

Contents

Preface.....	xix
Preface to the Second Edition.....	xxi
Preface to the First Edition.....	xxiii
Authors	xxv
Nomenclature	xxvii
1. Introduction	1
1.1 What Is Design for Manufacture and Assembly?	1
1.2 History	1
1.3 Implementation of Design for Assembly	4
1.4 Design for Manufacture	5
1.5 Producibility Guidelines	5
1.6 How Does DFMA Work?	8
1.7 Falsely Claimed Reasons for Not Implementing DFMA	15
1.7.1 No Time.....	15
1.7.2 Not Invented Here	15
1.7.3 Ugly Baby Syndrome.....	15
1.7.4 Low Assembly Costs	15
1.7.5 Low Volume.....	17
1.7.6 We Have Been Doing It for Years	17
1.7.7 It Is Only Value Analysis	17
1.7.8 DFMA Is Only One among Many Techniques	17
1.7.9 DFMA Leads to Products that are more Difficult to Service.....	18
1.7.10 I Prefer Design Rules.....	18
1.7.11 I Refuse to Use DFMA.....	18
1.8 What Are the Advantages of Applying DFMA during Product Design?.....	19
1.9 Overall Impact of DFMA on U.S. Industry	22
1.10 Conclusions.....	23
References	26
2. Selection of Materials and Processes	29
2.1 Introduction	29
2.2 General Requirements for Early Materials and Process Selection.....	29
2.2.1 Relationship to Process and Operations Planning	31
2.3 Selection of Manufacturing Processes	31
2.4 Process Capabilities	34
2.4.1 General Shape Attributes.....	34
2.4.2 DFA Compatibility Attributes.....	35
2.5 Selection of Materials	35
2.5.1 Grouping of Materials into Process Compatible Classes	35
2.5.2 Material Selection by Membership Function Modification	41
2.5.3 Material Selection by Dimensionless Ranking.....	43
2.6 Primary Process/Material Selection	52
2.7 Systematic Selection of Processes and Materials.....	57

2.7.1	Computer-Based Primary Process/Material Selection	57
2.7.2	Expert Processing Sequence Selector	57
2.7.3	Economic Ranking of Processes	61
	References	70
3.	Product Design for Manual Assembly	73
3.1	Introduction	73
3.2	General Design Guidelines for Manual Assembly	74
3.2.1	Design Guidelines for Part Handling	74
3.2.2	Design Guidelines for Insertion and Fastening	74
3.3	Development of the Systematic Design for Assembly Methodology	79
3.4	Assembly Efficiency	81
3.5	Classification Systems	82
3.6	Effect of Part Symmetry on Handling Time	85
3.7	Effect of Part Thickness and Size on Handling Time	88
3.8	Effect of Weight on Handling Time	89
3.9	Parts Requiring Two Hands for Manipulation	90
3.10	Effects of Combinations of Factors	90
3.11	Effect of Symmetry for Parts That Severely Nest or Tangle and May Require Tweezers for Grasping and Manipulation	90
3.12	Effect of Chamfer Design on Insertion Operations	91
3.13	Estimation of Insertion Time	94
3.14	Avoiding Jams during Assembly	95
3.15	Reducing Disc-Assembly Problems	97
3.16	Effects of Obstructed Access and Restricted Vision on Insertion of Threaded Fasteners of Various Designs	98
3.17	Effects of Obstructed Access and Restricted Vision on Pop-Riveting Operations	99
3.18	Effects of Holding Down	100
3.19	Manual Assembly Database and Design Data Sheets	103
3.20	Application of the DFA Methodology	104
3.20.1	Results of the Analysis	107
3.21	Further Design Guidelines	110
3.22	Large Assemblies	113
3.23	Types of Manual Assembly Methods	114
3.24	Effect of Assembly Layout on Acquisition Times	118
3.25	Assembly Quality	121
3.26	Applying Learning Curves to the DFA Times	123
	References	131
4.	Electrical Connections and Wire Harness Assembly	133
4.1	Introduction	133
4.2	Wire or Cable Harness Assembly	135
4.3	Types of Electrical Connections	138
4.3.1	Solder Connections	139
4.3.2	Low-Pressure Connections	139
4.3.3	High-Pressure Connections	141
4.4	Types of Wires and Cables	143
4.5	Preparation and Assembly Times	144

