. The DFA analysis is first conducted leading to a simplification of the product structure. Then,

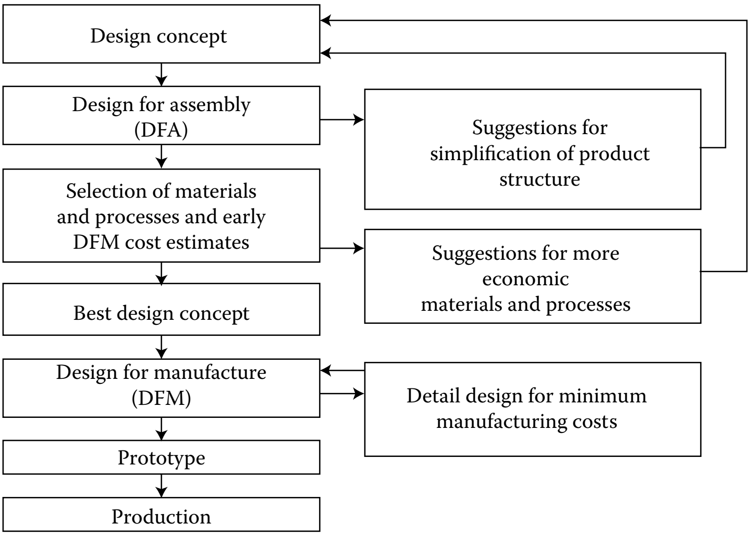


FIGURE 1.10
Typical steps taken in a DFMA study using the DFMA software.

using DFM, early cost estimates for the parts are obtained for both the original design and the new design in order to make trade-off decisions. During this process the best materials and processes to be used for the various parts are considered. In the example, would it be better to manufacture the cover in the new design from sheet metal? Once the final selection of materials and processes has occurred, a more thorough analysis for DFM can be carried out for the detailed design of parts. All these steps are considered in the following chapters.

1.7 Falsely Claimed Reasons for Not Implementing DFMA

1.7.1 No Time

In making presentations and conducting workshops on DFMA, the authors have found that the most common complaint among designers is that they are not allowed sufficient time to carry out their work. Designers are usually constrained by the urgent need to minimize the design-to-manufacture time for a new product. Unfortunately, as was illustrated earlier (Figure 1.4), more time spent in the initial stages of design reaps benefits later in terms of reduced engineering changes after the design has been released to manufacturing. Company executives and managers must be made to realize that the early stages of design are critical in determining not only manufacturing costs, but also the overall design-to-manufacturing cycle time.

1.7.2 Not Invented Here

Enormous resistance can be encountered when new techniques are proposed to designers. Ideally, any proposal to implement DFMA should come from the designers themselves. However, more frequently it is the managers or executives who have heard of the successes resulting from DFMA and who wish their own designers to implement the philosophy. Under these circumstances, great care must be taken to involve the designers in the decision to implement these new techniques. Only then will the designers support the idea of applying DFMA. If they do not support DFMA, it will not be successfully applied.

1.7.3 Ugly Baby Syndrome

Even greater difficulties can exist when an outside group or a separate group within the company undertakes to analyze current designs for the ease of manufacture and assembly. Commonly, it is found that significant improvements could be made to the current design, and when these improvements are brought to the attention of those who produced the design this can result in extreme resistance. Telling a designer that their designs could be improved is much like telling a mother that her baby is ugly! It is important, therefore, to involve the designers in the analysis and provide them with the incentive to produce better designs. If they perform the analysis, they are less likely to take as criticism any problem that may be highlighted.

1.7.4 Low Assembly Costs

The earlier description of the application of DFMA showed that the first step is a DFA analysis of the product or subassembly. Quite frequently, it is suggested that since assembly costs for a particular product form only a small proportion of the total manufacturing costs, there is no point in performing a DFA analysis. Figure 1.11 shows the results of an analysis where the assembly costs were extremely small compared with material and manufacturing costs. However, DFA analysis would suggest a replacement of the complete assembly with, say, a machined casting. This would reduce total manufacturing costs by at least 50%.

