

ABSTRACT

Title of Thesis: COST AND PERFORMANCE EVALUATION
MODELS FOR COMPARING MULTI-SHOT AND
TRADITIONAL INJECTION MOLDING

Degree candidate: Gregory Thomas Fowler

Degree and year: Master of Science, 2004

Thesis directed by: Associate Professor Satyandra K. Gupta
Department of Mechanical Engineering

Multi-shot molding is rapidly becoming a viable manufacturing process alternative to traditional injection molding with assembly operations due to potential benefits in both cost and quality of the end products. With these new manufacturing processes comes a need to develop new tools for analyzing products at the conceptual design level in order to choose the best manufacturing process.

This thesis presents two complementary models for comparing multi-shot molding with traditional injection molding using cost and performance-based metrics. This work is mainly for comparative analysis of two manufacturing processes. The models were developed by expanding and combining existing academic work with current industry practices to provide a comprehensive framework for product comparison and process selection. The models were shown to provide results on two separate case studies. This research is a step towards automating the design and process-selection of injection molded components.

COST AND PERFORMANCE EVALUATION MODELS FOR COMPARING MULTI-
SHOT AND TRADITIONAL INJECTION MOLDING

by

Gregory Thomas Fowler

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2004

Advisory Committee:

Associate Professor Satyandra K. Gupta, Chair/Advisor
Associate Professor Hugh A. Bruck
Associate Professor Jeffrey W. Herrmann

© Copyright by
Gregory Thomas Fowler
2004

ACKNOWLEDGEMENTS

Above all I would like to express my sincerest gratitude for Dr. Gupta, who has been a teacher, mentor, and friend throughout both my undergraduate and graduate education. Without his unfailing patience, guidance and motivation, none of this work would have been possible. It has truly been a pleasure working under him.

I would also like to thank Dr. Bruck and Dr. Herrmann, both for being on my thesis committee as well as for their individual contributions to my education through collaborations and teaching.

Furthermore, I must show my appreciation for various behind-the-scenes faculty and staff at the University of Maryland, especially in the Mechanical Engineering Department and the Institute for Systems Research. Without their invaluable academic and administrative assistance, this work could have never been completed.

Additionally, I would like to thank all of my wonderful friends and colleagues for supporting me and enriching my life. Special mention should be given to Kristin, who I appreciate more than words can tell. She inspires and motivates me to do the best I can. Thanks for putting up with me throughout the years!

Finally, I would like to dedicate this work to my parents, Jay and Stephanie Fowler. Their incessant generosity, support, and love have fueled me through the various obstacles in my life. Without them, I would not be where I am today.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ABBREVIATIONS	xii
CHAPTER 1 – INTRODUCTION	1
1.1 – Background.....	1
1.1.1 – Multi-Material Terminology	1
1.1.1.1 – Multi-Material Objects	1
1.1.1.2 – Multi-Material Molding.....	2
1.1.1.3 – Multi-Material Interfaces.....	3
1.1.1.4 – Combination Interfaces	5
1.1.2 – Advantages of Multi-Material Technology	5
1.1.2.1 - Multi-Color Components.....	5
1.1.2.2 - Skin/Core Arrangement Components.....	6
1.1.2.3 - In-Mold Assembled Components	8
1.1.2.4 - Selective Compliance Components.....	9
1.1.2.5 - Soft-Touch Components.....	10
1.1.2.6 – Economic Benefits and Summary.....	11
1.1.3 – Disadvantages of Multi-Material Technology	11
1.2 – Injection Molding Processes	12
1.2.1 – Single-Material Molding	12
1.2.1.1 – Single-Material Molding Equipment.....	13
1.2.1.2 – The Single-Material Injection Molding Process	19
1.2.2 – Multi-Material Molding.....	20
1.2.2.1 – General Multi-Material Molding Equipment.....	21
1.2.2.2 – Insert Molding and Over molding	23
1.2.2.3 – Multi-Component Molding	25
1.2.2.4 – Multi-Shot Molding	28
1.3 – Research Issues in Evaluation of MSM.....	37
1.3.1 – Manufacturing Feasibility and Design-for-Manufacture.....	38
1.3.2 – Multi-Shot Molding Cost Estimation.....	39
1.3.2.1 – Material Costs	40
1.3.2.2 – Labor Costs.....	40
1.3.2.3 – Equipment Costs.....	41
1.3.2.4 – Tooling Costs	41
1.3.2.5 – Processing Costs	42
1.3.3 – Multi-Shot Molding Performance Evaluation	44
1.3.3.1 – Weight and Size	45
1.3.3.2 – Strength and Durability	45
1.3.3.3 – Tolerances and Accuracy of Movement	46
1.3.3.4 – Aesthetics and Ergonomics	47
1.4 – Summary and Thesis Scope.....	48
CHAPTER 2 – RELATED RESEARCH	49
2.1 – General Cost Modeling	49
2.1.1 – Levels of Cost Estimation Models	49

2.1.2 – Detailed Analysis Models	50
2.1.2.1 – Scaling Methods	50
2.1.2.2 – Resource-Based Modeling.....	51
2.1.2.3 – Technical Cost Modeling.....	52
2.1.2.4 – Activity-Based Costing	53
2.1.2.5 – Summary of Cost Analysis Models	54
2.1.3 – Types of Costs.....	54
2.1.3.1 – Fixed and Variable Costs.....	55
2.1.3.2 – Direct and Indirect Costs.....	57
2.1.3.3 – Overhead	57
2.2 – Process Selection and Comparison.....	59
2.2.1 – General Process Selection Methods	59
2.2.2 – Specific Process Comparison Methods.....	61
2.2.3 – Injection Molding Process Comparison	63
2.3 – Single Material Molding Cost Estimation	63
2.3.1 – Industrial Techniques.....	64
2.3.1.1 – Bryce’s Method	64
2.3.1.2 – Rosato’s Methods	69
2.3.1.3 – Space Limited’s Method.....	72
2.3.2 – Academic Work.....	74
2.3.2.1 – Boothroyd, Dewhurst and Knight’s Method	74
2.3.2.2 – Poli’s Method	81
2.3.2.3 – Fagade-Kazmer’s Method.....	89
2.3.3 – Software-Based Models	93
2.3.3.1 – Injection Molding Cost Estimator	93
2.3.3.2 – Manufacturing Advisory Service	94
2.3.3.3 – SEER DFM	96
2.4 – Multi-Material Molding Cost Estimation	97
2.4.1 – Case Study I: “Trio Knob”.....	97
2.4.2 – Case Study II: “Concept Part”.....	99
2.5 – Summary.....	102
CHAPTER 3 – COST ESTIMATION	103
3.1 – Introduction	103
3.1.1 – Model Purpose.....	103
3.1.2 – Model Embodiment.....	104
3.1.3 – Model Scope and Assumptions	107
3.1.3.1 – Input Parameters and Absolute/Relative Accuracy	107
3.1.3.2 – Process Capability Assumptions	108
3.1.3.3 – Molding Process and Equipment Assumptions	108
3.1.3.4 – Factory Dynamics and Labor Assumptions	110
3.1.3.5 – Product Restrictions.....	111
3.1.3.6 – Mold Tooling Assumptions.....	112
3.1.3.7 – Other Assumptions	113
3.1.4 – Model Application Example	113
3.2 – Model Formulation	115
3.2.1 – Notation Scheme	115
3.2.2 – Overall Cost Equations	117
3.2.2.1 – Case Switching	117
3.2.2.2 – Generic Per-Piece Costs	117
3.2.2.3 – Total Manufacturing Costs	121
3.2.3 – Production Parameters.....	124
3.2.3.1 – Production Quantities.....	126
3.2.3.2 – Production Rates	128
3.2.4 – Material Cost.....	135
3.2.4.1 – Resin Cost	135

3.2.4.2 – Fasteners Cost.....	139
3.2.4.3 – Miscellaneous Material Costs	139
3.2.5 – Tooling Cost.....	140
3.2.5.1 – Mold Bases Cost.....	140
3.2.5.2 – Mold Machining Cost	146
3.2.5.3 – Tolerance Costs	156
3.2.5.4 – Surface Finishing Costs	161
3.2.5.5 – Ejector System Costs.....	166
3.2.5.6 – Cooling System Costs.....	169
3.2.5.7 – Side Action Systems Costs.....	176
3.2.5.8 – Hot Runner Systems Costs.....	183
3.2.5.9 – Mold Setup Costs.....	185
3.2.6 – Basic Overhead Costs.....	186
3.2.6.1 – Labor Rates	188
3.2.6.2 – Machine Rates	190
3.2.6.3 – Factory Overhead Rates.....	192
3.2.7 – Capital Investment Costs.....	193
3.2.7.1 – Equipment Cost	193
3.2.7.2 – Capital Investment Parameters	199
3.2.8 – Plant Floor Space Costs.....	201
3.2.8.1 – Floor Space Used by Production Line	202
3.2.8.2 – Hourly Cost of Space	204
3.3 – Summary.....	204
CHAPTER 4 – PERFORMANCE EVALUATION	205
4.1 – Introduction	205
4.1.1 – Model Purpose.....	206
4.1.2 – Model Embodiment.....	206
4.1.3 – Model Scope and Assumptions	207
4.1.4 – Model Application Example	207
4.2 – Model Formulation	208
4.2.1 – Performance Aspect 1: Weight.....	208
4.2.2 – Performance Aspect 2: Interface Strength	209
4.2.2.1 – Definition of Interface Strength	209
4.2.2.2 – Types of Interface Strength Tests.....	210
4.2.2.3 – Prescribed Loadings and Constraints	211
4.2.2.4 – Conducting the Strength Tests	213
4.2.2.5 – Validity of Performance Aspect 2.....	219
4.2.3 – Performance Aspect 3: Assembly Clearance Tolerances	220
4.2.3.1 – Definition of Assembly Clearance Tolerances	220
4.2.3.2 – Causes for Clearance Variations	222
4.2.3.3 – Measurement of Clearance Variations	224
4.2.3.4 – Validity of Performance Aspect 3.....	226
4.2.4 – Performance Aspect 4: Aesthetics and Ergonomics	227
4.2.4.1 – PA 4a: Flash	227
4.2.4.2 – PA 4b: Crush.....	233
4.2.4.2 – Validity of Performance Aspect 4.....	235
4.3 – Summary.....	235
CHAPTER 5 – CASE STUDIES	237
5.1 – Case Study I: Knob	237
5.1.1 – Knob Product Description	237
5.1.1.1 – Functionality	238
5.1.1.2 – Materials	239
5.1.1.3 – Comparison of Variants	239
5.1.1.4 – Molding Considerations	240

5.1.2 – Knob Cost Estimation	241
5.1.3 – Knob Performance Evaluation	243
5.1.3.1 – PA1: Weight	243
5.1.3.2 – PA2: Interface Strength.....	243
5.1.3.3 – PA3: Assembly Clearances	244
5.1.3.4 – PA4a: Flash	244
5.1.3.5 – PA4b: Crush.....	247
5.1.3.6 – Summary and Conclusions	248
5.2 – Case Study II: Vent	248
5.2.1 – Vent Product Description	248
5.2.1.1 – Functionality	249
5.2.1.2 – Materials	250
5.2.1.3 – Comparison of Variants	251
5.2.1.4 – Molding Considerations	251
5.2.2 – Vent Cost Estimation	251
5.2.3 – Vent Performance Evaluation.....	254
5.2.3.1 – PA1: Weight	254
5.2.3.2 – PA2: Interface Strength.....	254
5.2.3.3 – PA3: Assembly Clearances	257
5.2.3.4 – PA4a: Flash	258
5.2.3.5 – PA4b: Crush.....	260
5.2.3.6 – Summary and Conclusions	261
5.2 – Summary.....	262
CHAPTER 6 – CONCLUSIONS	263
6.1 – Summary.....	263
6.2 – Research Contributions	265
6.3 – Industrial Benefits	265
6.4 – Directions for Future Work.....	267
6.4.1 – Expanding to <i>n</i> -Material Objects	267
6.4.2 – Including Other Multi-Shot Molding Processes	268
6.4.3 – Increasing Level of Automation	268
6.4.4 – Validation in Industry	269
APPENDICES.....	270
Appendix A – Input Variables	270
Appendix B – MATLAB Files	279
Appendix C – Engineering Drawings	288
Appendix D – FEA Loads & Restraints.....	292
REFERENCES.....	293

LIST OF TABLES

1) Table 2.1 – Resource-Based Modeling Parameters.....	51-52
2) Table 2.2 – Comparison of Three Cost-Estimation Techniques.....	91
3) Table 2.3 – Inputs/Outputs for IMCE.....	93-94
4) Table 2.4 – Inputs/Outputs for MAS’s IM module.....	95
5) Table 2.5 – Cost Comparison for Trio Knob Case Study.....	98
6) Table 2.6 – Cost Comparison for Concept Part Case Study.....	100-101
7) Table 3.1 – Poli’s “Assembly Advisor” for Estimating Assembly Times.....	134
8) Table 3.2 – Mold Surface Finishes.....	163
9) Table 3.3 – Structure of an Indexed Undercut List.....	177
10) Table 3.4 – Common Equipment for MMM and SMM&A.....	194
11) Table 4.1 – Generic Example of Performance Evaluation Output.....	206-207
12) Table 5.1 – Results of Weight Analysis for the Knob.....	243
13) Table 5.2 – Results of Flash Analysis for Knob.....	247
14) Table 5.3 – Results of Cost & Performance Analyses for the Knob.....	248
15) Table 5.4 – Results of Weight Analysis for the Vent.....	254
16) Table 5.5 – Results of Flash Analysis for Vent.....	260
17) Table 5.6 – Results of Cost & Performance Analyses for the Vent.....	261

LIST OF FIGURES

1) Figure 1.1 – Two types of multi-material objects.....	2
2) Figure 1.2 – Varying amounts of bonding at a microscopic interface.....	4
3) Figure 1.3 – A macroscopic interface.....	4
4) Figure 1.4 – Examples of multi-color MMO's.....	6
5) Figure 1.5 – The skin/core arrangement.....	6
6) Figure 1.6 – Examples of skin/core arrangement products.....	8
7) Figure 1.7 – Examples of in-mold assembled products.....	9
8) Figure 1.8 – Comparison of traditional and selective compliance clips.....	10
9) Figure 1.9 – Examples of products with soft-touch grips.....	10
10) Figure 1.10 – Schematic of a typical injection molding machine.....	13
11) Figure 1.11 – Photo of a typical injection molding machine.....	14
12) Figure 1.12 – Highly simplified schematic of a two-plate mold.....	15
13) Figure 1.13 – Simplified anatomy of a two-plate mold.....	16
14) Figure 1.14 – Molds with undercuts.....	17
15) Figure 1.15 – Schematic of molds with and without hot runners.....	18
16) Figure 1.16 – Photographs of hot runner systems.....	19
17) Figure 1.17 – Schematic of the injection molding process.....	20
18) Figure 1.18 – Multi-material molding process tree.....	21
19) Figure 1.19 – Four typical bi-material injection unit configurations.....	22
20) Figure 1.20 – Examples of over molded components.....	24
21) Figure 1.21 – Examples of Insert Molded Components.....	25
22) Figure 1.22 – Schematized bi-injection molding machine.....	26
23) Figure 1.23 – Schematized bi-injection molding process.....	26
24) Figure 1.24 – Schematized co-injection molding machine.....	27
25) Figure 1.25 – Schematized co-injection molding process.....	28
26) Figure 1.26 – Schematized rotary platen multi-shot injection molding machine.....	30

27) Figure 1.27 – Schematized rotary platen molding process.....	31
28) Figure 1.28 – Schematized index plate multi-shot injection molding machine.....	32
29) Figure 1.29 – Schematized indexing plate molding process.....	33
30) Figure 1.30 – Schematized core toggle mold.....	34
31) Figure 1.31 – Schematized core toggle molding process.....	35
32) Figure 1.32 – A typical rotary platen.....	36
33) Figure 1.33 – A rotary platen in operation.....	36
34) Figure 1.34 – Examples of multi-shot molded components.....	37
35) Figure 2.1 – A typical cost breakdown for a manufacturing scenario.....	55
36) Figure 2.2– Comparing two processes based on fixed and variable costs.....	56
37) Figure 2.3 – Calculating projected area.....	68
38) Figure 2.4 – Mold/part notations for Equations 2.33-2.36.....	85
39) Figure 2.5 – Screen capture of Kazmer’s IMCE.....	94
40) Figure 2.6 – Example input/output for MAS.....	96
41) Figure 2.7– Cost comparison plot for tri knob case study.....	99
42) Figure 2.8 – X-section of concept Part for Case Study II.....	100
43) Figure 2.9 – Molding Variant #6 for Case Study II.....	101
44) Figure 3.1 – Black box view of cost model.....	105
45) Figure 3.2 – Generalized layout of model’s tree structure.....	106
46) Figure 3.3 – Two variants of the hinge box.....	114
47) Figure 3.4 – Condensed roadmap for cost estimation model.....	123
48) Figure 3.5 – Production parameters for both variants.....	125
49) Figure 3.6 – Notations for mold base dimension.....	144
50) Figure 3.7 – Partitioning the core insert.....	150
51) Figure 3.8 – Example volume decomposition for material removal estimation.....	154
52) Figure 3.9 – Typical drilled cooling channels in a mold core.....	170
53) Figure 3.10 – Four unique channel layouts required between MMM & SMM&A.....	173
54) Figure 3.11 – Example of cooling channels drilled through entire mold base.....	175