4.5.1	Preparation.....	144
4.5.2	Assembly and Installation.....	150
4.5.3	Securing	155
4.5.4	Attachment	158
4.6	Analysis Method.....	162
4.6.1	Procedure	163
4.6.2	Case Study	165
	References	184
5.	Design for High-Speed Automatic Assembly and Robot Assembly	185
5.1	Introduction	185
5.2	Design of Parts for High-Speed Feeding and Orienting.....	186
5.3	Example	189
5.4	Additional Feeding Difficulties	193
5.5	High-Speed Automatic Insertion.....	193
5.6	Example	197
5.7	Analysis of an Assembly.....	198
5.8	General Rules for Product Design for Automation.....	198
5.9	Design of Parts for Feeding and Orienting	203
5.10	Summary of Design Rules for High-Speed Automatic Assembly.....	206
5.10.1	Rules for Product Design.....	206
5.10.2	Rules for the Design of Parts.....	206
5.11	Product Design for Robot Assembly.....	206
5.11.1	Summary of Design Rules for Robot Assembly.....	212
	References	218
6.	Printed Circuit Board Design for Manufacture and Assembly	219
6.1	Introduction	219
6.2	Design Sequence for Printed Circuit Boards	219
6.3	Types of Printed Circuit Boards.....	220
6.3.1	Number of Sides.....	220
6.3.2	Number of Layers	221
6.3.3	Board Materials.....	221
6.3.4	Device Types.....	222
6.3.5	Copper Weight	222
6.4	Bare Board Manufacture.....	222
6.4.1	Basic Bare Board Costs.....	223
6.4.2	Number of Boards per Panel.....	225
6.4.3	Hole Drilling.....	226
6.4.4	Optional Bare Board Processes.....	226
6.4.5	Bare Board Testing.....	227
6.5	Terminology.....	227
6.6	Assembly of Printed Circuit Boards.....	228
6.6.1	Assembly Operations for Through-Hole Printed Circuit Boards.....	229
6.6.1.1	Automatic Dual Inline Package Insertion	230
6.6.1.2	Automatic Axial (VCD) Insertion	232
6.6.1.3	Automatic Single Inline Package Insertion	234
6.6.1.4	Automatic Radial Component Insertion.....	234
6.6.1.5	Semiautomatic Insertion	235

6.6.1.6	Manual Insertion.....	235
6.6.1.7	Robot Insertion.....	236
6.6.1.8	Inspection and Rework.....	236
6.6.2	Assembly of Surface-Mounted Devices.....	236
6.6.3	Soldering Processes.....	238
6.6.3.1	Wave Soldering.....	238
6.6.3.2	Reflow Soldering.....	238
6.6.4	Other Assembly Processes.....	239
6.6.4.1	Cleaning.....	239
6.6.4.2	Rework.....	239
6.6.4.3	Board Testing.....	240
6.6.5	Assembly Sequences for Printed Circuit Boards.....	240
6.7	Estimation of PCB Assembly Costs.....	242
6.7.1	Component Insertion Costs.....	243
6.7.1.1	Insertion Cost.....	244
6.7.1.2	Setup Cost.....	246
6.7.1.3	Rework Cost.....	247
6.7.1.4	Programming Cost.....	247
6.7.2	Worksheet for Printed Circuit Board Assembly Costs.....	248
6.7.3	Example.....	248
6.8	Case Studies in PCB Assembly.....	250
6.8.1	Measuring Instrument Connector Board.....	250
6.8.2	Power Supply.....	254
6.9	Glossary of Terms.....	256
	References.....	260
7.	Design for Machining.....	261
7.1	Introduction.....	261
7.2	Machining Using Single-Point Cutting Tools.....	261
7.3	Machining Using Multipoint Tools.....	266
7.4	Machining Using Abrasive Wheels.....	275
7.5	Standardization.....	281
7.6	Choice of Work Material.....	282
7.7	Shape of Work Material.....	284
7.8	Machining Basic Component Shapes.....	284
7.8.1	Disc-Shaped Rotational Components ($L/D \leq 0.5$).....	284
7.8.2	Short, Cylindrical Components ($0.5 < L/D < 3$).....	288
7.8.3	Long, Cylindrical Rotational Components ($L/D \geq 3$).....	288
7.8.4	Nonrotational Components ($A/B \leq 3$, $A/C \geq 4$).....	291
7.8.5	Long, Nonrotational Components ($A/B > 3$).....	293
7.8.6	Cubic, Nonrotational Components ($A/B < 3$, $A/C < 4$).....	293
7.9	Assembly of Components.....	296
7.10	Accuracy and Surface Finish.....	297
7.11	Summary of Design Guidelines.....	300
7.12	Cost Estimating for Machined Components.....	301
7.12.1	Material Cost.....	302
7.12.2	Machine Loading and Unloading.....	303
7.12.3	Other Nonproductive Costs.....	303