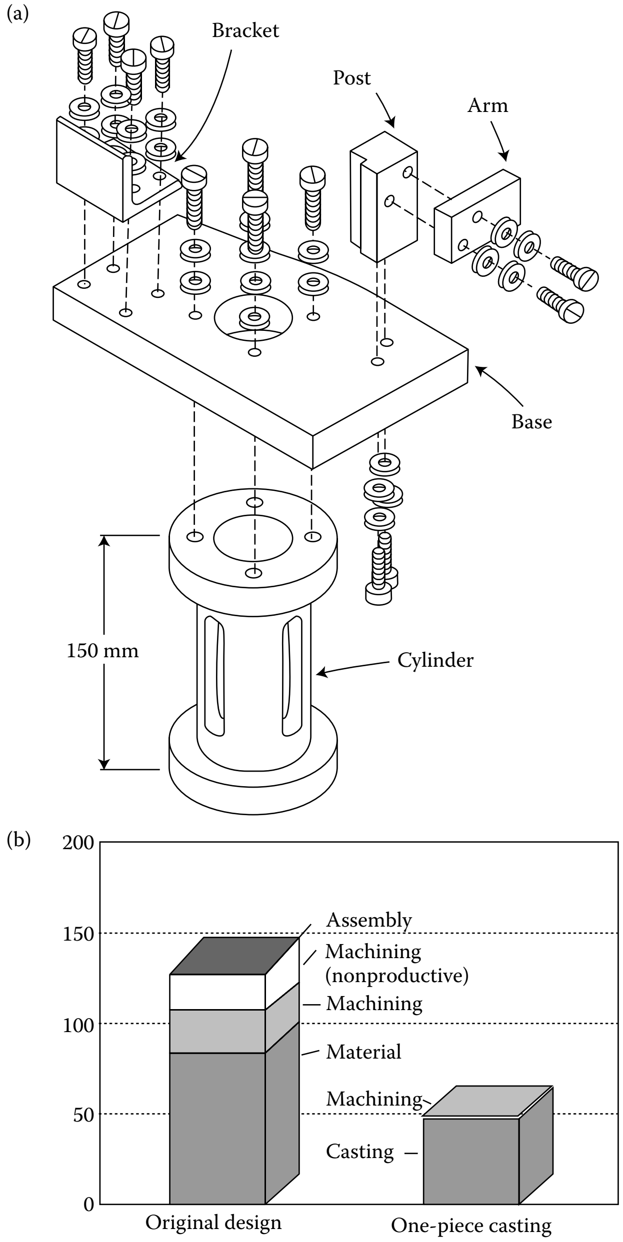


FIGURE 1.11
DFA analysis can reduce total costs significantly even though assembly costs are small.

1.7.5 Low Volume

The view is often expressed that DFMA is worthwhile only when the product is manufactured in large quantities. It could be argued, though, that the use of the DFMA philosophy is even more important when the production quantities are small. This is because, commonly, reconsideration of an initial design is usually not carried out for low-volume production. Figure 1.11 is an example of this where the assembly was designed to be built from items machined from stock as if the product were one-of-a-kind. The prototype then became the production model. Applying the philosophy "do it right the first time" becomes even more important, therefore, when production quantities are small. In fact, the opportunities for parts consolidation are usually greater under these circumstances, because it is not usually a consideration during design.

1.7.6 We Have Been Doing It for Years

When this claim is made, it usually means that some procedure for "design for producibility" has been in use in the company. However, design for producibility usually means a detailed design of individual parts for the ease of manufacture. It was made clear earlier that such a process should occur only at the end of the design cycle; it can be regarded as a "fine tuning" of the design. The important decisions affecting total manufacturing costs would already have been made. In fact, there is great danger in implementing the design for producibility in this way. It has been found that the design of individual parts for the ease of manufacture can mean, for example, limiting the number of bends in a sheet metal part. Again, experience has shown that it is important to combine as many features in one part as possible. In this way, full use is made of the abilities of the various manufacturing processes.

1.7.7 It Is Only Value Analysis

It is true that the objectives of DFMA and value analysis are the same. However, it should be realized that DFMA is meant to be applied early in the design cycle and that value analysis does not give proper attention to the structure of the product and its possible simplification. DFMA has the advantage that it is a systematic step-by-step procedure that can be applied at all stages of design and challenges the designer or design team to justify the existence of all the parts and to consider alternative designs. Experience has shown that DFMA still makes significant improvements of the existing products even after value analysis has been carried out.

1.7.8 DFMA Is Only One among Many Techniques

Since the introduction of DFMA, many other techniques have been proposed, for example, design for quality (DFQ), design for competitiveness (DFC), design for reliability, and many more. Many have even suggested that the design for performance is just as important as DFMA. One cannot argue against this. However, DFMA is the subject that has been neglected over the years, while adequate consideration has generally been given to the design of products for performance, appearance, and so on.

The other factors, such as quality, reliability, and so on, will follow when proper consideration is given to the manufacture and assembly of the product. In fact, Figure 1.12 shows

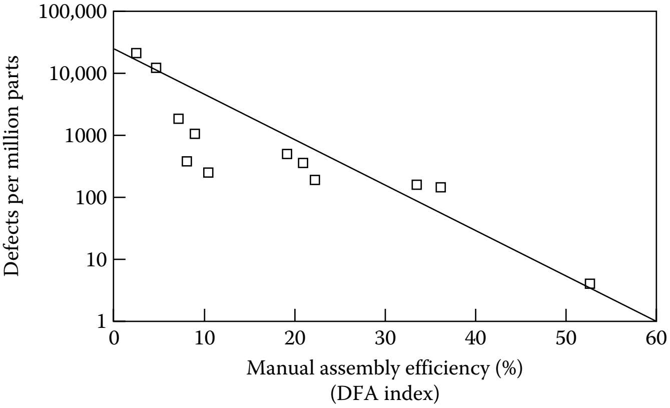


FIGURE 1.12
Improved assembly efficiency results in increased reliability. (Adapted from Branan, W. Six-Sigma quality and DFA *DFMA insight*, Boothroyd Dewhurst Inc., 2(1), winter 1991, 1–3.)

a relationship between the quality of a design measured by the assembly index obtained during DFA and the resulting product quality measured in defects per million parts assembled. Each data point on this graph represents a different product designed and manufactured by Motorola. It clearly shows that if DFA is carried out leading to simplified designs, then improved quality will follow.

1.7.9 DFMA Leads to Products that are more Difficult to Service

This is absolute nonsense. Experience shows that a product that is easy to assemble is usually easier to disassemble and reassemble. In fact, products that need continual service involving the removal of inspection covers and the replacement of various items should have DFMA applied even more rigorously during the design stage. How many times have we seen an inspection cover fitted with numerous screws, only to find that after the first inspection only two are replaced?

1.7.10 I Prefer Design Rules

There is a danger in using design rules, because they can guide the designer in the wrong direction. Generally, rules attempt to force the designer to think of simpler-shaped parts that are easier to manufacture. In an earlier example, it was pointed out that this can lead to more complicated product structures and a resulting increase in the total product cost. In addition, in considering novel designs of parts that perform several functions, the designer needs to know what penalties are associated when the rules are not followed. For these reasons, the systematic procedures used in DFMA that guide the designer to simpler product structures and provide quantitative data on the effect of any design changes or suggestions are found to be the best approach.