55) Figure 3.12 – Example of counting internal/external undercuts.....	178
56) Figure 3.13 – Example of calculating undercut areas.....	179
57) Figure 3.14 – Sizing the Rotary Platen.....	199
58) Figure 3.15 – Common dual injection unit molding machine configurations.....	203
59) Figure 4.1 – One appropriate tensile loading scenario for the hinge box.....	211
60) Figure 4.2 – Examples of determining loading directions.....	213
61) Figure 4.3 – A compatibility matrix for various polymers.....	215
62) Figure 4.4 – Application of tensile loads as surface forces.....	217
63) Figure 4.5 – Two types of physical testing specimens.....	218
64) Figure 4.6 – optional testing specimen geometry (PA's 2e and 2f).....	219
65) Figure 4.7 – Examples of determining critical clearance dimensions.....	221
66) Figure 4.8 – Example of part shrinkage.....	223
67) Figure 4.9 – Notations for determining assembly accuracy.....	225
68) Figure 4.10 – Photo of multi-shot flash.....	228
69) Figure 4.11 – Example of flash forming in a single-material mold.....	229
70) Figure 4.12 – Example of flash forming in a multi-shot mold.....	230
71) Figure 4.13 – Determining flash lengths.....	232
72) Figure 4.14 – Example of multi-shot crush.....	233
73) Figure 4.15 – Schematic of multi-shot crush.....	234
74) Figure 5.1 - Three rendered views of the knob variants.....	238
75) Figure 5.2 - Drawings of the knob variants.....	239
76) Figure 5.3 - Plot Ia: Total Cost vs. Production Quantity.....	241
77) Figure 5.4 - Plot Ib: log-log plot of Unit Cost vs. Production Quantity.....	241
78) Figure 5.5 - Flash measurement for SMM&A knob, part A.....	245
79) Figure 5.6 - Flash measurement for MMM knob, part B.....	246
80) Figure 5.7 - Crush measurement for MMM knob.....	247
81) Figure 5.8 - Rendered view of the vent (SMM&A variant only).....	249
82) Figure 5.9 - Sectioned views of both vent variants.....	249

83) Figure 5.10 - Drawings of the vent variants.....	250
84) Figure 5.11 - Plot IIa: Total Cost vs. Production Quantity.....	252
85) Figure 5.12 - Plot IIb: log-log plot of Unit Cost vs. Production Quantity.....	253
86) Figure 5.13 - Stress distribution results from FEA analysis.....	256
87) Figure 5.14 – Close-up view of vents’ hinges and fit requirements.....	257
88) Figure 5.15 - Flash measurement for SMM&A vent, part A.....	259
89) Figure 5.16 - Flash measurement for SMM&A vent, part B.....	259
90) Figure 5.17 - Crush measurement for MMM vent.....	261
91) Figure 6.1 – Example of a multi-shot product studied for this research.....	265
92) Figure C1 – Detailed drawing of SMM&A knob, Part A.....	288
93) Figure C2 – Detailed drawing of SMM&A knob, Part B.....	289
94) Figure C3 – Detailed drawing of SMM&A vent, Part A.....	290
95) Figure C4 – Detailed drawing of SMM&A vent, Part B & hinge pin.....	291
96) Figure D1 – Constrained surfaces for FEA analysis.....	292
97) Figure D2 – Applied Loadings for FEA analysis.....	292

LIST OF ABBREVIATIONS

BD&K	- Boothroyd, Dewhurst, & Knight (3 authors)
DFM	- design for manufacture
DFX	- design for “X”
DIC	- digital image correlation
Eq./Eqs.	- Equation/Equations
FEA	- finite element analysis
F&K	- Fagade & Kazmer (2 authors)
FGM	- functionally gradient material (or functionally graded material)
Fig./Figs.	- Figure/Figures
IM	- injection molding
G&L	- Goodship & Love (two authors)
IMCE	- Injection Molding Cost Estimator (Dr. David Kazmer’s application)
MAL	- Manufacturing Automation Lab (at University of Maryland, College Park)
MAS	- Manufacturing Advisory Service (University of Berkeley’s application)
MM	- multi-material
MMM	- multi-material molding
MMO	- multi-material object
MMSLS	- multi-material selective laser sintering
MS	- multi-shot
MSM	- multi-shot molding
PA	- performance aspect
PBCM	- process-based cost modeling
SM	- single material
SDM	- shape deposition manufacturing
SMM	- single material molding
SMM&A	- single material molding and assembly

CHAPTER 1 – INTRODUCTION

This chapter presents the motivation behind the research. It begins by introducing the relevant terminology and technical background, and then details the advantages and disadvantages of using multi-material molding using several industry examples. A brief review of single material molding is included before an overview of several multi-material molding processes is presented. Finally, the main research issues are identified, and the scope of the thesis is stated.

1.1 – Background

This section introduces the basic concepts relevant to multi-material molding. Some common multi-material terminology is defined. Multi-material interfaces are discussed and the various advantages and disadvantages of multi-material molding are presented.

1.1.1 – Multi-Material Terminology

1.1.1.1 – *Multi-Material Objects*

Multi-material objects (MMO's) are defined as the class of objects consisting of two or more different materials; that is, they are heterogeneous. MMO's can have either continuously-varying material compositions or discrete sections of different homogenous materials. An example of the former type of MMO is “functionally graded materials” or “functionally gradient materials” (FGM's) [20]. FGM's are advanced composite structures in which the composition changes gradually over the volume, resulting in corresponding changes in the properties of the structure. An example of the latter type of MMO is any

type of object with distinct interfaces or boundaries separating the various materials. An example of each type of MMO is given in Fig. 1.1.

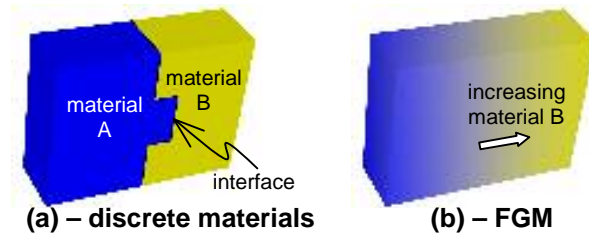


Figure 1.1 – Two types of multi-material objects

Different classes of MMO's can be produced by different types of non-traditional manufacturing processes, including layered manufacturing and multi-material molding. Layered manufacturing techniques such as shape deposition manufacturing (SDM) [34], [41], and multi-material selective laser sintering (MMSLS) [3] can be used to produce FGM's. Various polymer molding techniques can be used to produce MMO's with discrete material sections.

This research focuses solely on manufacturing discrete-sectioned MMO's using multi-material injection molding processes, so SDM processes and FGM's will not be discussed hereafter. Subsequently, the term “MMO” will refer only to discrete sectioned heterogeneous objects produced via some type of multi-material molding (MMM).

1.1.1.2 – Multi-Material Molding

MMM is usually accomplished through some form of specialized injection molding technique. This means that the various polymers composing the different material sections are heated to their melting temperatures, then injected in sequence into a mold or set of molds. The liquefied polymers then solidify into their desired shapes by taking on the form of the mold cavities in which they reside.

Because MMM techniques can be significantly different than traditional single-material molding (SMM), some new terminology has been adopted to better explain these

techniques and processes. The term ‘molding stage’ refers to a single step in the molding process in which one of the materials is injected into the mold. For example, an object composed of three different material sections has three distinct molding stages (one for each material). Because most molding involves injecting or shooting the polymer into the mold cavity, the word ‘shot’ is sometimes used in stead of ‘stage’. Two more terms that arise frequently in the context of MMM are ‘substrate’ and ‘overmold’. The substrate is the material that is injected first in a MMM process, usually forming the base or majority of the final component. The overmold is the subsequent shot which tends to form at least partially over top of the substrate.

Unlike single material (SM) components, multi-material (MM) components have a unique feature that is of great importance when designing effective components. Because the materials in MM objects must be somehow mated without the use of traditional fasteners (e.g. screws, welds, etc...), the topic of MM interfaces becomes important; that is, where and how do the separate materials connect to form the desired product. The three major types of interfaces are microscopic, mesoscopic, and macroscopic. These types of interfaces will be discussed below.

1.1.1.3 – Multi-Material Interfaces

Microscopic, or more commonly, “chemical” interfaces, are formed as a result of bonding along the mating surface between two materials. In particular, the driving force is cross-polymerization of the differing molecules of the two polymers. The extent and strength of the chemical interface is a complex function of many variables, including: molecular properties (e.g. size and weight), material processing temperatures, and viscosities. Fig. 1.2 shows three simple bi-material bars with different degrees of cross polymerization.

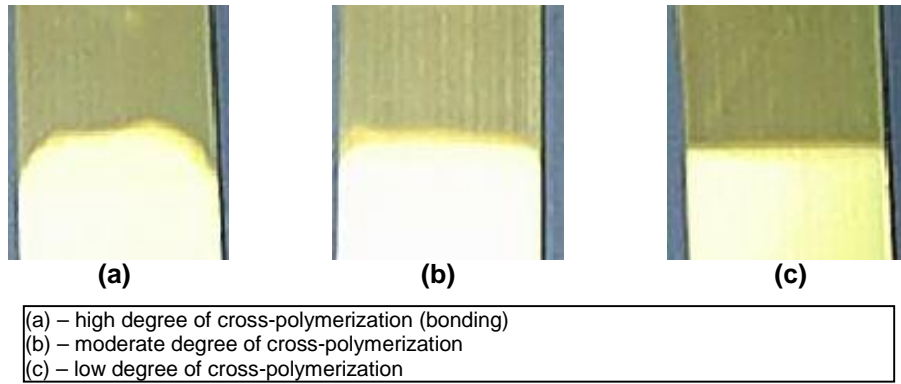


Figure 1.2 – Varying amounts of bonding at a microscopic interface

Macroscopic, or “interlocking” interfaces, are formed by mechanically locking the two materials together via some form of geometric interface. Such types of interfaces can be used to join two chemically incompatible materials (e.g. ABS and aluminum). Additionally, interlocking interfaces can be used to selectively control the relative movement of the separate materials along various degrees of freedom. Fig. 1.3 shows a schematic of a bar with a macroscopic, T-shaped interface. This configuration will only allow relative movement of the two materials along the z-axis.

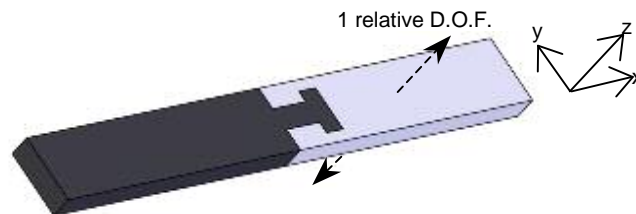


Figure 1.3 – A macroscopic interface

Mesoscopic interfaces fall right between microscopic and macroscopic interfaces; that is, they possess features with length scales on the order of 1-1000 nanometers. The mechanism via which mesoscopic interfaces maintain their integrity shares characteristics with molecular bonding and interlocking. Mesoscopic bonds can be formed by molding the first material and then finishing the surface along its shared interface with a bumpy or

grooved texture and then molding the second material around it where it will form along the mesoscopic features.

1.1.1.4 – Combination Interfaces

Some MMM processes allow components to be designed with any combination of the above mentioned interfaces. For example, it is possible to form an interface with molecular bonding along a geometric interlocking surface. Preliminary research shows that combination microscopic/macroscopic interfaces performed much better in tensile loading over flat bonded interfaces, which in turn, performed much better than non-bonded interlocking interfaces [22]. This suggests that when component strength is an important consideration, combination interfaces should be used whenever physically possible and financially feasible. The next best alternative would be to ensure the materials mate at a non-interlocking but bonded interface.

1.1.2 – Advantages of Multi-Material Technology

Multi-material manufacturing is becoming increasingly popular across multiple industries because MMO's possess many characteristics superior to traditional homogenous objects. These beneficial traits justify the manufacture, sale and use of products containing multi-material (MM) components. In fact, entire product assemblies are being replaced by single MM components with similar or better performance and cost characteristics. The majority of MMO's are produced using a class of manufacturing called multi-material molding (MMM). The major advantages of using MMM are detailed below.

1.1.2.1 - Multi-Color Components

MMM can produce MMO's that consist of a single, continuous body with sections of different colors and opacities [27]. This allows built-in features such as clear viewing windows and colored labels. This can provide significantly better aesthetics over an

assembly of different colored SM components, or just one SM component that is painted different colors on the surface. A multi-colored MMO will not experience paint chipping/flaking and eliminates the need for the costly secondary operations of assembly and/or painting. Fig. 1.4 shows some example multi-color MMO's. Fig. 1.4a shows an automotive taillight with a translucent red section and a translucent white section. Fig. 1.4b shows several examples of products with durable integrated labels. This eliminates the need to apply an adhesive label as a secondary operation.



(a) – multi-color taillight
Source: <http://bayerplastics.com>

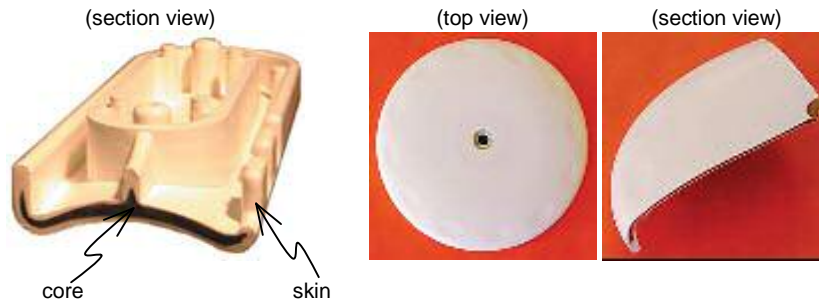


(b) – various bottles with molded-in labels
Source: <http://www.multicolor.com>

Figure 1.4 – Examples of multi-color MMO's

1.1.2.2 - Skin/Core Arrangement Components

Perhaps the current most popular use of MMM is in producing products with skin/core arrangements. A component with a skin/core arrangement has an outer 'skin' covering the inner 'core' of the component. Fig. 1.5a shows a skin/core car armrest and Fig. 1.5b shows a skin/core Frisbee.



(a) – skin/core armrest (b) – skin/core frisbee

Figure 1.5 – The skin/core arrangement

Sources: (a) <http://www.plasticstechnology.com/articles/200112cu1.html>
(b) http://www.immnet.com/article_printable.html?article=1766

The main benefit of the skin/core arrangement involves having the core completely insulated from the outside environment by the skin. This allows the core to be purely structural and/or cost-effective while the skin provides other functions. This arrangement can be exploited in many ways.

For one, the skin can serve as a thin coating which completely protects the interior of the component from such harmful agents as corrosive chemicals (e.g. acids, bases, salts, greases, etc...), extreme weather, and radiation. For example, a product that is intended to spend a majority of the time in the sun can be molded with a UV-resistant skin covering the structural core (e.g. lawn furniture).

Alternatively, the skin can offer visually or tactilely appealing aesthetics, while the less attractive core is completely hidden. For example, a colorful, shiny skin can add visual appeal to a component with an otherwise dull core material (e.g. toilet seat covers); just as a rubber soft-touch skin can improve the feel of a component with a rough, rigid core [39]. This completely eliminates the need for after-molding operations such as painting or lacquering.

Finally, the skin/core arrangement can simply be economical. The core, forming the bulk of the component, can be composed of off-grade, recycled, impure, or otherwise inferior (i.e. inexpensive) material while the less voluminous skin is a high-quality, expensive virgin material. For example, the Frisbee in Fig. 1.5b was made with 33% scrap plastic [35]. Additionally, this can reduce the overall weight of the component by up to 15%, particularly if the core is composed of a foam-like material [51].

Fig. 1.6 shows three examples of consumer products with the skin/core arrangement. Fig. 1.5a shows a bumper fascia with a strong core material covered by an attractive shiny red material. Fig. 1.6b shows a toilet seat with reduced weight and cost due

to the foam core and glossy skin. Fig. 1.6c shows several household brushes with attractive outer skins and inexpensive core materials.



(a) – bumper fascia



(b) – toilet seat



(c) – assorted brushes

Figure 1.6 – Examples of skin/core arrangement products

Source (a): <http://www.engelmachinery.com/pro-spec-inject-case.htm>

Sources (b) & (c): <http://www.presma.com/>

1.1.2.3 - In-Mold Assembled Components

Another important advantage of MMM is its ability to produce fully assembled components ‘in-mold’. This means that entire assemblies consisting of multiple pieces can be produced by a single set of molds, thereby eliminating the need for secondary assembly and the use of bolts, welds, glue, or other fasteners. This translates to a reduced part count and negligible assembly costs.

Additionally, gaskets or seals can be molded directly onto parts that need to form tight seals, such as lids, connectors and the like. MMM can produce reliable, cost-effective seals without secondary operations.

Two examples of in-mold assembly are shown in Fig. 1.7. Fig. 1.7a shows some children’s toys which are all produced using MMM. The 3-material dolls come out of the molds completely assembled and have rotating limbs and heads as well as multiple colored sections. Fig. 1.7b shows a one-piece syringe with a molded-in seal, attached plunger, and a closeable integrated lid.