7.12.4	Handling between Machines.....	303
7.12.5	Material Type.....	305
7.12.6	Machining Costs	305
7.12.7	Tool Replacement Costs	307
7.12.8	Machining Data	308
7.12.9	Rough Grinding.....	310
7.12.10	Finish Grinding.....	313
7.12.11	Allowance for Grinding Wheel Wear	313
7.12.12	Allowance for Spark-Out.....	315
7.12.13	Examples	315
7.12.14	Machining Cost Estimating Worksheet.....	317
7.12.15	Approximate Cost Models for Machined Components	321
	References	329
8.	Design for Injection Molding	331
8.1	Introduction	331
8.2	Injection Molding Materials	331
8.3	Molding Cycle.....	332
8.3.1	Injection or Filling Stage	333
8.3.2	Cooling or Freezing Stage.....	334
8.3.3	Ejection and Resetting Stage	334
8.4	Injection Molding Systems	334
8.4.1	Injection Unit.....	335
8.4.2	Clamp Unit.....	335
8.5	Injection Molds.....	336
8.5.1	Mold Construction and Operation.....	336
8.5.2	Mold Types	338
8.5.3	Sprue, Runner, and Gates	340
8.6	Molding Machine Size.....	340
8.7	Molding Cycle Time.....	343
8.7.1	Injection Time.....	343
8.7.2	Cooling Time	344
8.7.3	Mold Resetting	347
8.8	Mold Cost Estimation.....	349
8.8.1	Mold Base Costs	349
8.8.2	Cavity and Core Manufacturing Costs.....	351
8.9	Mold Cost Point System	357
8.10	Estimation of the Optimum Number of Cavities.....	360
8.11	Design Example.....	363
8.12	Insert Molding.....	364
8.13	Design Guidelines.....	365
8.14	Assembly Techniques	366
	References	372
9.	Design for Sheet Metalworking	375
9.1	Introduction	375
9.2	Dedicated Dies and Pressworking	376
9.2.1	Individual Dies for Profile Shearing	377

9.2.2	Cost of Individual Shearing Dies	381
9.2.3	Individual Dies for Piercing Operations	387
9.2.4	Individual Dies for Bending Operations	389
9.2.5	Individual Dies for Deep Drawing	392
9.2.6	Miscellaneous Features.....	398
9.2.7	Progressive Dies.....	399
9.3	Press Selection	400
9.3.1	Cycle Times.....	405
9.4	Turret Pressworking	407
9.5	Press Brake Operations	410
9.6	Design Rules	413
	References	421
10.	Design for Die Casting.....	423
10.1	Introduction	423
10.2	Die-Casting Alloys.....	423
10.3	Die-Casting Cycle	425
10.4	Die-Casting Machines.....	425
10.4.1	Die-Mounting and Clamping Systems	425
10.4.2	Metal-Pumping and Injection Systems.....	426
10.4.3	Hot-Chamber Machines.....	426
10.4.4	Cold-Chamber Machines.....	427
10.5	Die-Casting Dies	428
10.5.1	Trimming Dies	429
10.6	Finishing.....	429
10.7	Auxiliary Equipment for Automation	431
10.8	Determination of the Optimum Number of Cavities.....	431
10.9	Determination of Appropriate Machine Size	436
10.9.1	Required Machine Clamp Force.....	436
10.9.2	Shot Volume and Material Cost per Part.....	438
10.9.3	Dimensional Machine Constraints	439
10.10	Die Casting Cycle Time Estimation.....	441
10.10.1	Ladling of Molten Metal	441
10.10.2	Metal Injection.....	441
10.10.3	Metal Cooling.....	442
10.10.4	Part Extraction and Die Lubrication	446
10.10.5	Trimming Cycle Time	448
10.11	Die Cost Estimation	449
10.11.1	Die Set Costs	449
10.11.2	Cavity and Core Costs.....	450
10.11.3	Trim Die Costs.....	451
10.12	Assembly Techniques.....	453
10.13	Design Principles	455
	References	458
11.	Design for Powder Metal Processing	461
11.1	Introduction	461
11.2	Main Stages in the Powder Metallurgy Process.....	462
11.2.1	Mixing	463