1.7.11 I Refuse to Use DFMA

Although a designer will not say this, if the individual does not have the incentive to adopt this philosophy and use the tools available, then no matter how useful the tools or how simple they are to apply, the individual will see to it that they do not work. Therefore, it is imperative that the designer or the design team be given the incentive and the necessary facilities to incorporate considerations of assembly and manufacture during design.

1.8 What Are the Advantages of Applying DFMA during Product Design?

DFMA provides a systematic procedure for analyzing a proposed design from the point of view of assembly and manufacture. This procedure results in simpler and more reliable products that are less expensive to assemble and manufacture. In addition, any reduction in the number of parts in an assembly produces a snowball effect on cost reduction because of the drawings and specifications that are no longer needed, the vendors that are no longer needed, and the inventory that is eliminated. All these factors have an important effect on overheads, which, in many cases, form the largest proportion of the total cost of the product.

DFMA tools also encourage dialogue between designers and the manufacturing engineers and any other individuals who play a part in determining final product costs during the early stages of design. This means that teamwork is encouraged and the benefits of simultaneous or concurrent engineering can be achieved.

A recent example [17] comes from the International Gaming Technology (IGT). IGT is a global Fortune 500 company involved in the design, manufacture, and marketing of electromechanical gaming equipment. When the current economic crisis impacted on their customers and the gaming industry worldwide, their engineers were challenged to seek new opportunities for cost reductions, alongside innovative design and development.

About 4 years ago, Sam Mikhail, who had previous experience with DFMA, raised the possibility of using DFMA in IGT for cost reduction. This proposal was met with the attitude that DFMA implementation was not necessary within the company and that the prevailing processes in the company had already incorporated any potential cost reduction. Typical responses included: "Why? we have no time for this," "we don't need it," and "we have always been doing it this way"

Initially, the engineers believed that DFMA is a time-consuming practice with unknown benefits and that the size of the company would make it challenging to implement. There were also a number of engineers who believed that they had been, or were, working with DFMA principles and therefore had nothing to gain by formally introducing DFMA in the company.

Eventually, Sam was successful in introducing DFMA through a pilot workshop. When the selected participants for the workshops were invited to attend, reluctance was expected. This was reflected in the results of a preworkshop questionnaire (Figure 1.13).

As the workshop progressed, the participants' enthusiasm grew significantly as they applied DFMA techniques to their existing designs, and ultimately welcomed the challenge to improve the designs. Pushing design boundaries beyond the status quo and with open communication between the manufacturing, mechanical, and electrical disciplines resulted in innovative approaches to solving design challenges. After the workshop, another survey was conducted. The results (Figure 1.14) indicated a complete change in attitude on the part of the participants.

Following the success of the workshop in June 2008, the management approved an ongoing DFMA program with training for the engineers. As a result, cost savings in excess of 1 million had been achieved by June 2009 and more savings were expected.

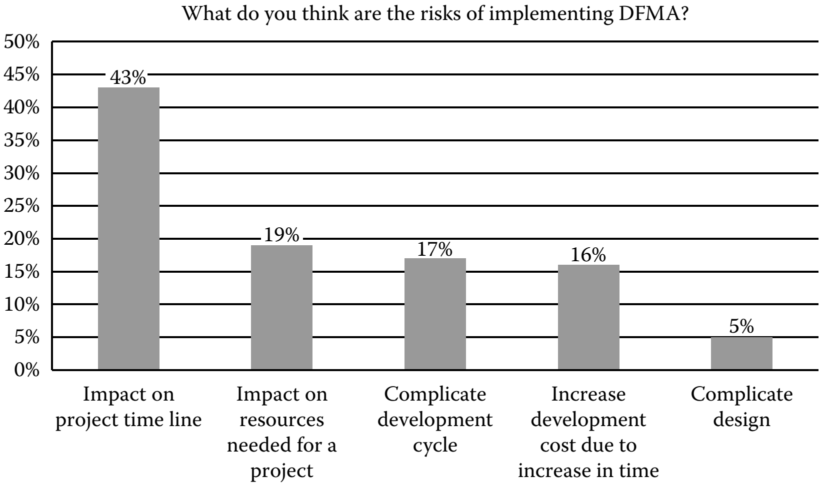


FIGURE 1.13
Responses to a questionnaire presented to IGT engineers prior to the introduction of DFMA. (Adapted from Mikhail, S. *Decision-making Process for Implementing DFMA at IGT*, International Forum on DFMA, Providence, RI, June 2009.)

Another recent example is from Aztalan Engineering; a precision machining company providing quality components for the American industry [18]. However, as General Manager Jim Hale points out "all this precision cutting and milling requires careful planning and tracking." During the course of a day's work, technicians assemble "to analyze proposed designs of parts for their manufacturability, establish process controls for parts being manufactured, and communicate with customers and the supply chain."