(a) – articulated toys



(b) – one-piece syringe

Figure 1.7 – Examples of in-mold assembled products

Source: (a) <http://www.fickenscher.com>

Source: (b) <http://www.life-like.com/csyringe.html>

1.1.2.4 - Selective Compliance Components

Yet another use of MMM is producing compliant mechanisms, where the compliance of the material is selectively varied at strategic locations in the structure so that large deformations necessary for the structure to function properly, will occur only at those locations. Thus, MM objects can provide local control of mechanical properties of an object, thereby realizing concepts that would otherwise be impractical and/or extremely difficult to produce [36]. A simple example of this is shown in Fig. 1.8, which compares a pair of compliant MM clips to a pair of clips manufactured traditionally by assembling three homogenous parts together. The clips in Fig. 1.8b function by means of a compliant hinge composed of a softer plastic that is embedded in a rigid plastic which forms the handles/grips. The familiar clips in Fig. 1.8a utilize a metal spring and two separate halves which all have to be manufactured and assembled separately.

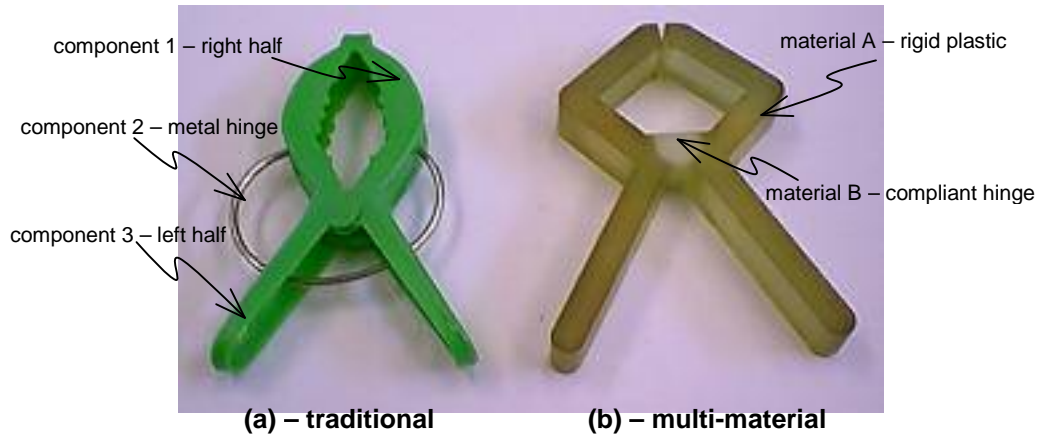


Figure 1.8 – Comparison of traditional and selective compliance clips

Additionally, the selective compliance components can allow selective vibration dampening. By discretely varying the material composition in select locations, certain frequencies can be attenuated by material discontinuities along interfaces.

1.1.2.5 - Soft-Touch Components

A final advantage of MMM is that allows products to be made with rigid plastic housings and softer rubbery gripping areas. Rigid substrate parts provide the necessary structural integrity, stiffness, and strength, while the soft-touch materials provide improved aesthetics, better tactile properties, and enhance the grip of products, while absorbing vibrations and reducing hand fatigue. Adding a soft feel also differentiates products and gives them a high-end look and feel. The end result is more durable products that are comfortable to use. Fig. 1.9 shows two examples of products using soft-touch plastics on the grip sections and hard plastic for the housings.

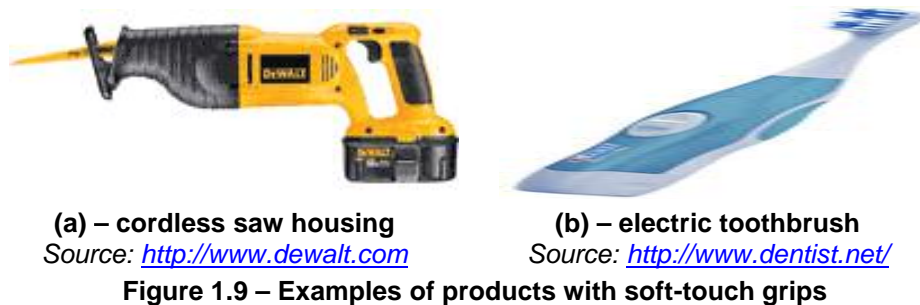


Figure 1.9 – Examples of products with soft-touch grips

1.1.2.6 – Economic Benefits and Summary

In summary, the above advantages of MMM, among others, are contributing to the growing industry popularity of replacing SM assemblies with MM components. The use of MM components over SM component assemblies can significantly reduce the cost and number of components required. It also reduces or eliminates downstream assembly and manufacturing operations, and thus reduces the time and expense. Most importantly, the use of different materials in different portions of an object allows the designers to fulfill different technical and aesthetic requirements in a single object. This expands the design space and allows designers to realize concepts that were not possible with single material objects [36].

The advantages discussed above can make MM products appear more attractive to potential consumers, possibly increasing market share and company profits. This important trait, along with the potential manufacturing cost savings are making MMM an increasingly appealing and viable set of processes.

1.1.3 – Disadvantages of Multi-Material Technology

Although the benefits discussed above seem to make MM technology far superior to traditional manufacturing techniques, there are a few main disadvantages that must be considered along with the benefits.

The bottom line is that the tooling and capital equipment required for MMM cost significantly more than single-material molding (SMM) equipment. While the total manufacturing costs associated with some MMM processes may in fact be less than SMM processes, the higher initial investment costs may discourage manufacturers from considering MMM. In the end, profits must be made and the use of such costly manufacturing technologies must be justified by increased savings in production or better

product sales. It becomes a difficult task for the decision-makers (executives, process engineers, designers, etc...) to accurately predict whether or not using MMM will be more profitable than conventional manufacturing methods.

A second disadvantage of MMM is its relative immaturity when compared with the established traditional molding methods. MMM technology is not fully developed and the processes are not fully understood like SMM. This can also cause manufacturing engineers to hesitate when choosing MMM over their tried-and-true traditional processes. Furthermore, the decision to adopt MMM requires machine operators, product designers, and manufacturing engineers to be specially trained for each process.

A final disadvantage worth note is the high degree of specialization inherent in the various MMM processes. There are a myriad of special processes each restricted to making a particular class of MMO's. For instance, co-injection and sandwich molding can only be used to make MMO's with a skin/core arrangement. The high specialization makes MMM technologies harder to reconfigure for different product lines

1.2 – Injection Molding Processes

This section describes the various manufacturing process used to make MMO's. It commences with a refresher subsection on SMM. Those familiar with basic injection molding may skip on to section 1.2.2.

1.2.1 – Single-Material Molding

Plastic injection molding (IM) is a versatile manufacturing process for producing large quantities of plastic parts. The possible materials and feasible geometries are countless, making IM the most popular process for manufacturing thermoplastic products. Traditional IM is only capable of producing SM parts. The SMM process is described below.

In essence, the IM process is simple: plastic is melted and injected into a cavity where it then cools and re-hardens in the shape of the cavity. The cooled part can then be ejected, and the cycle repeats. Although the concept is simple, the actual process must be carefully controlled to produce acceptable parts. Additionally, expensive and sophisticated equipment is required to produce even the simplest of parts. The basic equipment required is discussed below.

1.2.1.1 – Single-Material Molding Equipment

IM is carried out on a molding machine. There are many different types of specialized molding machines, but they all share the same four basic components: 1) an injection unit, 2) a clamping unit, 3) a mold, and 4) a controller [11]. A schematic of a generalized IM machine is illustrated in Fig. 1.10, and a photo of an industrial IM machine is shown in Fig. 1.11. Note that there are two platens (or “plattens”) on a molding machine - one moving, and one stationary. These plates are located on the clamping side and injection side of the machine, respectively.

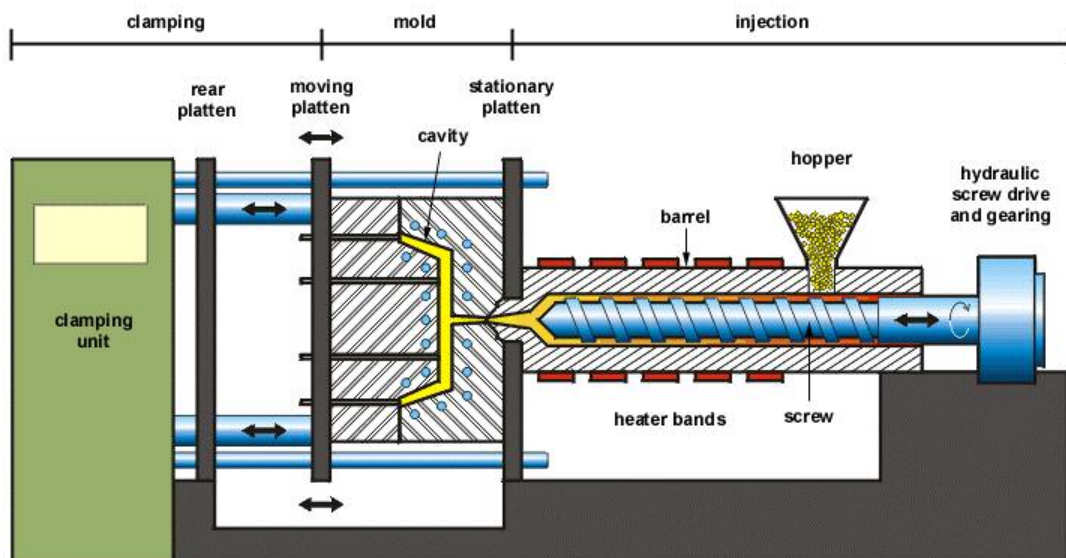


Figure 1.10 – Schematic of a typical injection molding machine
Source: http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm



Figure 1.11 – Photo of a typical injection molding machine

Source: http://www.arburg.com/english/products/po_a0001.htm

- The Injection Unit

Unsurprisingly, the purpose of the injection unit is to force, or “inject”, the molten plastic into the mold under pressure. The injection unit consists of a plastic-feeding hopper, a heated barrel (or “heating cylinder”), an injector, and an outlet nozzle. The injector is usually a reciprocating screw, but can also be a simpler hydraulic plunger-type device [11]. All of these components work in conjunction to feed the plastic, melt it, and then inject it into the mold. There are many different injection unit configurations available, based on the needs of the particular molding job.

- The Clamping Unit

The clamping unit works to hold the mold closed during injection and actuates the ejector when it opens. The clamping mechanism is either a hydraulic press or a mechanical lever system and must be strong enough to resist the large forces generated by the injection pressure on the mold walls. Additionally, the clamping unit must incorporate some sort of ejector device to facilitate part removal from the mold [11].

- The Mold

The mold is a complex tool that contains the cavity or cavities in which the plastic parts will cool. Because of its complexity, and the fact that it significantly affects the total cost of a molding operation, the mold receives special attention here. There are several

different types of molds, including two-plate molds, three-plate molds and multi-piece molds (“space puzzle molds”). Two-plate molds are the most common and will be the only type discussed hereafter.

In essence, two plate molds consist of a cavity located inside a set of plates divided into two halves: 1) a moving half, and 2) a stationary half [9]. The stationary half is located on the injection side of the molding machine, bolted onto the stationary platen and connected to the injection unit. The moving half of the mold is bolted onto the clamping unit and moves with it during the mold opening and closing phases. A highly simplified schematic of a two-plate mold and the part it would produce is illustrated in Fig. 1.12.

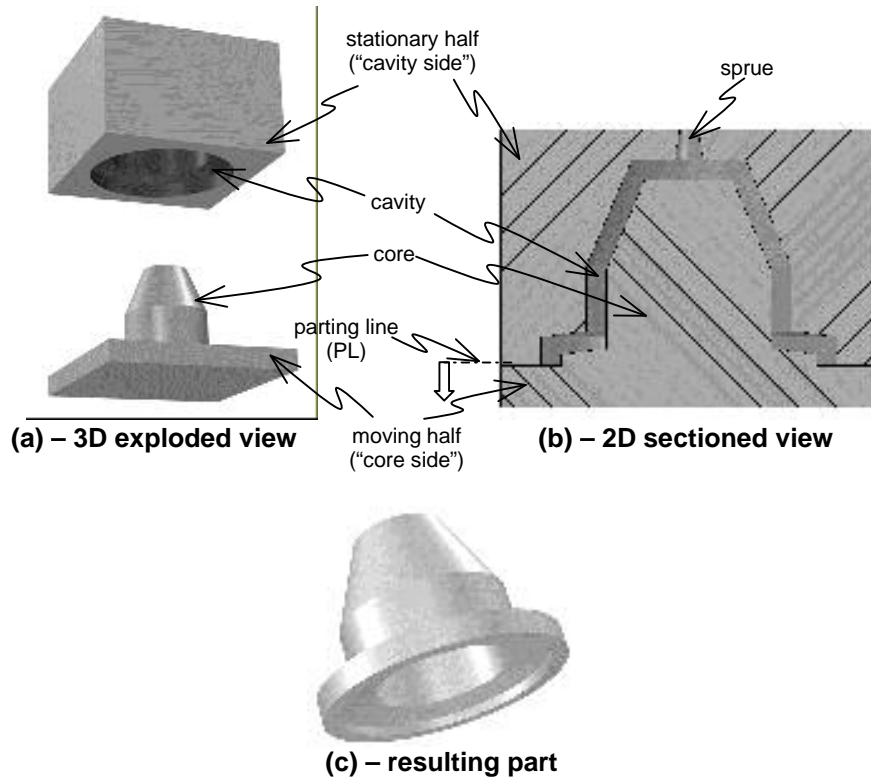


Figure 1.12 – Highly simplified schematic of a two-plate mold

In reality, the mold is not simply two halves with a single cavity. Rather, it is an intricate system of moving plates with a resin flow system (gates, runners, and a sprue) that feeds multiple cavities. Additionally, molds must have and a network of hydraulic cooling

lines as well as some type of part ejection system. Fig. 1.13 schematically illustrates a two-cavity, two-plate mold in greater detail than Fig. 1.12. Note that the only components of the mold that actually contain the geometry of the molded part are the core insert and cavity insert. The rest of the components serve as a support infrastructure for these pieces and are collectively referred to as the “mold base”. In many cases, it is possible to produce a family of different (but similarly-sized) parts on the same mold base by using different core/cavity inserts.

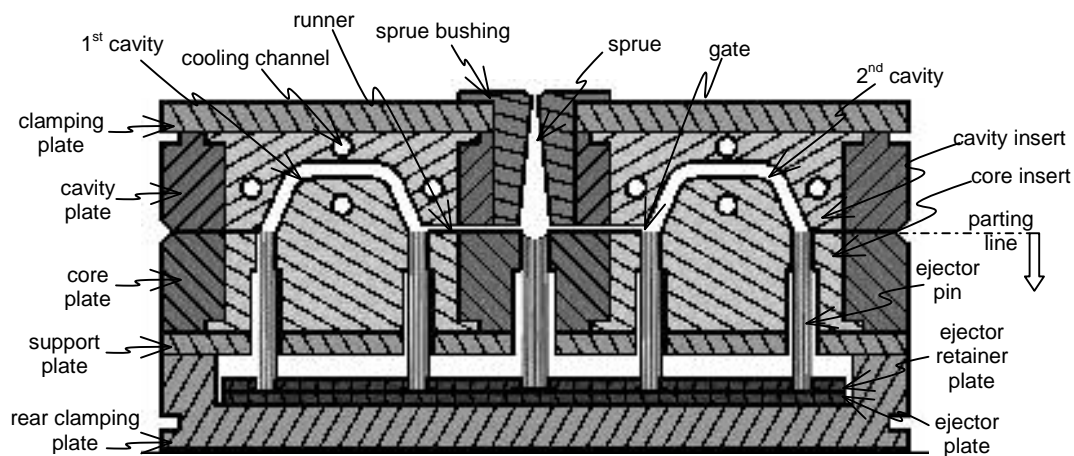


Figure 1.13 – Simplified anatomy of a two-plate mold

- **Optional Mold Subsystems**

There are several types of mold subsystems sometimes employed in special molding situations. While not required for general injection molding, they may serve to increase part quality, reduce costs, and/or produce features and geometries not normally realizable with standard equipment. Normally these devices must be custom-built directly into the mold base. Two common subsystems are described below.

A common type of optional mold subsystem is called a “side action”. Side actions are mechanisms which allow features known as undercuts to be molded into the part. Undercuts, or “cross-features” are features in the part that prevent standard two-piece molds from opening after the shot has solidified (this is called “mold locking”). For example, any

kind of external depression or hole parallel to the mold parting plane is a type of undercut. As a general rule, undercuts should be avoided wherever possible - there are numerous DFM rules that address this issue. However, if undercuts are essential in a particular part design, there are several means for producing such features, the most common of which are side action mechanisms. In essence, side actions are devices which actuate some sort of sliding mechanism that moves in a direction perpendicular to the mold opening direction. Figs. 1.14a and 1.14b illustrates an undercut created by part geometry, and Fig. 1.14c and 1.14d illustrates one way to produce undercuts without mold locking. After the part cools, the cam in Fig. 1.14d is shifted to the right, allowing the mold to be opened. The sideways movement of the slide can be actuated by one of several different kinds of side actions including a side-pull pin, or a hydraulic piston. It should be noted that such devices must be specifically made for each case, and can significantly drive up the cost of the mold base.