11.2.2	Compaction.....	463
11.2.3	Sintering	464
11.3	Secondary Manufacturing Stages.....	464
11.3.1	Repressing and Resintering	464
11.3.2	Sizing and Coining.....	464
11.3.3	Infiltration	464
11.3.4	Impregnation.....	465
11.3.5	Resin Impregnation.....	465
11.3.6	Heat Treatment.....	466
11.3.7	Machining.....	466
11.3.8	Tumbling and Deburring	466
11.3.9	Plating and Other Surface Treatments.....	466
11.3.10	Steam Treating.....	466
11.3.11	Assembly Processes.....	466
11.4	Compaction Characteristics of Powders	467
11.4.1	Powder Compaction Mechanics	468
11.4.2	Compression Characteristics of Metal Powders.....	470
11.4.3	Powder Compression Ratio	473
11.5	Tooling for Powder Compaction	473
11.5.1	Compaction Dies.....	474
11.5.2	Punches for Compaction.....	475
11.5.3	Core Rods for Through Holes	475
11.5.4	Die Accessories.....	476
11.6	Presses for Powder Compaction	476
11.6.1	Factors in Choosing the Appropriate Press	476
11.6.1.1	Punch Motions.....	476
11.6.1.2	Load Required	477
11.6.1.3	Fill Height.....	477
11.6.1.4	Ejection Stroke	478
11.6.1.5	Maximum Die Diameter	478
11.6.2	Presses for Coining, Sizing, and Repressing	478
11.7	Form of Powder Metal Parts.....	479
11.7.1	Profile Complexity	480
11.8	Sintering Equipment Characteristics	481
11.8.1	Sintering Equipment	481
11.8.1.1	Continuous-Flow Furnaces.....	482
11.8.1.2	Batch Furnaces.....	484
11.9	Materials for Powder Metal Processing	484
11.10	Contributions to Basic Powder Metallurgy Manufacturing Costs	486
11.10.1	Material Costs.....	486
11.10.2	Compacting Costs.....	492
11.10.2.1	Press Selection.....	492
11.10.2.2	Setup Cost.....	494
11.10.3	Compaction Tooling Costs.....	495
11.10.3.1	Initial Tooling Costs.....	495
11.10.3.2	Tool Material Costs	495
11.10.3.3	Tool Manufacturing Costs	497
11.10.3.4	Dies.....	497
11.10.3.5	Punches	498

11.10.3.6	Core Rods	500
11.10.3.7	Total Tool Manufacturing Costs	501
11.10.4	Tool Accessory Costs	501
11.10.5	Tool Replacement Costs	502
11.10.6	Validation of the Tool Cost-Estimating Procedure.....	503
11.10.7	Sintering Costs	503
11.10.7.1	Continuous-Flow Furnaces.....	504
11.10.7.2	Batch Furnaces.....	505
11.10.8	Repressing, Coining, and Sizing	506
11.11	Modifications for Infiltrated Materials	506
11.11.1	Material Costs.....	506
11.11.2	Compaction Costs	507
11.11.3	Sintering Costs	507
11.12	Impregnation, Heat Treatment, Tumbling, Steam Treatment, and Other Surface Treatments	507
11.12.1	Processing Costs	507
11.12.2	Additional Material Costs	507
11.12.2.1	Self-Lubricating Bearing Materials.....	508
11.12.2.2	Materials Impregnated with Oil or Polymer.....	508
11.13	Some Design Guidelines for Powder Metal Parts	509
11.14	Powder Injection Molding	510
11.14.1	Feedstock Preparation and Pelletization.....	511
11.14.2	Molding	512
11.14.3	Debinding	512
11.14.4	Sintering	514
11.14.5	Secondary Operations.....	515
11.14.6	Feedstock Characteristics	515
11.14.7	Material Costs.....	519
11.14.8	Mold Cavity Geometry	521
11.14.9	Molding Costs	521
	References	525
12.	Design for Sand Casting	527
12.1	Introduction	527
12.2	Sand Casting Alloys	528
12.3	Basic Characteristics and Mold Preparation	529
12.3.1	Sand Preparation.....	529
12.3.2	Gating System.....	529
12.3.3	Mold Risers and Chills.....	530
12.3.4	Pattern Types	531
12.3.5	Sand Compaction Methods	532
12.4	Sand Cores	533
12.5	Melting and Pouring of Metal.....	533
12.6	Cleaning of Castings	534
12.7	Cost Estimating	535
12.7.1	Metal Cost	535
12.7.2	Sand Costs.....	538
12.7.3	Tooling Costs	539