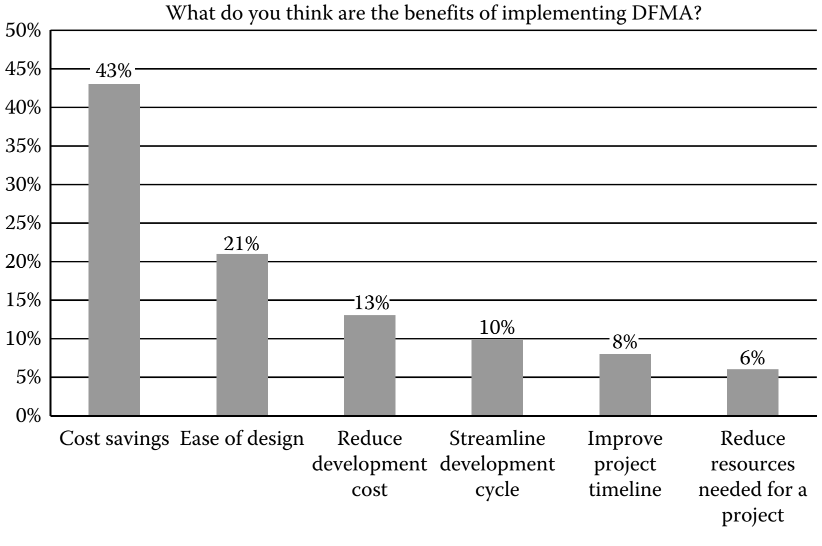


FIGURE 1.14
Responses to a questionnaire presented to IGT engineers following the pilot workshop on DFMA. (Adapted from Mikhail, S. *Decision-making Process for Implementing DFMA at IGT*, International Forum on DFMA, Providence, RI, June 2009.)

In 2008 Jim Hale found a valued ally to help him execute these tasks more efficiently, namely the DFMA software. According to Jim, the company uses this software in a number of ways.

Quoting. "When a customer sends a CAD model of a proposed new part, we transfer the geometry from CAD into DFMA. Based on the geometry, the material, and the initial machining process selected for manufacturing the part, the software can identify significant blocks of machining time, part handling and fixturing time, tooling costs and secondary process costs."

Design review. Sometimes, it is not the process but the design of the part that affects costs. In that case, Aztalan shares its design analysis with the design engineer. "Often, we are addressing a series of questions that come from our analysis" Hale says. "Is the part complex? Can it be made simpler, maybe more machine-friendly?"

"Are the specified tolerances overly tight? Is there a way to reduce the number of secondary operations, or can we reduce costs by making the part from a different material?" The answers to these questions can help engineers design costs out of a part while preserving its functionality.

Alternative manufacturing processes. After establishing a benchmark, Aztalan can study different methods of manufacturing the part to see if one is potentially less expensive. Here the process library in DFMA is especially helpful. "We are expert machinists" Hale points out, "but we can't be experts in every single process out there—Investment casting, or forging for instance." At this stage, the software provides valuable guidance—first in exploring which processes can manufacture the current design of the part, then in providing initial time and cost estimates including the cost of any tooling. "Once we have determined which are viable, affordable processes, we can consult experts in those processes for more information" says Hale "but the software helps us to focus our exploration."

The savings in manufacturing costs obtained by many companies who have implemented DFMA are astounding. As mentioned earlier, Ford Motor Company has reported savings in billions of dollars as a result of applying DFMA to the original Ford Taurus line of automobiles [19]. This is a high-volume product. At the other end of the spectrum, where production quantities are low, Brown & Sharpe were able, through DFMA, to introduce their revolutionary coordinate-measuring machine, the MicroVal, at half the cost of their competitors, resulting in a multimillion dollar business for the company [20].

QSTAR is a mass spectrometer manufactured by MDS Sciex. Mass spectrometers are large, sophisticated instruments produced in low volumes. The manufacturing team recognized that the ease of assembly would largely determine the cost, manufacturing efficiency, and field performance for the product. As originally constructed, the prototype was difficult to assemble and needed days of testing and tweaking. QSTAR engineers used the DFA software to analyze the existing design and to spark innovative ways to consolidate parts and eliminate assembly difficulties [21].

The DFA software flagged the number of fasteners connecting a stack of resistors and metal rings. In the initial concept, each of the 32 resistors were secured with four screws, which contributed heavily toward the 8-h assembly time. As an alternative, they designed a connection that allows a technician to press the resistors into the metal base.

In the end, the QSTAR team designed one reflector subassembly that can be put together in only 45 min and can be removed and serviced without disrupting the rest of the instrument. Whereas the prototype reflector contained 289 parts with 26 unique components, the final reflector module contains 144 parts with 21 unique components. Only three screws and three nuts hold all 144 parts together.

DFA practices saved money in other ways too. By reducing the part count, QSTAR engineers cut material costs by $35,000 per unit and reduced opportunities for design and manufacturing errors.

Most importantly, DFA helped shorten the development cycle by 20%. MDS SCIEX management calculates that getting to market in 14 months increased revenue by $20 million and allowed QSTAR to capture one-fifth of the global market in the first year of sales.

The next case illustrates that DFMA reduces service time as well as assembly time.

At Dell Corporation, the redesign of the Optiframe® chassis for PCs, saved Dell an estimated $32.5 million in reduced direct labor costs [22]. The company saved millions more by increasing throughput and thus postponing facility relocations that otherwise would have been required to boost manufacturing capability. The savings in material costs from chassis integration and the related supply chain optimization program was $11.6 million for 1998 and was predicted to be $35 million in 1999.

Mechanical assembly time was reduced by an average of 32%.
Purchased part count was reduced by 50%.
Screw type count was reduced by 67%.
Screw min/max count was reduced by 55%.
Average service time was reduced by 44%.

These reductions resulted in substantial gains in productivity for Dell. Throughput per hour per square foot in the factories showed a 78% improvement. Operator productivity increased from 1.67 units per hour per operator to 3.07 units, an 84% improvement.