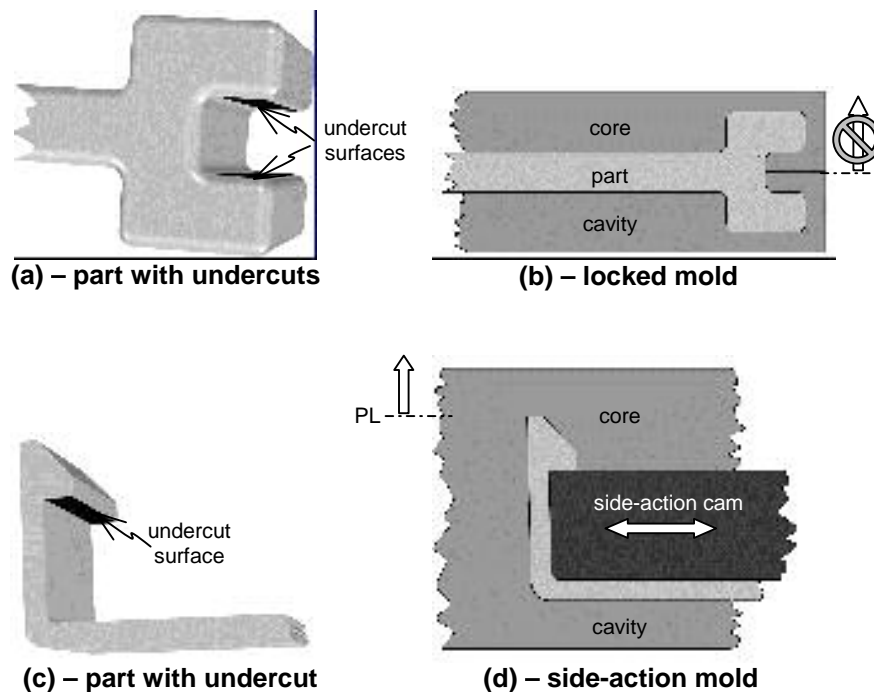


Figure 1.14 – Molds with undercuts

Another common type of mold subsystem is called a “hot runner system”. These devices essentially extend the nozzle of the injection unit directly into the cavity gate by keeping the resin molten through a system of heated channels. This eliminates the undesirable solidification of the sprue and runners, which are then ejected with the part (and in many cases still attached to it). This cuts down on resin scrap, manual runner-removal operations, and generally improves the resin flow characteristics inside the mold. Fig. 1.15 illustrates two molding scenarios: one without a hot runner system and one with. The resulting parts are shown below their respective mold configurations. The key difference to note is that the part in Fig. 1.15b has the hardened sprue attached to it while the part in Fig. 1.15d does not. It would have to be later removed through grinding or some other method. The removed sprues would then either be discarded or recycled into resin pellets and re-used. As with side actions, hot runner systems must be custom-built into each mold and drive up the total cost of the tool. Fig. 1.16 shows photos of typical hot runner systems.

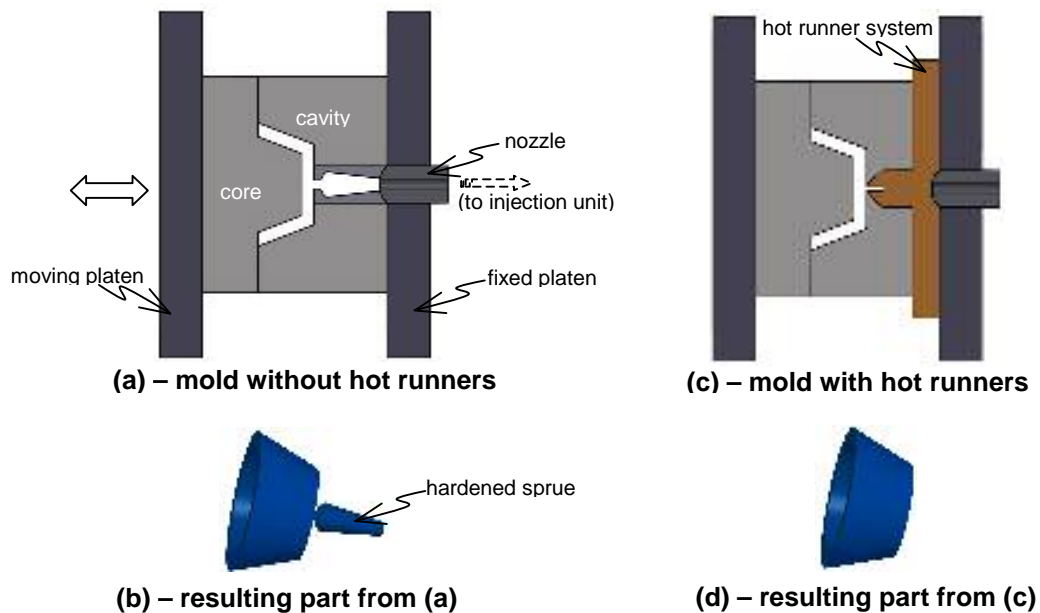


Figure 1.15 – Schematic of molds with and without hot runners

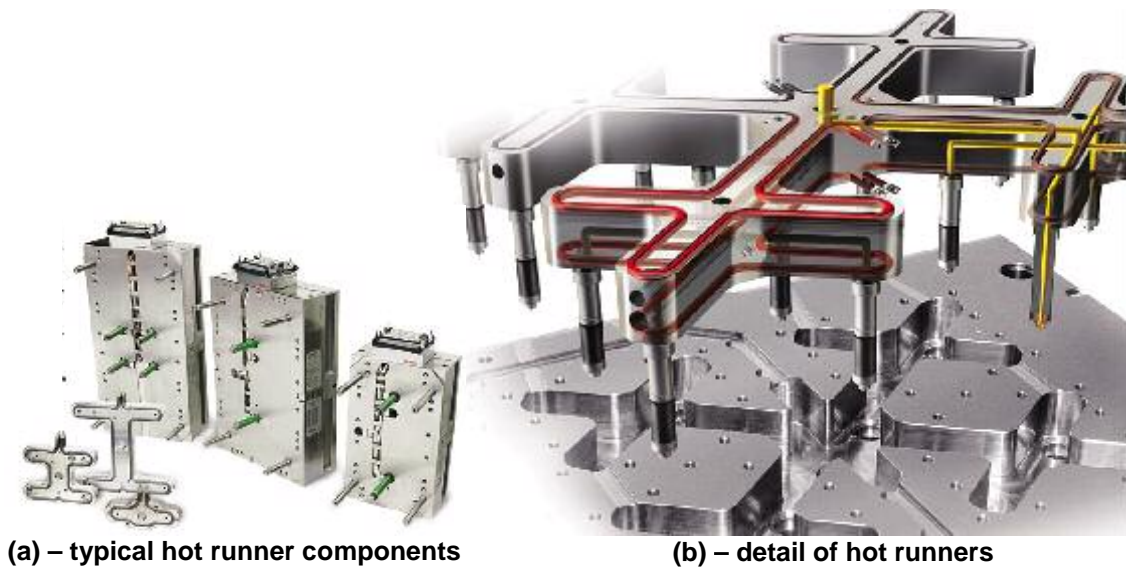


Figure 1.16 – Photographs of hot runner systems

Source: Husky Inc. product brochure

- **The Controller**

In order to operate the various machine components all molding machines must include a controller unit. The controller is a sophisticated programmable computer, responsible for a host of tasks. This includes: attaining and holding the desired process variables (e.g. injection pressure and temperature), controlling the cooling system, and actuating the clamp mechanism and any mold subsystems. It must be able to accurately control the process temperatures and time the various actions in order to produce decent molded parts. Typically, the controller is fully integrated with the molding press and can be specially configured to meet the specific needs of the molding job.

Machine manufacturers are able to provide custom IM machines with whatever combination of injection units, clamping units, controllers, and auxiliary equipment necessary for most particular molding applications.

1.2.1.2 – The Single Material Injection Molding Process

The basic SM injection molding process, as illustrated in Fig. 1.17, is outlined as follows:

- 1) **Closing the mold:** the mold closes so the cycle can begin.

- 2) **Plasticizing the resin:** (Figure 1.17a) the hopper feeds solid pellets or grains of the plastic resin into the barrel where it becomes molten due to the heating bands and friction caused by the rotating screw. The molten plastic accumulates at the front of the barrel (the nozzle side) as the screw retracts to the rear of the barrel.
- 3) **Injecting the resin:** (Figure 1.17b) when enough molten plastic has accumulated for a full shot, a valve in the nozzle is opened and the screw rapidly advances forward, quickly injecting the plastic into the mold cavity.
- 4) **Cooling the part:** (Figure 1.17c) The screw continues to push plastic into the mold in order to create a holding pressure. This ensures adequate filling. As this happens, the molten plastic begins to cool and solidify toward the inside. This natural cooling is expedited by convection due to coolant flowing through channels inside the mold.
- 5) **Ejecting the part:** (Figure 1.17d) After adequate cooling time has elapsed, the mold is opened. Some sort of ejector device is actuated in this process and the part is ejected from the mold and collected. After this, the cycle repeats from step 1.

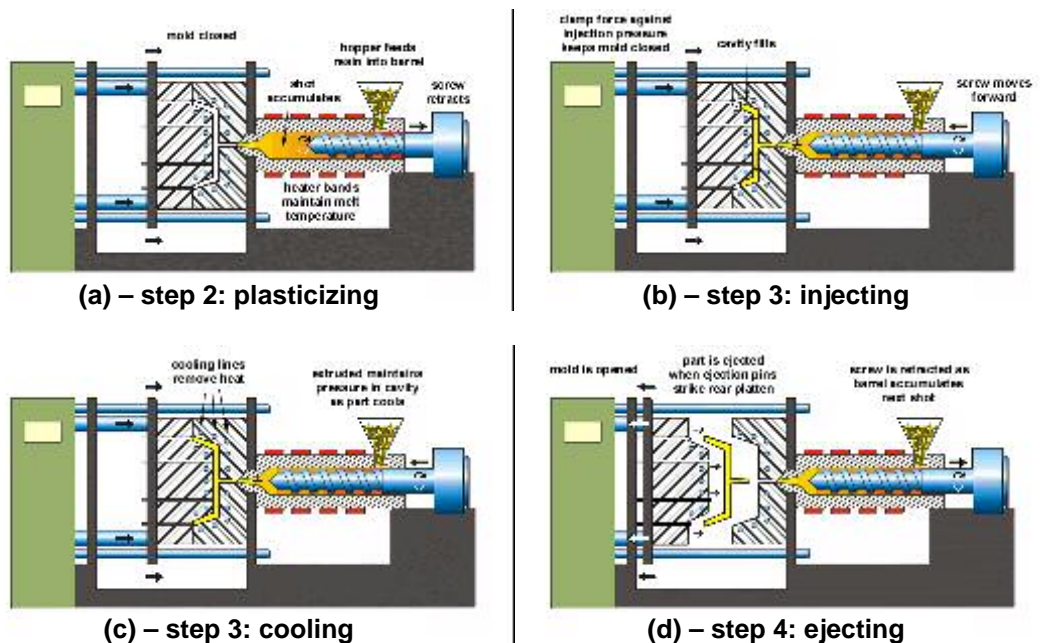


Figure 1.17 – Schematic of the injection molding process

Source: http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm

1.2.2 – Multi-Material Molding

MMM actually encompasses a wide range of processes, all capable of producing different types of MMO's. However in general, MMM is a more-advanced variation of SMM capable of producing objects with two or more different polymeric materials. Fig. 1.18 relates some of the more common MMM processes.

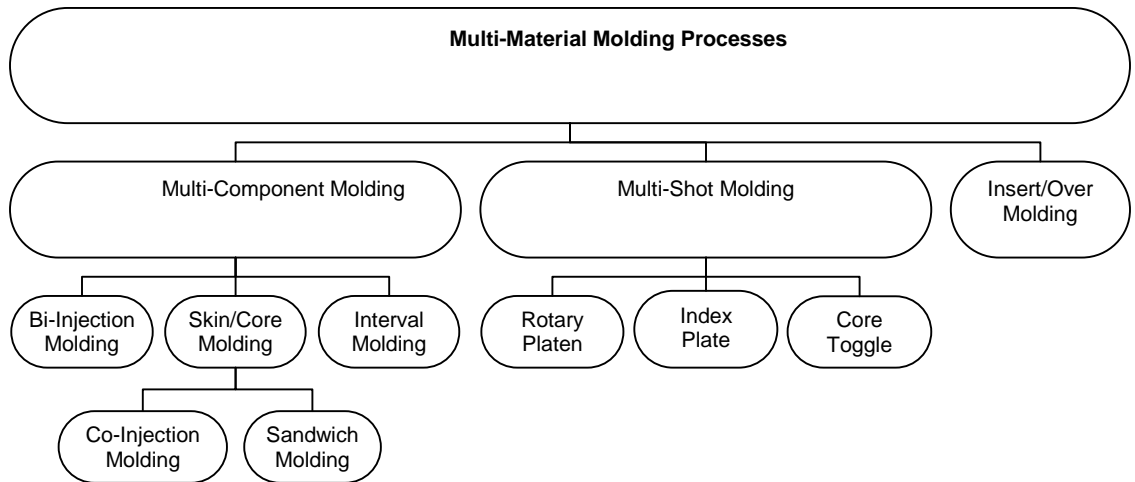


Figure 1.18 – Multi-material molding process tree

Multi-component molding is perhaps the simplest and most common form of MMM. It involves the simultaneous (or sometimes sequential) injection of two different materials through either the same or different gate locations in a single mold. Multi-shot (or “multi-stage”) molding is the most complex and versatile of the MMM process. It involves injecting the different materials into the mold in a specified sequence, where the mold cavity geometry may partially or completely change between sequences. Over-molding and insert molding simply involve molding a resin around a preformed part; either metal (as in insert molding), or a previously-made injection-molded plastic part (as in over-molding). Each of the three classes of MMM are considerably different. Each specific MMM process requires its own set of specialized equipment; however, there are certain equipment requirements that are generally the same for all types of MMM. This is discussed below.

1.2.2.1 – General Multi-Material Molding Equipment

As with SMM, all MMM machines have at least one injection unit, a clamp, and a mold. Unlike SMM, all MMM machines must have a separate material-feed system for each material used. Additionally, with the exception of some multi-component processes, all MMM machines must have a separate injection unit for each material. Furthermore, the

machine controller must be capable of controlling multiple separate injection sequences. Because two or more injection units are usually necessary, molders have many options in locating the separate injection units within the machine. There are many options, each with their own advantages, disadvantages, and capabilities. Some common injection unit configurations are schematically illustrated in Fig. 1.19.

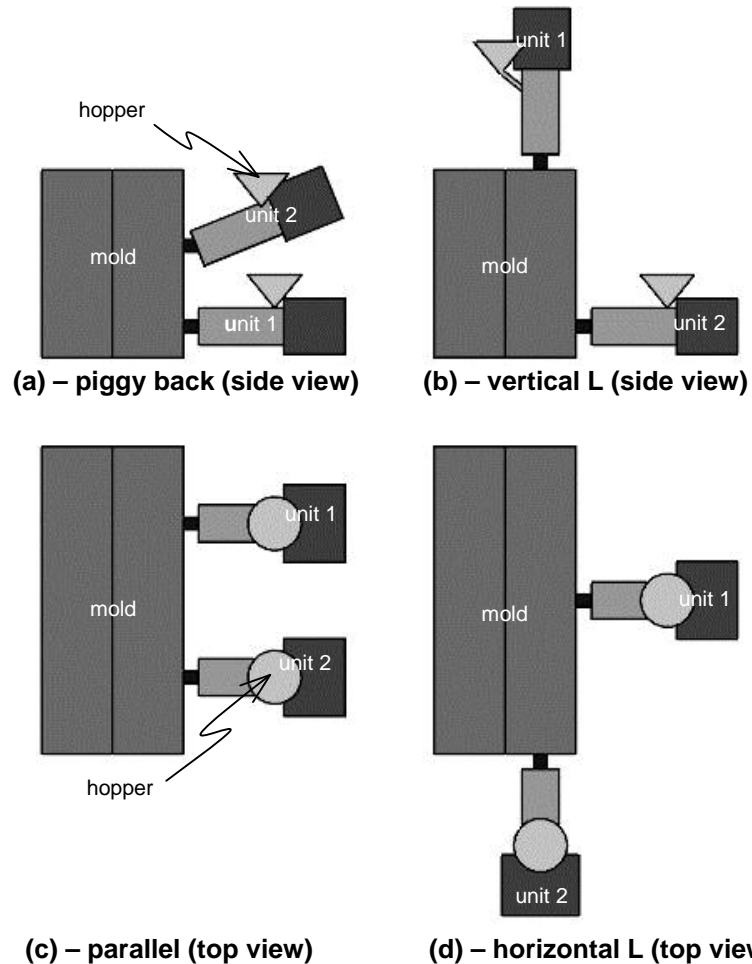


Figure 1.19 – Four typical bi-material injection unit configurations

As far as the clamping unit goes, no special equipment is usually required for MMM. That is, standard hydraulic or mechanical clamping units can be utilized, provided they provide enough clamping force.

The key equipment differences between SMM and MMM lie in the molds. Each process uses some modified form of the standard injection mold. The individual MMM process and their equipment will be discussed in detail below.

1.2.2.2 – Insert Molding and Over molding

Insert and over molding are simple variations of SMM. In particular, the only difference is that a preform, either metal or plastic, is placed into the mold before the resin is injected. Once the resin is injected into the mold, it flows over, under, and/or around the preform and hardens, locking the preform inside of it [49].