12.7.4	Processing Costs	542
12.8	Design Rules for Sand Castings.....	545
12.8.1	Avoid Sharp Angles and Multiple-Section Joints	545
12.8.2	Design Sections of Uniform Thickness	546
12.8.3	Proportion Inner Wall Thickness	547
12.8.4	Consider Metal Shrinkage in the Design	547
12.8.5	Use a Simple Parting Line	547
12.8.6	Define Appropriate Machining Allowances.....	548
12.8.7	Use Economical Tolerances	548
12.9	Example Calculations.....	549
	References	556
13.	Design for Investment Casting.....	559
13.1	Introduction	559
13.2	Process Overview.....	559
13.3	Pattern Materials	561
13.4	Pattern Injection Machines	561
13.5	Pattern Molds.....	563
13.6	Pattern and Cluster Assembly.....	563
13.7	Ceramic Shell Mold.....	563
13.8	Ceramic Cores.....	564
13.9	Pattern Meltout.....	565
13.10	Pattern Burnout and Mold Firing	565
13.11	Knockout and Cleaning	565
13.12	Cutoff and Finishing.....	566
13.13	Pattern and Core Material Cost.....	566
13.14	Wax Pattern Injection Cost	568
13.15	Fill Time.....	570
13.16	Cooling Time	570
13.17	Ejection and Reset Time.....	571
13.18	Process Cost per Pattern or Core	573
13.19	Estimating Core Injection Cost	574
13.20	Pattern and Core Mold Cost.....	575
13.21	Core Mold Cost.....	579
13.22	Pattern and Cluster Assembly Cost.....	579
13.23	Number of Parts per Cluster	581
13.24	Pattern Piece Cost.....	582
13.25	Cleaning and Etching.....	583
13.26	Shell Mold Material Cost.....	583
13.27	Investing the Pattern Cluster.....	584
13.28	Pattern Meltout.....	585
13.29	Burnout, Sinter, and Preheat.....	585
13.30	Total Shell Mold Cost.....	585
13.31	Cost for Melting Metal	586
13.32	Raw Base Metal Cost	590
13.33	Ready-to-Pour Liquid Metal Cost	590
13.34	Pouring Cost	590
13.35	Final Material Cost.....	591

13.36 Breakout.....	592
13.37 Cleaning.....	593
13.38 Cutoff.....	593
13.39 Design Guidelines.....	596
References.....	597
14. Design for Hot Forging.....	599
14.1 Introduction.....	599
14.2 Characteristics of the Forging Process.....	599
14.2.1 Types of Forging Processes.....	599
14.3 Role of Flash in Forging.....	600
14.3.1 Determination of the Flash Land Geometry.....	601
14.3.2 Amount of Flash.....	603
14.3.3 Webs in Forgings.....	605
14.4 Forging Allowances.....	605
14.5 Preforming during Forging.....	606
14.5.1 Die Layout.....	611
14.6 Flash Removal.....	613
14.7 Classification of Forgings.....	614
14.7.1 Forging Complexity.....	616
14.7.1.1 Shape Complexity Factor.....	616
14.7.1.2 Number of Surface Patches in the Part.....	617
14.8 Forging Equipment.....	617
14.8.1 Gravity Drop Hammers.....	617
14.8.2 Double Acting or Power Hammers.....	618
14.8.3 Vertical Counterblow Hammers.....	618
14.8.4 Horizontal Counterblow Hammers.....	619
14.8.5 Mechanical Presses.....	619
14.8.6 Screw Presses.....	620
14.8.7 Hydraulic Presses.....	620
14.8.8 Choice of Forging Machine Type.....	620
14.8.9 Comparisons of Forging Equipment.....	621
14.9 Classification of Materials.....	621
14.10 Forging Costs.....	624
14.10.1 Material Costs.....	626
14.10.2 Equipment Operating Costs.....	627
14.10.3 Examples of Equipment Selection.....	629
14.10.4 Forging Processing Costs.....	630
14.10.5 Forging Machine Setup Costs.....	632
14.11 Forging Die Costs.....	633
14.11.1 Initial Die Costs.....	633
14.11.2 Estimation of Costs for Multi-Impression Forging Dies.....	634
14.11.2.1 Die Material Costs.....	634
14.11.2.2 Multi-Impression Die Manufacturing Costs.....	636
14.12 Die Life and Tool Replacement Costs.....	638
14.13 Costs of Flash Removal.....	640
14.13.1 Flash Removal Processing Costs.....	640
14.13.2 Tooling Costs for Flash Removal.....	641

14.14 Other Forging Costs 642

 14.14.1 Billet Preparation 642

 14.14.2 Billet Heating Costs 643

References 646

Index 649