1.9 Overall Impact of DFMA on U.S. Industry

The preceding case studies describe a few of the successes resulting from the application of DFMA software. A summary of the results of published case studies from various companies is presented in Table 1.5, which shows that the average part count reduction

TABLE 1.5

Results of 123 Published Case Studies Showing Improvements from the Application of the DFMA Software

	Average Reduction (%)	Number of Cases
Labor costs	42	8
Part count	53	103
Separate fasteners	57	21
Weight	22	21
Assembly time	59	68
Assembly cost	45	20
Assembly operations	54	25
Product development cycle	45	2
Total cost	50	32

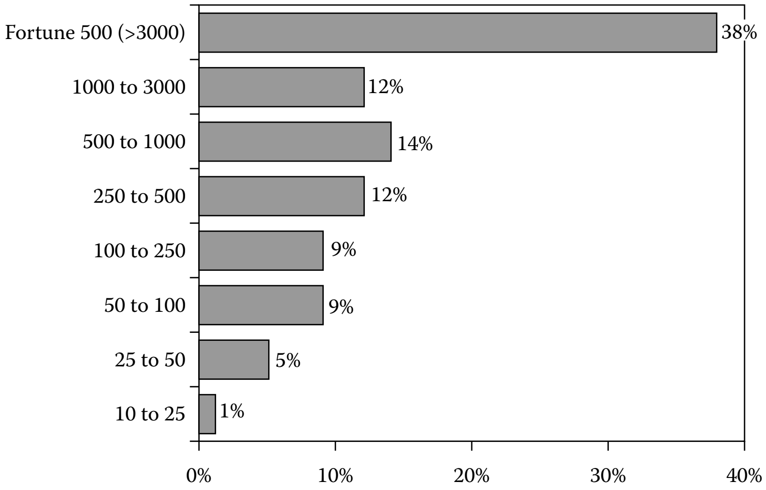


FIGURE 1.15
Percentage distribution of DFMA software users by company annual revenue.

is around 53%. The table also shows other improvements due to DFMA applications mentioned in the case studies. For example, 32 studies reported an average 50% reduction in the product cost.

According to our records, over 800 different U.S. companies have implemented the DFMA software since 1990. Of course, this figure does not indicate the number of individual users. The largest company, GM, reportedly has 1500 users, whereas others have only one. No other similar design methodology has had a significant impact on the U.S. industry as a whole. In the early 1980s, the Hitachi Assembly Evaluation Method (AEM) was licensed by a few major manufacturers; almost all now use DFMA instead.

Of course, not all the successful applications of DFMA are publicized. Companies are often reluctant to reveal their developments—certainly not before the product in question appears on the market. Thus, the published case studies form only a small proportion of the successes resulting from DFMA applications.

Of the Fortune 500 companies (those with annual revenues greater than about $3 billion) that are manufacturers, 60% have divisions or own companies that have licensed DFMA software. These represent about 38% of the licensed manufacturers (Figure 1.15).

The incentive to implement DFMA or concurrent engineering often arises because a company is under pressure to reduce manufacturing costs, improve time to market, and so on, because of competitive pressures. This was certainly true of the U.S. computer equipment and transportation industries 20 years ago. More recently, the U.S. aerospace and defense industries have been under pressure to become more competitive. It is not surprising that these developments are reflected in the industries using the DFMA software (Figure 1.16).

1.10 Conclusions

It is clear that the use of the DFMA software has a tremendous impact when properly applied in a concurrent engineering environment. Our experience in running DFMA

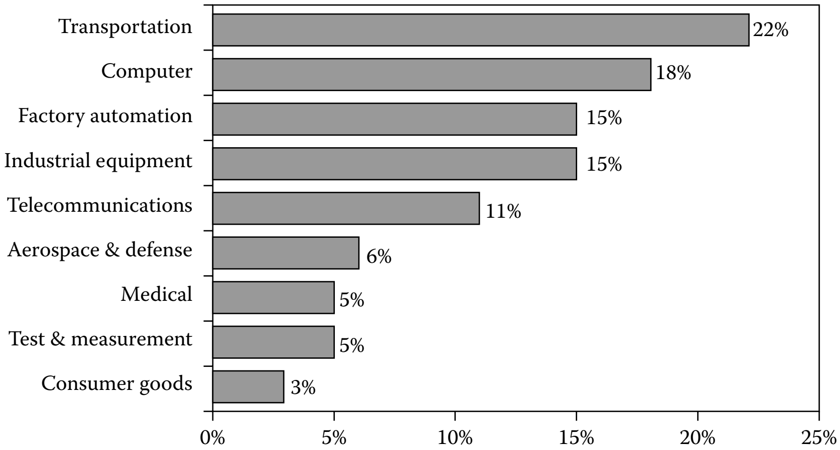


FIGURE 1.16
Percentage distribution of DFMA software users by industry.

design workshops has shown that significant ideas for design improvements can invariably be made in the space of only a few hours. Unfortunately, small manufacturers have not been able to take advantage of the huge potential of DFMA; they do not have the manpower or the necessary experience. Even with large companies, proven successes in one division do not necessarily spread to other divisions without management support and commitment. However, we remain encouraged by the continuing reports of substantial product improvements and often staggering cost savings obtained by both high- and low-volume manufacturers in the United States.

It should be noted that in all the published case studies mentioned, a systematic step-by-step DFMA analysis and quantification procedure was used. However, as pointed out earlier, it is still claimed by some that design rules or guidelines (sometimes called producibility rules) by themselves can give similar results. This is not so. In fact, guidelines or the qualitative procedures cart lead to increased product complexity, because they are usually aimed at simplifying the individual component parts, resulting in a design that has a large number of parts and poor quality and involves greater overheads, due to larger inventory, more suppliers, and more record keeping. Rather, the objective should be to utilize the capabilities of the individual manufacturing processes to the fullest extent in order to keep the product structure as simple as possible.