Over molding involves using SMM to manufacture a preform, then transferring it to another mold after it has at least partially cured. Then a second material is shot into the new mold with the preform inside. The preform is usually made in-house on a separate injection unit.

Insert molding is really just a special variation of over molding in which the preform is made some time before the injection cycle. This means the preform can be outsourced to a supplier. Additionally, the preform is often made of metal. The preform can be made by any standard injection molding or metal-forming or machining process. Usually the preform is knurled, roughened, or treated with an adhesive so that the resin bonds to its surface better. Additionally, mechanical interlocking is usually used to hold the preforms to the injected resin.

The only real difference between insert/over molding and SMM is that the preform has to be inserted, either manually or robotically, into the mold before each shot. Only one injection unit per molding machine is required, and there are no special equipment requirements on the mold or clamp side of the machine.

Overmolding is one process capable of producing a variety of products, including in-mold assemblies. In many cases, overmolding is used to provide soft-touch user-interface sections on rigid product housings. Typical applications are generally in the consumer goods industry, including such products as: power tools, hand tools, telephones, pagers, computer peripheral devices, small appliances, writing instruments, personal care products (e.g. hairbrushes and toothbrushes), and toys [31]. Additionally, overmolding is used extensively for producing electronic cabling. Fig. 1.20 shows some typical components manufactured using overmolding. Fig. 1.20a shows a paintball gun with a soft-touch handle. Fig. 1.20b shows a headset with rubberized earcup surrounds. Fig. 1.20c shows various tool housings with overmolded sections.



(a) – paintball gun housing
Source: <http://www.brasseagle.com>



(b) – headset earcups
Source: <http://www.avshop.com>



(c) – various tool housings
Source: <http://www.ammagazine.com>

Figure 1.20 – Examples of over molded components

Typical insert molding applications are wire and vacuum hose connectors, automobile air ducts, loudspeakers, hose end-connectors, and fill tubes. Fig. 1.21 shows some typical components manufactured using insert molding. Fig. 1.21a shows some

standard cables with clear plastic connector preforms. Fig. 1.21b shows various urethane rollers with metal axle preforms. Fig. 1.21c shows some steering column switch components with metal connector preforms.



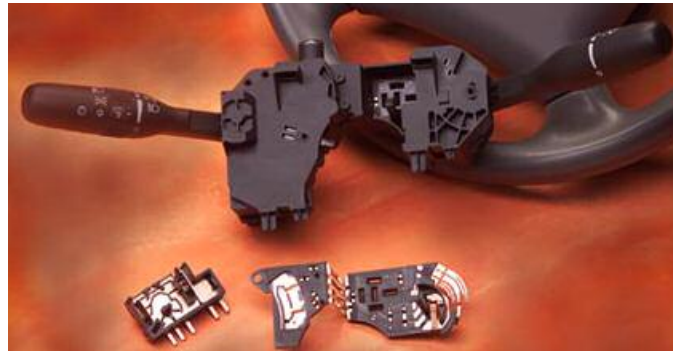
(a) – digital cables

Source: <http://www.psigroup.ca/products/>



(b) – urethane rollers

Source: <http://www.urethane.net/>



(c) – steering column switch components

Source: <http://www.triconinc.com>

Figure 1.21 – Examples of Insert Molded Components

1.2.2.3 – Multi-Component Molding

Multi-component molding simply involves simultaneously injecting two materials into a mold, via either the same or separate nozzles. There are several variations of this concept, with the most popular being co-injection molding, sandwich molding, bi-injection molding, and interval molding. These are all briefly discussed below.

Bi-injection molding is a process in which two different resins are simultaneously injected at different locations in the same mold. As the materials flow into the mold, they meet along a common interface and cross-polymerize. Bi-injection is relatively simple and is

only used to produce simple, low-tolerance parts. The interfaces naturally formed when the separate resins meet are usually very simple planar surfaces. Fig. 1.22 schematically illustrates a bi-injection molding machine and Fig. 1.23 illustrates the process.

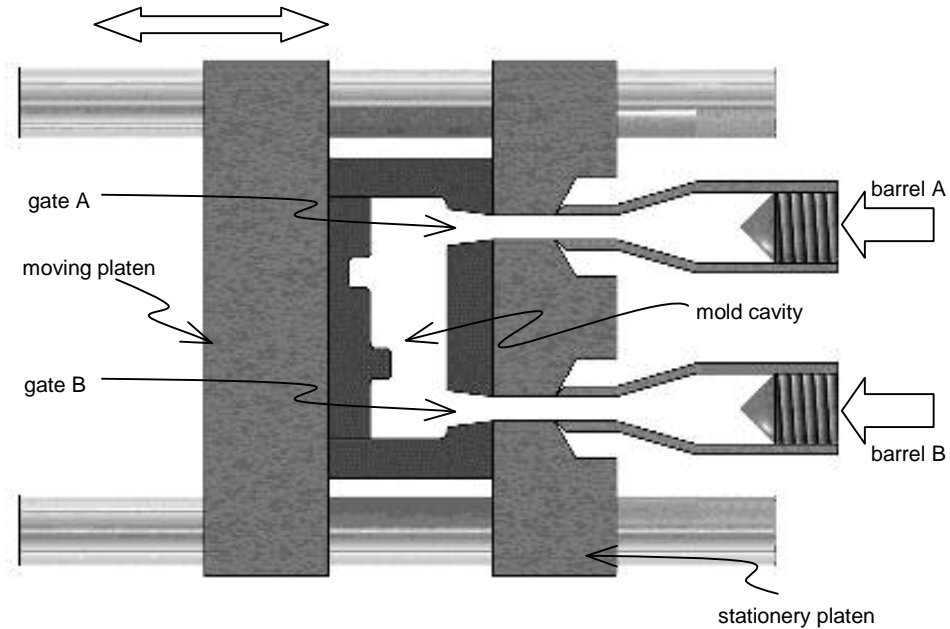


Figure 1.22 – Schematized bi-injection molding machine

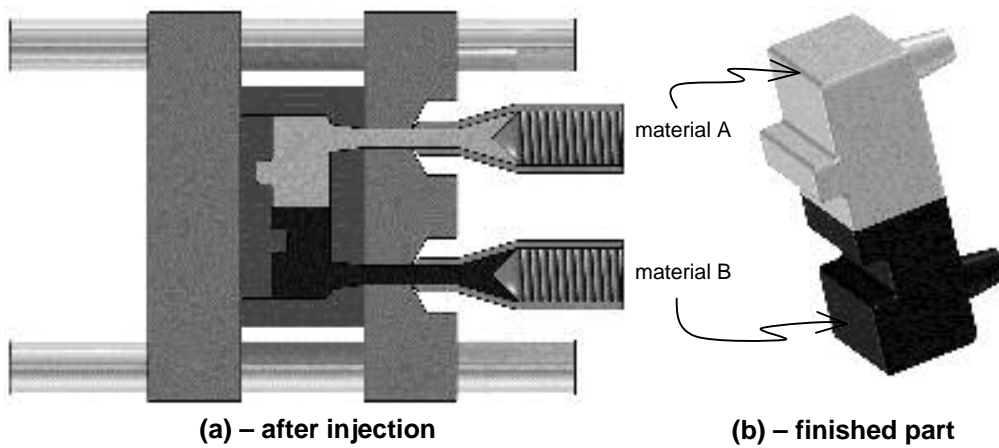


Figure 1.23 – Schematized bi-injection molding process

Interval marbling is perhaps the simplest and limited of the multi-component molding processes. Interval molding is also referred to as “marbling” because it involves intermittently injecting two materials through the same nozzle into a mold which results in a

part with a random, bi-color marbled appearance [48]. The only difference between marbled components and SM components is that they have different aesthetic appearances. There is no real interface where the distinct materials can be separated.

Co-injection is the most popular and perhaps most useful of the multi-component molding processes. It involves carefully controlled injection of two different resins through the same nozzle into a mold in order to produce components with the skin/core arrangement. Co-injection molding utilizes a property of liquid polymers called “fountain flow” to keep the core material inside of the skin material as they flow and subsequently harden in the mold.

Fig. 1.24 shows a simplified schematic of a 2-material co-injection machine. It is quite similar to a typical SM injection molding setup, with the exception of the two barrels which are connected by a common manifold and nozzle. Barrels A and B are responsible for the injection of the skin and core materials, respectively. Additionally there is a valve system that controls which material is allowed to enter the mold cavity.

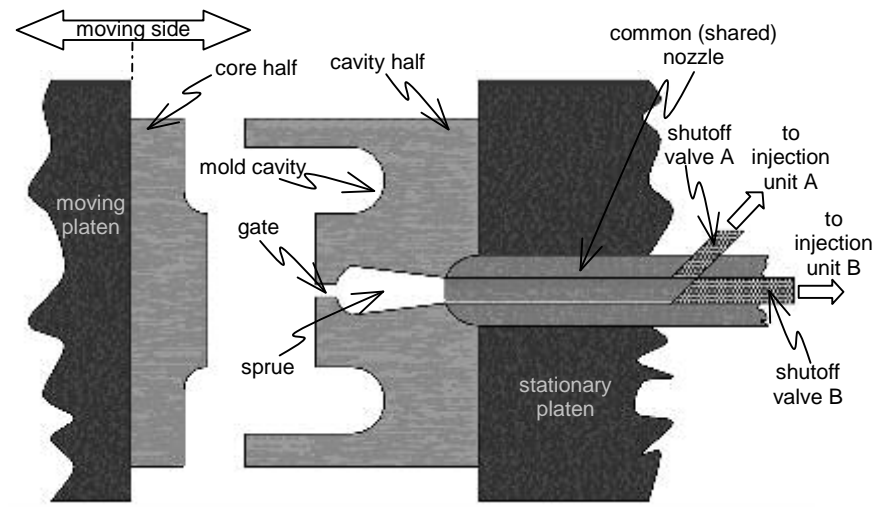


Figure 1.24 – Schematized co-injection molding machine

Fig. 1.25 illustrates a typical A-B-A co-injection sequence for producing a simple skin/core arrangement component. The process is as follows:

- 1) In stage 1 (Figure 1.25a), the valve to barrel A is open while the valve to barrel B is closed. This allows some skin material to be injected, partially filling the cavity.
- 2) In stage 2 (Figure 1.25b), the valve to barrel A is closed while the valve to barrel B is opened. This allows the core material to be injected into the cavity, penetrating the initial skin layer. The two materials do not mix and the core will not puncture the skin due to laminar flow.
- 3) In the optional stage 3 (Figure 1.25c), more skin material is injected as in stage 1. This ensures complete encapsulation of the core material.
- 4) The finished part (Figure 1.25d) then cools and hardens so it can be ejected from the mold.

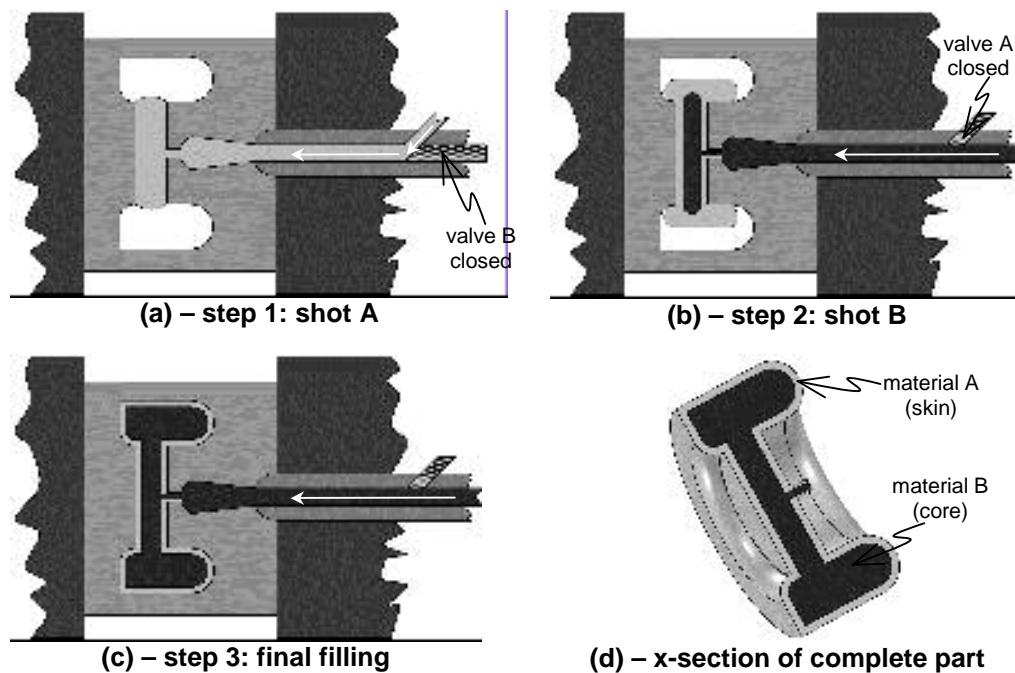


Figure 1.25 – Schematized co-injection molding process

Sandwich molding is just a variation of co-injection molding in which the whole shot of A-B-A material is fed into the barrel by two separate extruders and then shot into the mold all at once. The configuration of skin-core-skin material in the barrel resembles a sandwich, hence the name.

1.2.2.4 – Multi-Shot Molding

Multi-shot molding (MSM) is by far the most versatile, complex and interesting of the MMM process and will henceforth be the sole focus of this research. MSM involves the sequential injection of separate materials into different locations in a mold. Furthermore, the

mold geometry may be partially or completely changed between injection stages. The basic idea of MSM is that after each material shot, the mold (containing the partially completed component) is manipulated in some way, in order to prepare for the subsequent shot. This allows for geometrically complex MMO's with complex interfaces. There are several variations of MSM, three of which are detailed below.

- Rotary Platen Multi-Shot Molding

Rotary Platen MSM is the simplest and most common incarnation of MSM. The basic idea is that the moving half of the mold contains as many cavities as there are shots, and it rotates these cavities to the injection position before each shot.

Fig. 1.26 shows a simplified schematic of a rotary platen MSM machine. The key feature to note is the rotary platen on the left side of the diagram. The rotary platen is attached to the core plate which contains two identical cores mirrored across the centerline of the platen with coincides with the axis of rotation. The cavity plate attached to the stationary platen contains two corresponding cavities with differing geometries. In essence, the rotary platen accomplishes the task of switching the partially completed component between molds for each stage. This eliminates the need for manually changing molds via hand or robot. For this type of MSM, the core for both material stages is exactly the same while the cavity is different.

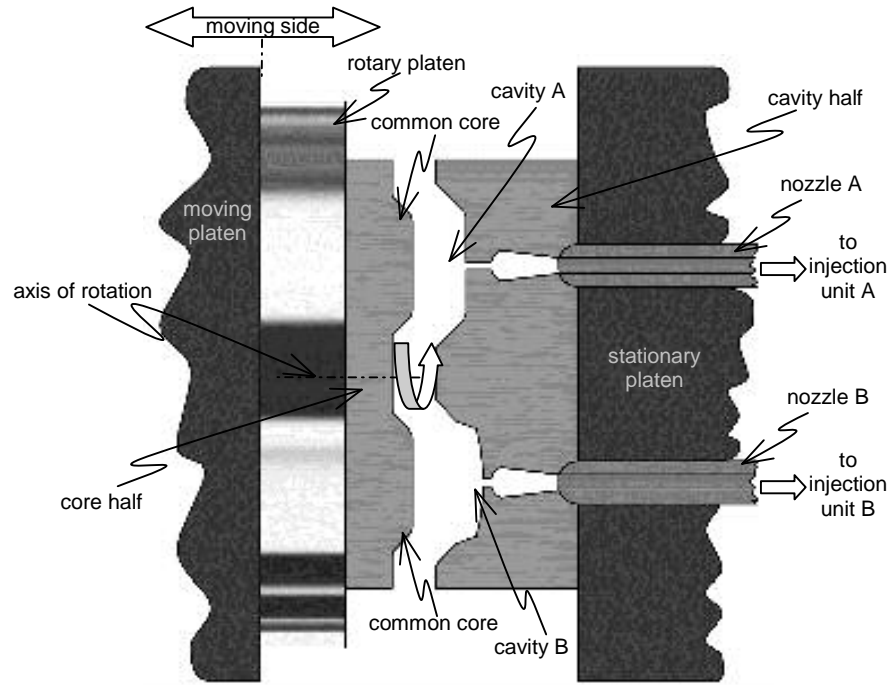


Figure 1.26 – Schematized rotary platen multi-shot injection molding machine

The rotary platen molding process, as illustrated in Fig. 1.27, is described as follows:

- 1) The mold must first reach steady state operation, where at least one complete component AB has been produced. This ensures the system is ready for the subsequent (“ $(n+1)^{\text{th}}$ ”) cycle. The partially-complete n^{th} component is in cavity B (Figure 1.27a).
- 2) The $(n+1)^{\text{th}}$ shots of materials A and B are simultaneously injected into their respective cavities and allowed to cool. This produces the n^{th} complete component AB in cavity B and the $(n+1)^{\text{th}}$ partially-complete component AB in cavity A (Figure 1.27b).
- 3) The mold opens and the n^{th} complete component AB is ejected (Figure 1.27c). A cross section of a complete component AB is shown in Figure 1.27d.
- 4) The rotary platen rotates 180° and the mold closes (not shown). The cycle is now ready to repeat.

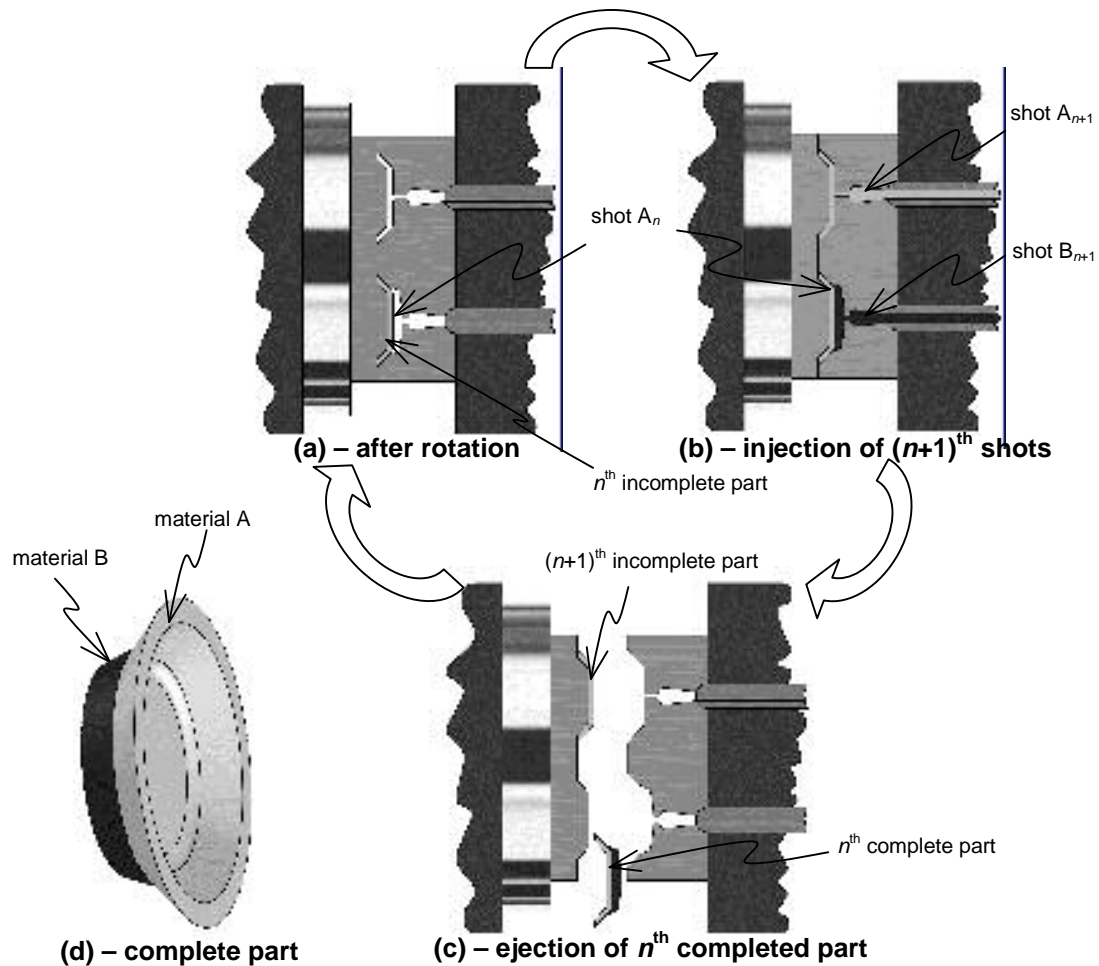


Figure 1.27 – Schematized rotary platen molding process

Although Figs. 1.26 and 1.27 only show a two-material rotary platen machine, it is possible to accommodate more materials. Three-shot and four-shot injection molding machines are also available to manufacture three-material and four-material objects, respectively. Normally, depending on how many different materials there will be, the rotary platen can be rotated by 90° , 120° , or 180° . Special molding presses are required to provide the rotation needed for the core side. This can drive up the mold cost significantly.

- **Index Plate Multi-Shot Molding**

Indexing plate MSM is similar to rotary platen MSM, with the addition of an extra capability: the rotary platen can now retract away from the core half. Additionally, both the cavities *and* cores for each stage possess different geometry. The index plate performs the

function of switching the partially completed components between the different core/cavity sets. In fact, the only common mold piece between stages is the index plate. Fig. 1.28 shows a simplified schematic of an indexing plate MSM machine.

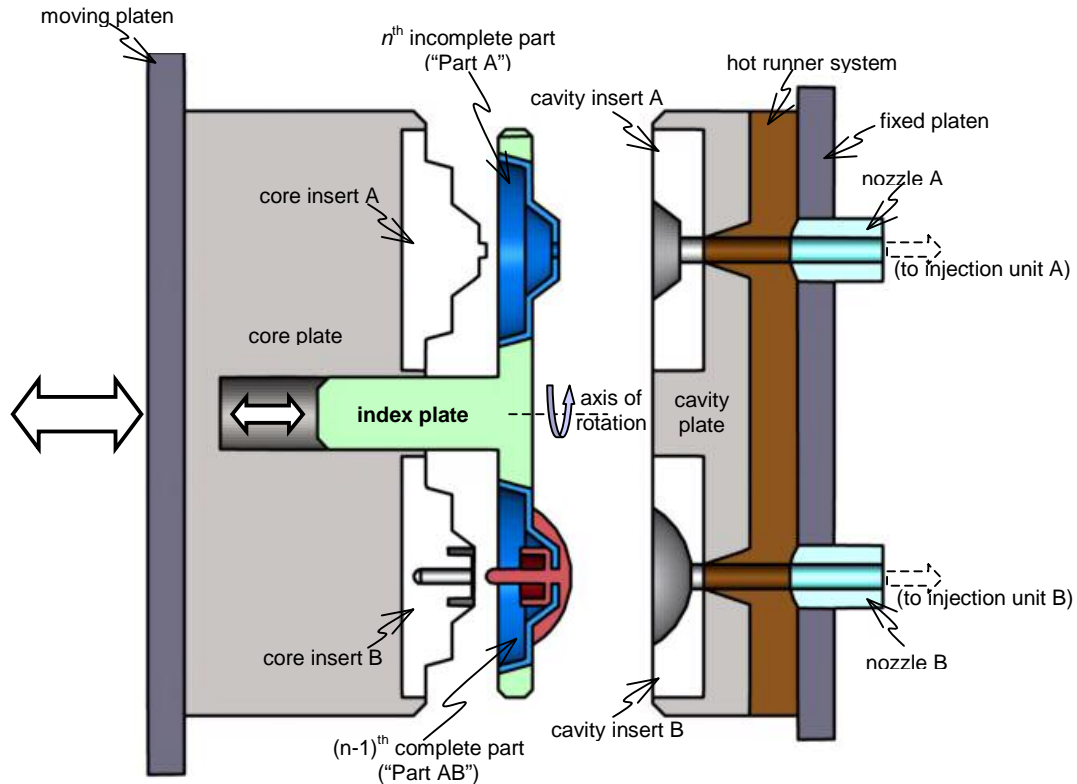


Figure 1.28 – Schematized index plate multi-shot injection molding machine

The process, as illustrated in Fig. 1.29, is described as follows:

- 1) The mold must first reach steady state operation, where at least one complete component AB has been produced. This ensures the system is ready for the subsequent (" $(n+1)^{\text{th}}$ ") cycle. The partially-complete n^{th} component is in cavity B. The mold is closed and the index plate is retracted in place against the core plate (Figure 1.29a).
- 2) The $(n+1)^{\text{th}}$ shots of materials A and B are simultaneously injected into their respective cavities and allowed to cool. This produces the n^{th} complete component AB in cavity B and the $(n+1)^{\text{th}}$ partially-complete component AB in cavity A (Figure 1.29b).
- 3) The mold opens and index plate extends away from the core (Figure 1.29c).
- 4) The n^{th} complete component AB is then ejected (Figure 1.29d). A cross section of a complete component AB is shown in Figure 1.29f.
- 5) The index plate rotates 180°, retracts back onto the core plate, and the mold closes (Figure 1.29e). The cycle is now ready to repeat.

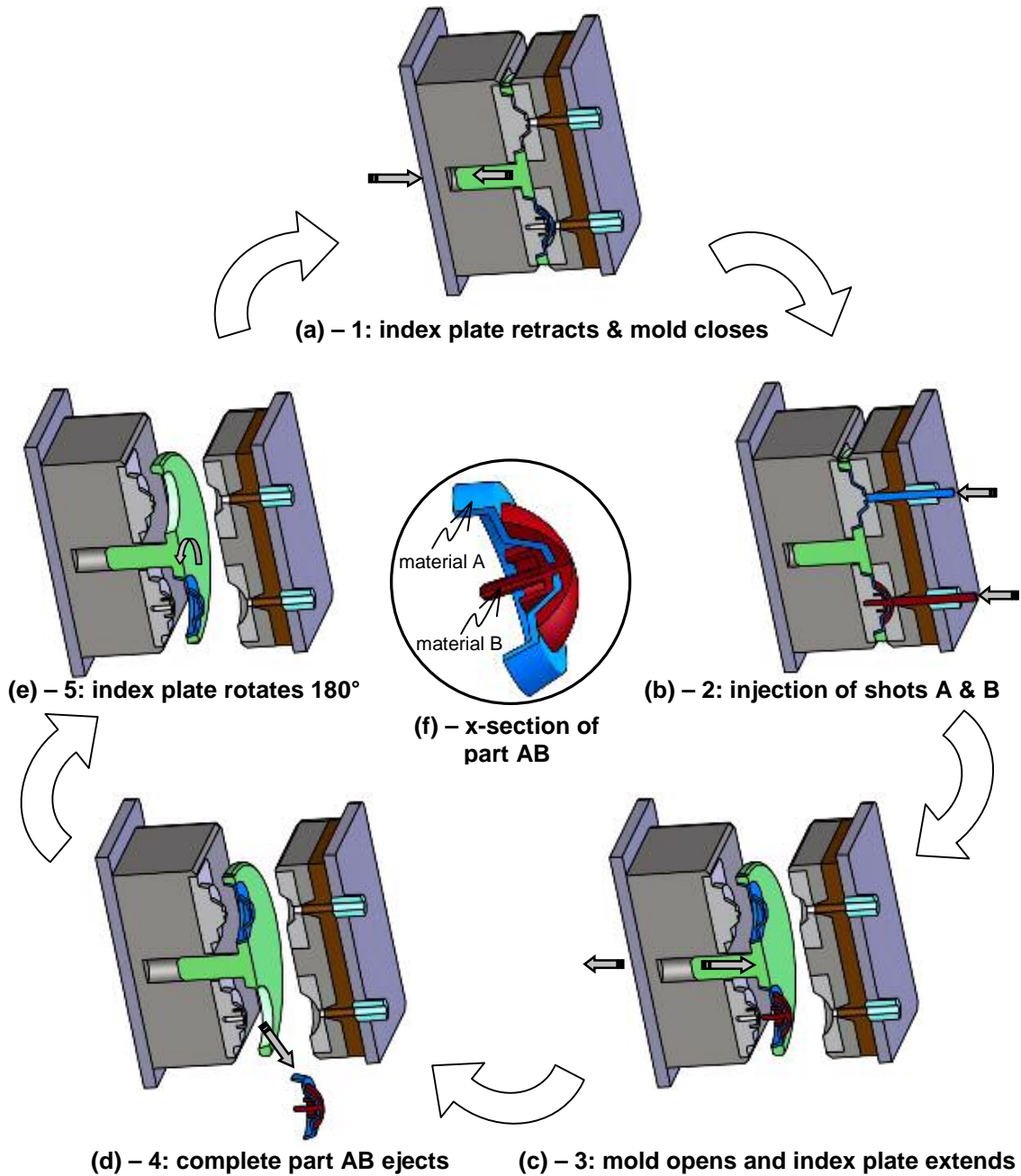


Figure 1.29 – Schematized indexing plate molding process

Indexing plate MSM is more complicated than rotary platen MSM and requires a more complex mold. This complexity further increases the mold cost and cycle time, but it also allows more complicated objects to be manufactured.

- Core Toggle Multi-Shot Molding

The core toggle MSM process is the simplest because neither the core nor the cavity side of the mold moves between shots. In stead, a sliding mechanism is used to slightly change the geometry of the mold cavity between shots. Because the change is quite subtle, only a close-up of the simplified mold for the core toggle MSM process is illustrated in Figs. 1.30 and 1.31. The key feature to note in Fig. 1.30 is the slide which can move left and right to uncover or cover parts of the cavity. Unlike rotary platen or indexing plate MSM, the slide in core toggle MSM is the only piece that reconfigures the mold cavity.

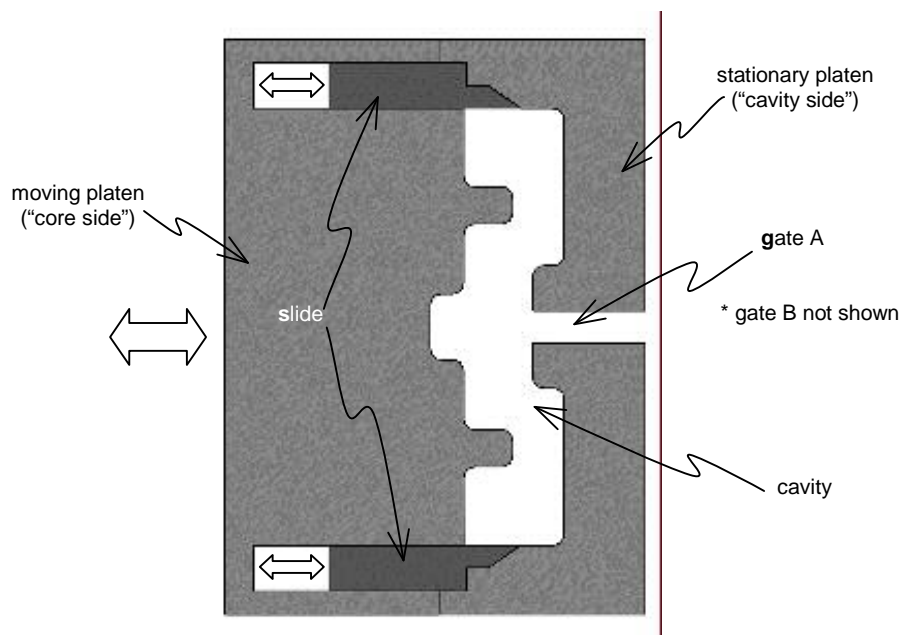


Figure 1.30 – Schematized core toggle mold

The core toggle MSM process, as illustrated in Fig. 1.31, is described as follows:

- 1) Material A is injected into the mold cavity with the slide in the fully extended position (to the far right in this example, Figure 1.31a).
- 2) The slide is retracted to uncover a new part of the mold cavity (to the left in this example, Figure 1.31b).
- 3) Material B is injected into the reconfigured cavity via a separate gate (not shown), filling the void left by moving the slide (Figure 1.31c).
- 4) The final component (Figure 1.31d) hardens and is ejected from the mold.

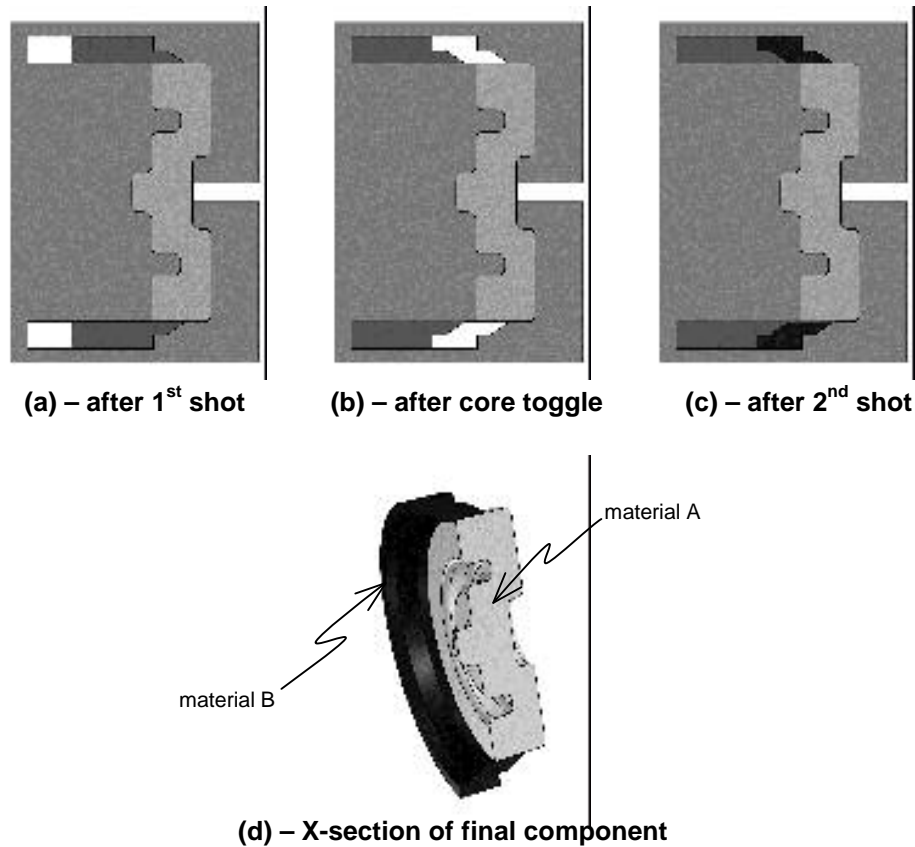


Figure 1.31 – Schematized core toggle molding process

The addition of the moving slides into the mold increases the tooling cost, but it can still be considerably less than the cost of rotary platen or indexing plate molds. Unfortunately, core toggle molding cannot produce components as complicated as the former MSM techniques.