In spite of all the success stories, the major barrier to DFMA implementation continues to be human nature. People resist new ideas and unfamiliar tools, or claim that they have always taken manufacturing into consideration during design. The DFMA methodology challenges the conventional product design hierarchy. Designers are traditionally under great pressure to produce results as quickly as possible and often perceive DFMA as yet another time delay.

In fact, it has been established that the overall design development cycle is shortened through use of early manufacturing analysis tools, because designers can receive rapid feedback on the consequences of their design decisions where it counts—at the conceptual stage.

In conclusion, it appears that in order to remain competitive in the future, almost every manufacturing organization has to adopt the DFMA philosophy and apply cost quantification tools at the early stages of product design.

PROBLEMS

1. For each example in Figure 1.17, determine the theoretical minimum part count. Also, establish the part count when practical considerations are taken into account. In example b, assume both box and cover are die castings and, in example c, assume that the purpose is to cover the hole in the base plate.
2. Estimate the theoretical minimum part count for the Latch Mechanism shown in Figure 1.18.
3. Figure 1.3 shows a design recommendation which is shown to be misleading under a wide range of conditions. List the circumstances where the design recommendation might lead to a lower total manufacturing cost.
4. Perform a literature search to uncover reports where the applications of DFA or DFMA-type studies have resulted in product simplification or reductions in manufacturing costs. For each report give the reference and a brief summary of the findings.

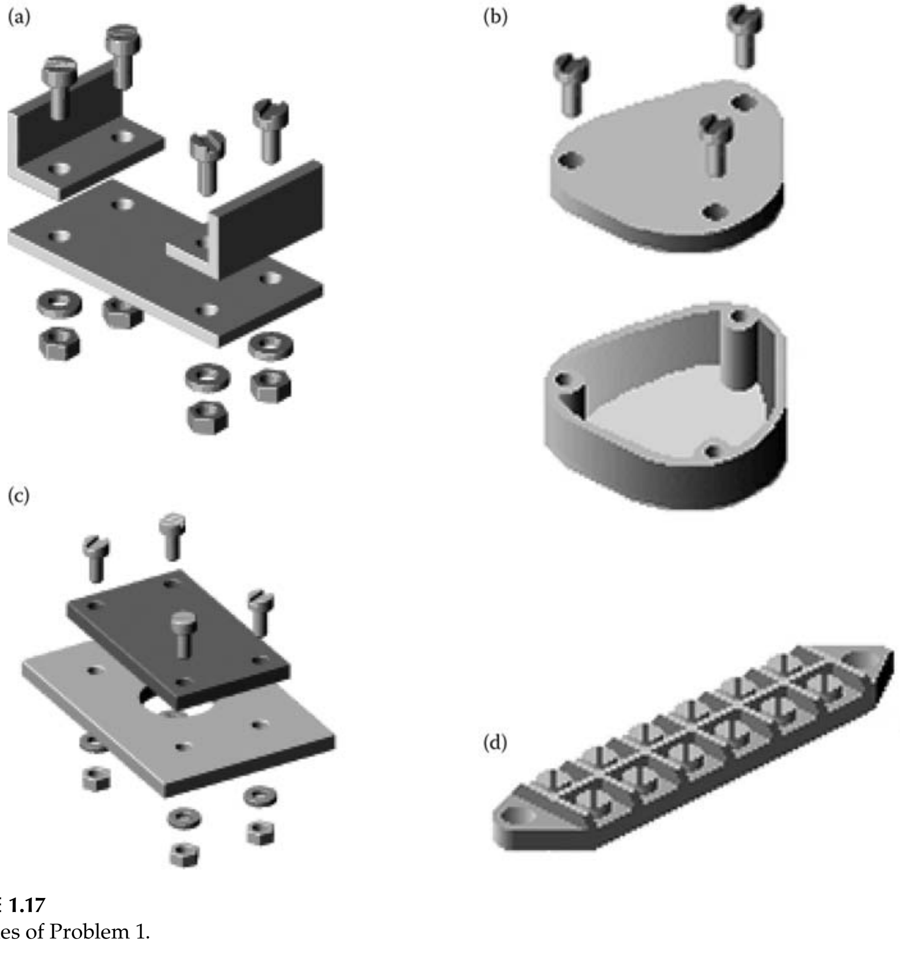


FIGURE 1.17
Examples of Problem 1.