All of the MSM processes require specialized equipment not found in standard SMM. In terms of the mold side of the equipment, molding presses designed specifically for each MSM process must be used to produce multi-shot (MS) components. Fig. 1.32 shows a typical rotary platen installed in a MSM machine. Fig. 1.33a shows a rotary platen machine making cell phone housings, and Fig. 1.33b is the corresponding schematic.

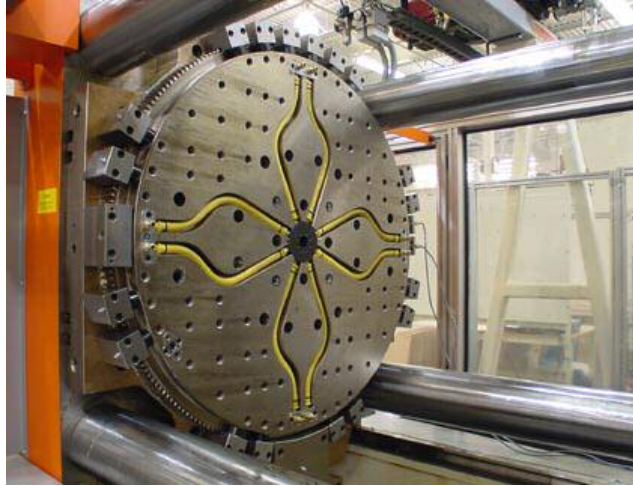
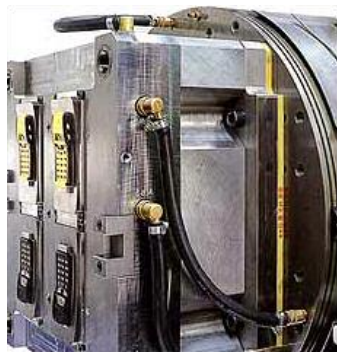
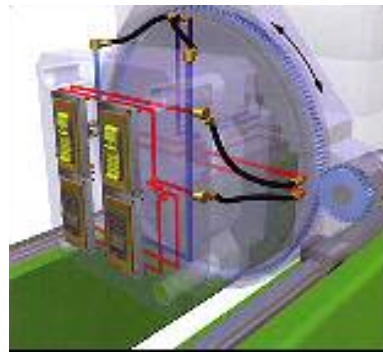


Figure 1.32 – A typical rotary platen

Source: <http://www.multishot.com/platens/technical.htm>



(a) – photo



(b) – schematic

Figure 1.33 – A rotary platen in operation

Source: <http://www.engelmachinery.com/1fpro.htm>

Because MS molds utilize more translating and rotating components than traditional molds, the equipment tends to be bulkier than traditional machines, requiring more factory floor space as well as making mold changeups more awkward and time consuming. Additionally, great care must be taken in mold design to avoid damaging and/or wearing out the cooling and oil lines during mold rotation/translation.

Multi-shot molding also requires careful control of the mold temperature at all times so that any moving or rotating components can function properly. For instance, if a brass slide or core lifter is incorporated into a steel mold, the temperatures have to be controlled

so that the slide/lifter will not lock up or jam due to different coefficients of thermal expansion between the two metals.

MSM can produce the widest variety of MM components due to its versatility. In general, it can be used to manufacture many of the same types of products as the previously described processes (with the exception of skin/core arrangements and metal performs). Some example products made using MSM are shown in Fig. 1.34. Fig. 1.34a shows some swimming goggles with soft eyecups and clear lenses. Fig. 1.34b shows an automotive panel with a rigid base plate and softer 2-color knobs. Fig. 1.34c shows some 3-shot vials (left) and 2-shot tubing connectors with inner moving sleeves (right).



(a) – swimming goggles



(b) – automotive dome light control panel

Source (a) & (b): <http://www.comptec-international.com/>



(c) – medical vials and tubes



(d) – assorted products

Source: <http://www.plasticstechnology.com>

Source: <http://www.rolcoinc.com/multishot.html>

Figure 1.34 – Examples of multi-shot molded components

1.3 – Research Issues in Evaluation of MSM

Because MMM is a relatively new class of processes that are all gaining popularity in the molding industry, it is a field ripe with many research issues. Unfortunately, very little

published work has surfaced in the area of MMM. In particular, MSM is the most complex of the processes, and hence, has a lot of maturing left before it can become truly competitive with more established and understood processes. Much academic research, as well as internal corporate R&D needs to be conducted to help MSM reach its full potential. This section will touch upon some of the important work that needs to be conducted in the field of MSM.

First, consider the following scenario: A manufacturer is designing a new product. After the product's features and functions are established at the conceptual design level, the detailed design must begin. In deciding on the physical embodiment of the product, the designers realize that there are two alternatives that are feasible: 1) An assembly of traditional injection-molded parts with fasteners, springs, gaskets, etc..., or, 2) One multi-material component with all of the desired functionality. Based on several criteria, the designers must choose the most appropriate alternative. Then, after the embodiment and corresponding manufacturing and assembly processes are chosen, the product must go through several design iterations to optimize it for the selected process. Finally, after the design configuration is fully fleshed out, it becomes necessary to estimate the cost and time required to manufacture the product, as well as its relative performance. This seemingly straightforward scenario involves several difficult tasks and decisions that must be completed by the design team. Unfortunately, the actual process is never straightforward or easy. There are many research-worthy issues that should be addressed to make this design process simpler, quicker, and more structured.

1.3.1 – Manufacturing Feasibility and Design-for-Manufacture

The most fundamental issue regarding MSM is whether or not it can actually be used to feasibly manufacture a desired product. The end goal is to totally replace assemblies

consisting of several SM injection molded parts with single MM components. That is, given a conceptual design that is manufacturable using a sequence of traditional SM injection molding and assembly (SMM&A) operations, can a more favorable MSM process be used to create it instead? However, if this is simply not possible, a secondary question is: “Can the product be somehow redesigned so that it is in fact manufacturable via MSM while still maintaining the same (or better) functionality and reducing manufacturing cost?” In the rare case that the answer to both questions is a resounding “no”, then the situation is trivial: SMM&A processes must be used to manufacture the product.

However, the answers to these questions are usually not so clear. In many cases, a detailed analysis and/or redesign session must be conducted in order to determine whether MSM is a feasible manufacturing solution for a desired product. It may turn out that there are many MM design alternatives for a given concept, and the best one needs to be chosen.

The process of designing or redesigning a product for MSM is a complex task that needs to be conducted by experienced designers and process engineers. This usually involves the application of a specialized set of design for manufacture (DFM) rules. For instance, one recent trend has been to produce complex components with many consolidated features rather than assemble numerous simple components with fewer features. An example of this is to use MSM to produce single components with built-in gaskets or seals. Much DFM work has been conducted along this vein. For examples of some relevant DFM rules, see [9], [38], and [50].

1.3.2 – Multi-Shot Molding Cost Estimation

Provided that a given design can be manufactured using either SMM&A or MSM, the next important question is: “Which process is more cost-effective?” The problem entails estimating the cost for both manufacturing alternatives and choosing the better one.

Significant theoretical and experiential work has been devoted to estimating the cost of SM injection-molded components. There are a myriad of available methods with varying detail and complexity that can be used to get an estimate of the manufacturing cost of a given quantity of identical SM objects. Some of these more sophisticated estimation models have even been implemented into commercial software such as Seer DFM.

It seems natural that these methods should be generalized to work for MMO's with n different materials. However, at this time there are no established methods for estimating the cost of a MMO. It turns out that there are several difficulties in expanding existing cost-estimation models to incorporate MSM. While some SMM cost-estimation concepts carry over nicely to the domain of MSM, many issues simply cannot be addressed using the same reasoning. The main factors affecting cost are detailed below.

1.3.2.1 – Material Costs

For SMM, material costs are simply estimated by calculating the total weight of material required to form one part and multiplying that by the unit cost of material. More complex analyses work in scrap rates and virgin vs. recycled material costs as well. It turns out that this concept can be easily expanded to include MSM as well. The only difference is the cost of each material subsection of the part must be calculated as before and then summed to get the total cost.

1.3.2.2 – Labor Costs

Calculating labor costs for MSM is also just as straight-forward as for SMM. After the number of laborers (e.g. machine operators, assemblers, packagers, etc...) is decided upon, the labor cost is estimated by multiplying the hourly labor rate by the time required to produce a finished part. The required work force and work loads may be different for MSM, but the labor costs are estimated in the exact same manner as with SMM.

1.3.2.3 – Equipment Costs

The cost of the equipment required to produce a SM product is usually computed as a simple function of the shot size. The driving factor influencing machine cost is simply the machine size, measured in clamp tonnage. Based on the volume and projected area of the total shot, a mold clamping force can be estimated and from that a proper machine size can be selected. Additionally, a proper injection unit can be selected based on the shot volume and injection pressure requirements.

Unfortunately, given the detail design of a desired MMO, it is not always readily apparent what equipment is required, and hence the associated cost needed to produce it. An appropriate combination of molding press, injection units, mold-reconfiguration equipment (e.g. a rotary platen), and ancillary equipment needs to be selected based on the product's processing requirements. Unlike SMM, it is not always a simple task in choosing an appropriate molding machine, and in many cases, a proper machine configuration has to be custom made for the specific MSM application. For example, the proper clamp force has to be carefully selected to have enough force to adequately seal the mold while not damaging the mold and its associated mold-reconfiguration equipment. Furthermore, given a product design, it is not always clear which of the three MS processes should be chosen. For instance, it may be possible to use either a rotary platen or an indexing plate to produce the desired MMO. In general, the equipment cost estimation cannot simply be based on the shot size as with SMM. This is one important research issue that must be explored.

1.3.2.4 – Tooling Costs

The tooling cost associated with manufacturing a SM mold is a difficult and detailed task in itself. It is a complex function of the mold size, machining and finishing requirements, and the complexity of the desired part. Costly special mold equipment, such

as side-actions, core pullers and/or threaders may need to be incorporated into the mold. Gating and venting considerations also add into the tooling costs.

These considerations, along with several unique ones, carry into MSM tooling estimation. A given MS mold is always much more complex than a SMM mold with similar features. MSM requires molds with more cavities and more complex gating systems. MSM always requires hot runner systems, and more sophisticated control schemes. Additionally, specialized subsystems such as rotary platens, index plates, or core toggles must be built into MS molds.

Furthermore, specialized DFM rules have to be considered when designing proper MS molds. Issues such as mold shut-offs that deform partially-complete components (“crush”), interface problems such as flash/weld lines, and more complex flow and cooling characteristics need to be considered. In general, the increased complexity of MS mold tooling requires a revised set of the existing cost-estimation tools based on SMM. This is another important research issue in the domain of MSM cost estimation.

1.3.2.5 – Processing Costs

A final important cost factor that needs to be assessed is the set of costs associated with performing the injection molding process. These costs include power consumption, auxiliary operation costs (such as inspection), and factory overhead costs. For SMM, the most common processing cost estimation scheme simply involves multiplying the total part processing time (the cycle time) by an averaged machine hourly rate (MHR). This rate is usually a simple function of machine size and geographical location. Because there exists an abundance of historic cost-estimation data for SMM, computing a MHR for a given SM machine is simple task of performing a table-lookup. For MSM, this simple scheme could

be adapted as well, provided the MHR was known. Unfortunately, no such data yet exists for MSM.

Obtaining this MHR for MSM is a complex task because of the inherent differences in MSM. The multiple injection units and rotating mold components can have significantly different power and other resource consumption rates. Additionally, the secondary operations associated with injection molding (e.g. assembly, inspection, packaging, etc...) can be totally different for SMM and MSM. For example, a MSM version of a product will require no assembly, but may require a more advanced inspection procedure than a SMM version of the same product. These, among several other factors must be considered in calculating an appropriate MHR.

Further complicating matters is the issue of cycle time. Cycle time is perhaps the single most important factor affecting processing cost. With SMM, the cycle time is usually estimated by computing an approximate part cooling time. This cooling time is in turn affected by several parameters such as part volume, wall thickness, and material properties. However, for MSM, the cycle time becomes an even more complex function due to the multiple materials' cooling requirements as well as differences in the process itself. For instance, in a two-material product, the cooling time for each material and the time required to rotate a rotary platen by 180° must be factored into the cycle time, among other things. Estimating the total processing cost of a MSM job is yet another crucial research issue.

When attempting to justify the use of MSM for a given application, it is crucial to have immediately available the accurate cost-estimation data based on the conceptual CAD model of the desired object. In order to promote MSM as a viable alternative to SMM&A, a cost-estimation model needs to be developed and implemented. The model should be efficient, accurate and insensitive to small changes in the input. An optimal model would

use geometric information derived from the CAD model to calculate all of the costs associated with producing a certain number of desired pieces. The problem of cost-estimation for MSM will be one of the primary topics undertaken in this research.

1.3.3 – Multi-Shot Molding Performance Evaluation

While cost estimation is an important task from the manufacturer's point of view, the cost of a product does not completely define it. In the end, the actual performance, or 'quality', of the product becomes the chief factor differentiating it from other products. For even if a product is produced at the cheapest possible cost to the manufacturer, yet it proves inferior in its intended use compared to competing products, sales will be greatly compromised. Therefore, it becomes critical to consider the tradeoffs between manufacturing cost and performance issues. Unfortunately, while cost is an easily quantifiable characteristic, performance and quality are much harder to measure in an absolute sense [47]. Each different product type has different performance characteristics and dimensions of quality that are relevant. For injection molded products in particular, it is hard to establish a universal measure of performance.

This general looseness in the definitions of 'performance' or 'quality' complicates the task of comparing similar MM and SM products. That is, given two molded products with the same intended functionality, how do we objectively quantify their performance within a set of universal and relevant attributes? Moreover, how can these relative numbers be used to determine which product is "better"?

Unfortunately, there is no universal set of criteria for quantitatively determining the relative quality of an artifact, let alone methodology for determining which product out of a set of similar alternatives is best in an absolute sense. However, it seems feasible that a set of well-defined and measurable characteristics can be chosen that can at least partially define

the performance of injection molded components and hence be used to aid the decision-makers in choosing the better design, in a relative sense.

There are many attributes of a product that can be used to define its performance. Some, like size and weight, are easily measurable while others, like strength and accuracy, are harder to define universally for every kind of product. In terms of both SMOs and MMOs, a set of valid performance characteristics must be identified in order to form the basis of a comparison. Furthermore, a reliable system for evaluating and quantifying these characteristics for any given product type must be developed.

While it is by no means a comprehensive list, the following sections will detail some of the most important performance characteristics relevant to molded components and the difficulties and research issues associated with defining and measuring them:

1.3.3.1 – Weight and Size

Weight and size are usually important characteristics in comparing similar products. In most cases, it is best to minimize weight and size from both the manufacturer's and consumer's point of view. Fortunately, measuring the size and weight of an object is an easy task; these values can be accurately calculated from the CAD files. Although they are important performance characteristics, weight and size measurement is trivial and hence will not be considered as research issues.

1.3.3.2 – Strength and Durability

Product strength and durability are very important characteristics that need to be evaluated. Unfortunately, there is no universal way to measure or quantify them. Although there are a myriad of available “strength” tests (e.g. tensile, torsional, hardness, etc...), no one test or set of tests is adequate to quantify a universal strength value for all possible products. For instance, because the geometry produced by injection molding can be extremely complex, it will not suffice to subject every part to a typical longitudinal tension

test suited for rods and other for prismatic objects. A further complication arises when the strength or durability of a whole assembly is to be evaluated. It may not be readily apparent how to test and compare two similar products manufactured via SMM&A and MMM. A final problem is that, even if the strength/durability performance characteristics are well defined, it may be difficult to evaluate them without actually manufacturing the product and performing experimental testing.

Unfortunately, this is a luxury that may not be feasible during the conceptual design and process-selection stages. It is necessary to develop a system that can evaluate and compare the relevant strength and durability performance characteristics of injection molded components using only analytical or computational (e.g. FEA) methods.

1.3.3.3 – Tolerances and Accuracy of Movement

Another important performance characteristic regarding assemblies involves the dimensional tolerances and accuracy of movement of separate components relative to one another. More precisely, it is important to evaluate how well assembled components fit together, and resultantly, how well they move with respect to each other. Because SMM&A and MMM create assembled products in completely different ways, the resulting quality of the tolerances and movement could be significantly different for similar products. For instance, SMM&A products that are attached via fasteners (e.g. adhesives or bolts) will typically achieve weaker tolerances than MMM assemblies where the various components are joined by the resins forming directly upon contact. On the other hand, in terms of movement accuracy, built-in hinges or compliant mechanisms created via MMM will usually perform worse than SM assemblies with added-in metal bearings or springs.

Evaluating the quality of the tolerances and relative movement is not a trivial issue because, depending on the product and its movement requirements, it may be hard to tell

how well a given design will work without first building and testing it. These issues, among others, bring about a need for a model that will accurately quantify and compare the accuracies of tolerances and relative movement of injection molded products.