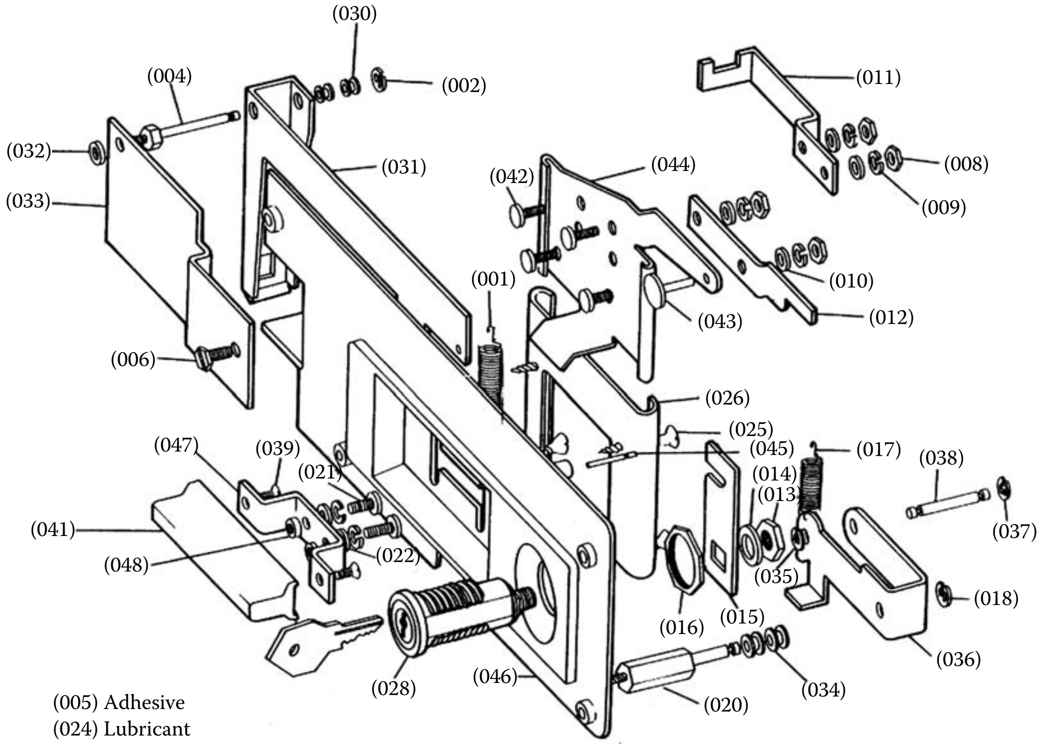


FIGURE 1.18
Latch mechanism.

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2

Selection of Materials and Processes

2.1 Introduction

An integral part of design for manufacture is the early selection of material and process combinations for the manufacture of parts, which can then be ranked according to various criteria. Unfortunately, designers tend to conceive parts in terms of the processes and materials with which they are most familiar, and they may, as a consequence, exclude from consideration processes and process/material combinations that might have proved to be more economic. Opportunities for major manufacturing improvements may be lost through such limited selections of manufacturing processes and the associated materials in the early stages of product design. This can be well illustrated by the results of a survey of designers' knowledge of manufacturing processes and materials carried out in Britain [1]. This survey covered a wide range of design offices in various sectors of industry. For manufacturing processes (Figure 2.1), more than half of those surveyed professed little or no knowledge of metal extrusion, two-third knew little about glass-reinforced molding, and over three quarters were uninformed about plastic extrusion, sintering, and the use of thermoset polymer fiber-reinforced sheet-molding compounds (SMC) and bulk-molding compounds (BMC). For less common processes, such as hot isostatic pressing, outsert molding, and superplastic forming, the percentage of designers claiming some process knowledge was only 6, 7, and 8, respectively. Similar results were found for materials, and Figure 2.2 illustrates designers' knowledge about a range of polymeric materials. This again shows a surprising lack of familiarity with some commonly used materials. The overall implication of these findings is that because material and process combinations are likely to be chosen from those with which designers are most comfortable, the possibilities of using other processes that may be much more cost-effective may be missed.

2.2 General Requirements for Early Materials and Process Selection

In order to be of real design value, the information on which the initial selection of material/process combinations and their ranking is to be based should be available at the early concept design stage of a new product. Such information might include, for example:

- Product life volume
- Permissible tooling expenditure levels
- Possible part shape categories and complexity levels

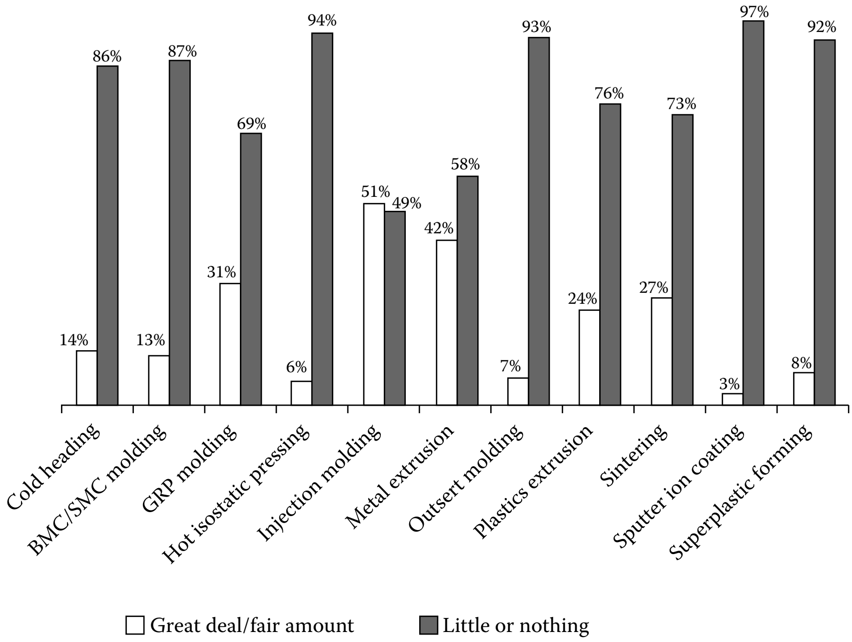

FIGURE 2.1
Survey of designers' knowledge of manufacturing processes. (Adapted from Bishop, R. *Huge Gaps in Designers' Knowledge Revealed*, Eureka, October 1985.)

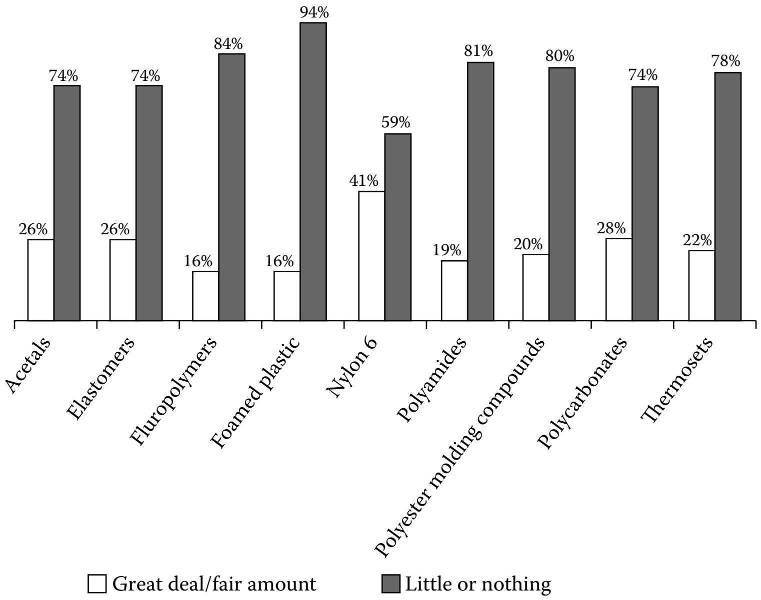

FIGURE 2.2
Survey of designers' knowledge of polymer materials. (Adapted from Bishop, R. *Huge Gaps in Designers' Knowledge Revealed*, Eureka, October 1985.)

- Service or environment requirements
- Appearance factors
- Accuracy factors

It is important to realize that for many processes the product and process are so intimately related that the product design must use an anticipated process as a starting point. In other words, many design details of a part cannot be defined without a consideration of processing. For this reason, it is crucial that an economic evaluation of competing processes be performed while the product is still at the conceptual stage. Such an early evaluation ensures that every economically feasible process is investigated further before the product design evolves to a level where it becomes process-specific.

As a design progresses from the conceptual stage to production, different methods can be used to perform the cost modeling of the product. At the conceptual stage, rough comparisons of the costs of products of similar size and complexity may be sufficient. While this procedure contains a certain degree of uncertainty, it only requires conceptual design information and is useful for the purpose of early economic comparison. As the design progresses and specific materials and processes are selected, more advanced cost modeling methods may be employed. These may be particularly useful in establishing the relationship between design features and manufacturing costs for the chosen process. The basis of several cost-estimation procedures for different processes is outlined in later chapters.

2.2.1 Relationship to Process and Operations Planning

There is an obvious relationship between the initial selection of process/material combinations and process planning. During process planning, the detailed elements of the sequence of manufacturing operations and machines are determined. It is at this stage that the final detailed cost estimates for the manufacture of the part are determined. Considerable work has been done in the area of computer-aided process planning (CAPP) systems [2–4], although closer examination shows that the majority of this work has been devoted to machining processes only. These systems are utilized after a detailed design of the part has been carried out, and the manufacturing processes are evident. The initial decision on the material and process combination to be used for the part is most important, as this determines the majority of subsequent manufacturing costs. The goal of systematic early material and process selection is to influence this initial decision on which combination to use, before a detailed design of the part is carried out and before detailed process planning is attempted.

2.3 Selection of Manufacturing Processes

The selection of appropriate processes for the manufacture of a particular part is based on a matching of the required attributes of the part and the various process capabilities. Once the overall function of a part is determined, a list can be formulated giving the essential geometrical features, material properties, and other attributes that are required. This represents a "shopping list" that must be filled by the material properties and process capabilities. The attributes on the "shopping list" are related to the final function of the part and are determined by geometric and service conditions.

Most component parts are not produced by a single process, but require a sequence of different processes to achieve all the required attributes of the final part. This is particularly the case when forming or shaping processes are used as the initial process, and material removal and finishing processes are required to produce some of the final part features. Even when using molding or casting processes, which can produce extremely complex geometries, there may be a number of features that are impossible to form and require subsequent machining operations. In other cases some of the features may be assigned to separate machining operations, because otherwise the die or mold may be uneconomically expensive. However, one of the goals of DFMA analysis is product structure simplification and parts consolidation. Experience shows that it is generally most economical to make best use of the capabilities of the initial manufacturing process in order to provide as many of the required attributes of a part as possible. As discussed in the introduction, the alternative approach of following guidelines to ensure that individual parts are as easy as possible to manufacture typically leads to an unnecessarily large number of separate parts, some of which add little value to the product.

There are hundreds of processes and thousands of individual materials. Moreover, new processes and materials are being developed continually. Fortunately, the following observations help to simplify the overall selection problem:

1. Many combinations of processes and materials are not possible. Figure 2.3 shows a compatibility matrix for a selected range of processes and material types.
2. Many combinations of processes are not possible and, therefore, do not appear in any processing sequences.
3. Some processes affect only one attribute of the part, particularly surface treatment and heat-treatment processes.
4. Sequences of processes have a natural order of shape generation, followed by feature addition or refinement by material removal and then material property or surface enhancement.

Processes can be categorized as:

- Primary processes
- Primary/secondary processes
- Tertiary processes

Some texts refer to primary processes as those used for producing the raw materials for manufacturing such as flat rolling, tube sinking, and wire drawing. In the context of producing component parts in this text, the term primary process refers to the main shape-generating process, assuming that the material has been purchased in the appropriate stock form (wire, tube, sheet, etc.). Such processes should be selected to produce as many of the required attributes of the part as possible and usually appear first in a sequence of operations. Casting, forging, and injection molding are examples of primary shape-generating processes.

Primary/secondary processes, on the other hand, can generate the main shape of the part, form features on the part, or refine features on the part. These processes appear at the start or later in a sequence of processes. This category includes material removal processes such as machining, grinding, and broaching.