1.3.3.4 – Aesthetics and Ergonomics

Although both aesthetics and ergonomics are very subjective qualities, and usually aren't identified as "performance" characteristics, they are very important characteristics nonetheless. One major factor that differentiates competing products is how well they look and feel to the user. Thus, it becomes crucial to somehow evaluate and compare the quality of products' aesthetics and ergonomics. Unfortunately, ergonomics and aesthetics are perhaps the hardest qualities to objectively quantify. It especially becomes difficult to establish a universal measure of aesthetics/ergonomics across different product types because features that may look or feel good in one product type may have completely opposite effects in another type of product.

Despite the difficulties in defining and measuring aesthetics and ergonomics, it may seem reasonable to identify a set of physical characteristics that do have a noticeable affect on these qualities, and can ultimately be measured. In particular, with regards to injection molded products, it may be possible to compare the relative qualities of different products using a specific set of traits common to all IM components. For instance, the location of the parting line and gate on a molded product could have a significant effect on how it looks and feels. These issues, among others, need to be researched in order to develop an effective model for evaluating aesthetics and ergonomics of SM products and MM products.

1.4 – Summary and Thesis Scope

In summary of this chapter, MMO's were defined and their benefits discussed. Then traditional SM injection molding was reviewed before several MMM processes were detailed. Finally, the important MMM research issues were identified and briefly discussed.

For the remainder of the discussions, the thesis will focus solely on comparing traditional single material molding with the rotary platen variant of MSM. No other MMM processes will be discussed henceforth. Of the three research issues discussed in Section 1.3, only the first two will be addressed. Namely, both cost estimation and performance evaluation will be exclusively covered.

Although the feasibility of using MSM in stead of SMM and redesign for DFM are complex issues that warrant much study in themselves, they will not be considered in this work. From here on, unless stated otherwise, it will be assumed that any considered design concept that is manufacturable via SMM&A will also be manufacturable (at least as a similar design variant) via some form of MSM.

CHAPTER 2 – RELATED RESEARCH

This chapter covers the recent work relevant to injection molding cost estimation. It commences with an overview of general cost-modeling techniques, where the goal is to model the costs associated with a process or system. Next, process comparison and selection techniques are discussed. Then, several popular cost estimation techniques specifically developed for SMM are detailed. Finally, the minimal work conducted in the field of MMM cost estimation is overviewed.

2.1 – General Cost Modeling

This section covers some of the basic theory that has been developed in the field of general cost modeling. It first discusses some general concepts, and then details some of the more popular types of cost estimation models. The section then concludes with discussion on the different types of costs, including overhead calculation.

2.1.1 – Levels of Cost Estimation Models

There are a variety of cost estimation models covered in the literature, each with their own level of detail/accuracy and domain of applicability. Some models are quite general and applicable as early as the conceptual product design stages whereas others are process-specific and can only be used after final detailed design has been completed [45].

In general, there are three levels of cost estimation, with increasing levels of detail [58]: 1) experts' opinion, 2) product comparison, and 3) detailed analysis. The first method involves pooling the collective experience of various experts inside the company to arrive at an educated guess of the product's cost. The second method involves comparing the

product with similar products within a database of historical product costs and adjusting the cost to suit the differences in material, labor, and processing variations. The third method involves carefully analyzing all of the important factors affecting the manufacture of the product as well as comparing with historical data. Obviously, the detail level of the model increases, so does the accuracy of the cost estimate. However, increasing detail also causes an increase in the time and money required to perform a valid cost estimation. Fortunately, many of the concepts of detailed analysis can be implemented into automated software, making the jobs of the personnel responsible for estimation much simpler. Due to the inherent complexity and accuracy of detailed analysis, it will be the only level of cost estimation discussed henceforth.

2.1.2 – Detailed Analysis Models

There are many ways to perform a detailed cost analysis. Four popular cost estimation models are [16]: 1) scaling methods, 2) resource-based methods, 3) technical cost modeling, and 4) activity-based costing. Each one of these models is increasingly more detailed than the previous and resultantly must be applied successively later in the product design stages. These four types of detailed analyses will be briefly discussed below.

2.1.2.1 – Scaling Methods

Scaling methods are just advanced versions of the product comparison level of cost modeling mentioned above. In general, scaling methods interpolate the cost of a component or product that is a variant of an existing family with known cost data. Many times, these methods simply modify the cost of a “reference” component to arrive at a cost estimate for the component under analysis. Much work has been conducted under scaling methods, including research by Boothroyd, Allen and Swift, Wierda, and French (see references of Esawi and Ashby: [16], [1]).

One notable example is a model developed and implemented by Rehman and Guenov, which is applicable throughout the conceptual design process [53]. At the heart of their method is a database, or “design case base”, of historical cost information for products divided into three hierarchical levels: 1) product, 2) sub-assemblies, and 3) components. Their model uses case-based and knowledge-based reasoning to retrieve the closest matching combination of products, sub-assemblies, and components to the product undergoing cost estimation in order to form a comparison basis. Additionally, their method incorporates a “blackboard architecture” that constantly monitors conceptual design modifications of the product and updates the cost estimate as necessary.

Scaling methods are very limited and will not be used in the development of the cost estimation model of this thesis.

2.1.2.2 – Resource-Based Modeling

Resource-based modeling is a broad, highly-applicable approach that assesses the costs of the resources associated with manufacturing a component. This method is useful early on in the conceptual design stages. “Resources” include the materials, energy, capital, time, space, information, and etc. needed to manufacture a product. Appropriate values for the various costs of the consumable resources and rates of consumption must be determined through reasoning based on knowledge of the specific process. A total per-piece product cost can be estimated by summing the various resource terms which are in turn, functions of resource costs, consumption rates, production quantities and production rates. Extensive work in resource-based modeling has been conducted by Ashby and Esawi [16], [17].

Because all manufacturing process can be modeled as a consumption of resources, six resource types used in any process have been defined and reproduced in table 2.1:

<p>Table 2.1 – Resource-Based Modeling Parameters (reproduced from [16])</p>

	Resource	Symbol	Units
Materials	(including consumables)	C_m	[\$/kg]
Capital	cost of equipment	C_c	[\$]
	cost of tooling	C_t	[\$]
Time	overhead rate	\dot{C}_L	[\$/hr]
Energy	power	\dot{P}	[kW]
	cost of energy	C_e	[\$/(kW•hr)]
Space	area	A	[m ²]
	cost of space	\dot{C}_s	[\$/(m ² •hr)]
Information	R&D, and royalty payments	\dot{C}_i	[\$/hr]

This thesis will use many of the concepts from resource-based modeling. Specifically, Ashby's generic cost resource consumption theories will be used to form the top-level cost equations, which deal with the consumption of the resources listed above.

2.1.2.3 – Technical Cost Modeling

Technical cost modeling is a refinement of resource-based cost modeling, in that it incorporates information regarding ways in which capital, tooling cost, production rate, etc. scale with the size, complexity and production volume of the component. This technique for estimating the costs of manufacturing is based upon process simulation models that are integrated with standard cost accounting and engineering estimation methods. Relevant work has been conducted by Field and de Neufville, and Clark et al. (see references of Esawi and Ashby [1], [16], [17]).

One branch of technical cost modeling is called process-based cost modeling (PBCM). PBCM tries to determine concrete relationships between the key cost-influencing engineering parameters for specific manufacturing processes [21]. A separate PBCM model must be defined for each different manufacturing process, because engineering parameters can be completely different between processes (e.g. wall thickness will have a major effect on part cooling time, and hence cycle time in injection molding, but won't have as large of an

effect on the cycle time of sheet metal bending). Significant work has been conducted in this area by the Materials Systems Laboratory at MIT [40].

While technical cost modeling is not explicitly utilized in this thesis, some of its general concepts will be adapted to help in the calculation of some difficult quantities. More specifically, while process simulation will not be directly integrated into the model, some types of simulations will be recommended to help accurately obtain certain input parameters. For example, the model suggests certain cutter-path machining simulations be performed to estimate the total machining times for the core and cavity inserts.

2.1.2.4 – Activity-Based Costing

Finally, activity-based costing (ABC) is a further refinement of technical cost modeling that requires the timing and costs of individual processing steps (e.g. retrieval of materials, set-up time to perform step, de-mounting time, time to pass to next step, etc...). ABC was first introduced by Cooper and Kaplan as an alternative to traditional accounting techniques [13], [14]. In essence, ABC can be used to divide overhead into separate costs, each of which is related to a specific activity [28]. This has been shown to be more accurate than traditional accounting methods, which attempt to link overhead directly to the products themselves. According to Baker, there are four basic steps to ABC cost allocation [2]:

- 1) Determine the relevant activities.
- 2) Allocate overhead costs to these activities.
- 3) Select an allocation base appropriate for each activity.
- 4) Allocate cost to products using this base.

Usually, the level of detail required for such information can only be attained after production has already been begun. For instance, if ABC is used to determine that the principal activities are, for instance, 1) requisition of material, 2) engineering support, 3) shipping, and 4) sales, then the total cost for all of these activities must be obtained (possibly

through traditional accounting) for the production run under consideration. Once these costs are determined, they must each be divided by the appropriate cost base to arrive at the unit overhead cost for that activity. For instance, the total cost of sales (in dollars) must be divided by corresponding base of sales calls (in number of calls). The direct computation of these quantities can be difficult to determine without highly detailed analysis, and/or historical data.

Several cost-estimation models based on ABC have been developed, such as Ben-Arieh and Qian's model for the design and development stages of a product [5], and Özbayrak et. al.'s model for push/pull manufacturing systems [46].

Besides very basic overhead accounting principles, the more advanced theories of ABC will not be used in this thesis. ABC is rather involved and beyond the scope of relative cost comparisons between manufacturing processes.

2.1.2.5 – Summary of Cost Analysis Models

In summary, various cost estimation models of increasing detail have been discussed. Each method has its own benefits and disadvantages in terms of accuracy and involvedness. More concisely, each model has its own appropriate domain of application.

Certain elements of all but the simplest (i.e. scaling methods) models will be adapted in the development of the novel MMM/SMM&A cost estimation/comparison model discussed in this thesis.

2.1.3 – Types of Costs

No matter what level of detail is used to develop a cost estimation model, all models must have some way to assign the various costs associated with manufacturing products. Fig. 2.1 shows a representative example of how the costs of a manufactured product are broken down. The numbers are just typical values collected by J.T. Black, and should by no

means be considered definitive [7]. However, it is of interest to note that the total cost associated with a product is dominated by the manufacturing cost, which in turn, is dominated by material cost and overhead.

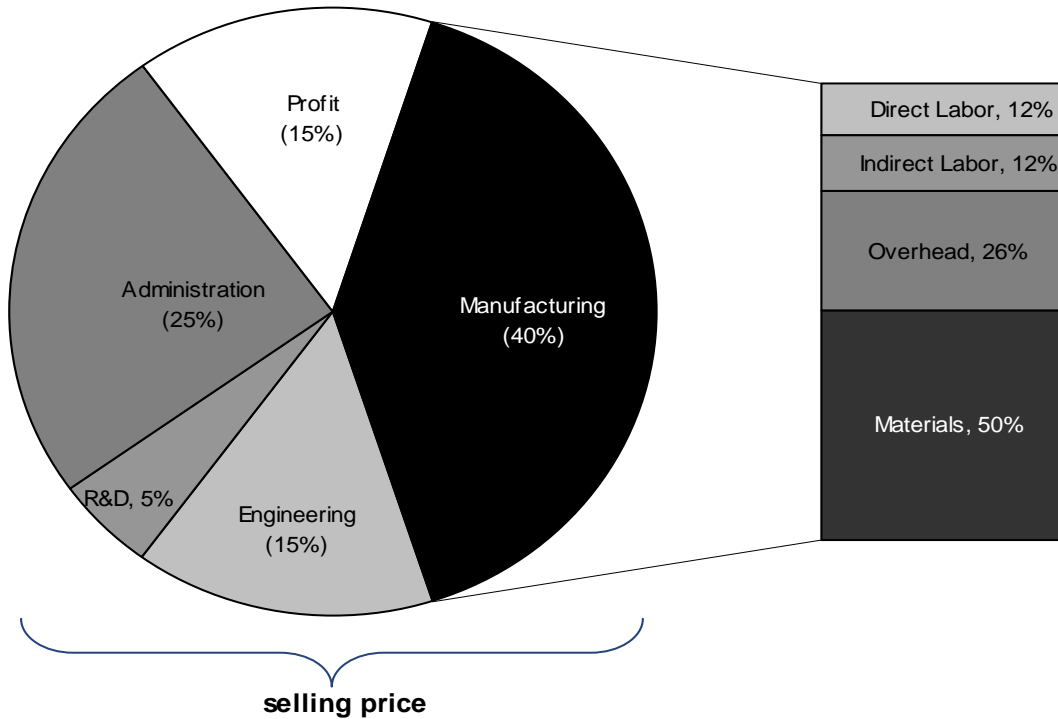


Figure 2.1 – A typical cost breakdown for a manufacturing scenario
(data from Black, [7])

Costs can be broken down into many different categories, several of which will be discussed below.

2.1.3.1 – Fixed and Variable Costs

All costs can either be classified as fixed or variable, depending on the effect of production quantity has on them [45]. Fixed costs do not change in direct proportion to the production volume; rather, they remain constant for any level of production. Examples of fixed costs include the cost of the factory and production equipment, insurance, and property taxes [25]. For instance, the capital cost of a milling machine (in dollars, [\$]) is the same regardless if only one piece is machined on it, or several thousand.

Variable costs grow in direct proportion to volume; that is, as output increases, cost increases linearly with it. Examples of variable costs include direct labor, raw materials, and power required to operate equipment [25]. For instance, the total cost of stock material (in dollars, [\$]) for a milled part depends on how many parts are milled.

If both the fixed and variable costs are known, the total cost can be computed by the following relation:

$$C = C_{\text{fix}} + Q \cdot c_{\text{var}} \quad (2.1)$$

Where the total cost, C [\$], is the sum of the fixed cost, C_{fix} [\$], and the product of the production quantity, Q [#], and the variable cost, c_{var} [\$/part]. This simple cost estimation method provides a useful tool for process selection. If all variable and fixed costs are accurately accounted for, then the total cost can be plotted as a function of production quantity. This plot then shows the ranges of production quantity where each process is economically advantageous. Additionally, this graphical method can help locate curve intersections called “break-even points”, that is, production quantities for which costs for the processes are identical. An example of this is illustrated in Fig. 2.2.

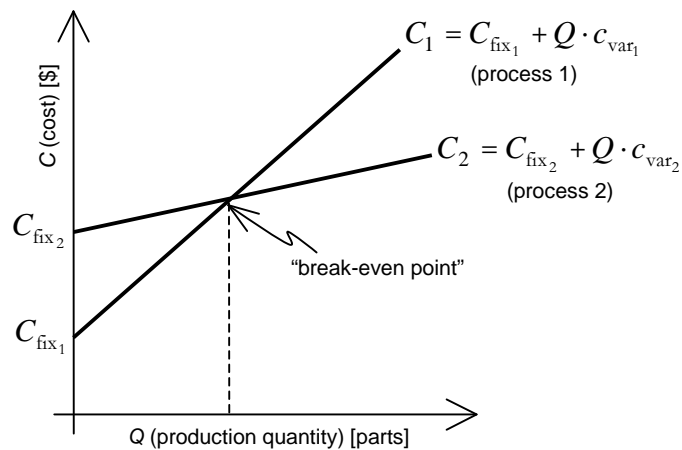


Figure 2.2– Comparing two processes based on fixed and variable costs

2.1.3.2 – Direct and Indirect Costs

In addition to the fixed/variable classification, costs can be further categorized as direct or indirect. Direct costs are those that can be traced to a specific product, such as direct labor and material costs. Indirect costs are those that cannot be traced to a specific product, but are still required for production. Some examples of indirect cost include: factory burden, product design, general/administrative costs and selling costs [58]. Sometimes indirect costs are all lumped into one sum called “overhead”. Overhead is simply a convenient tool for covering the quantities that are fuzzy or too difficult to assign a direct cost to. Overhead can be accounted for in the direct cost formulas by applying an overhead rate to direct overhead cost drivers [45]. Depending on the level of detail of the cost estimation model, the overhead can be decomposed into various direct costs and predicted more accurately. The accurate calculation of burden or overhead is important for cost estimation, and will be discussed in further detail below.

2.1.3.3 – Overhead

Overhead costs are all of the indirect expenses associated with running the manufacturing firm [25]. Overhead can be subdivided into two categories: 1) factory overhead, and 2) corporate overhead. Factory overhead covers the indirect fixed costs associated with running the factory, whereas corporate overhead deals with the other administrative expenses. Total overhead typically has units of dollars per year and represents all of the indirect expenses the company experienced in one year.

This total yearly overhead value can be accounted for in determining the total manufacturing cost of a product by appropriately absorbing it into the direct production costs. This can be accomplished via some form of transformation which converts the total overhead into an hourly cost. This is typically done by dividing the overhead costs by some appropriate base.

Groover suggests using the total direct labor cost as the base – the most common method used in industry. In order to calculate overhead rates, historical cost data from previous years is used to calculate total direct labor and indirect overhead costs. Then the labor rates are computed as follows:

$$\begin{aligned} \text{OH}_F &= \frac{C_{\text{OH}_F}}{C_{\text{labor}}} \\ \text{OH}_C &= \frac{C_{\text{OH}_C}}{C_{\text{labor}}} \end{aligned} \quad (2.2)$$

Where the factory overhead rate, OH_F [%], is simply the annual cost of factory overhead expenses, C_{OH_F} [\$/year], divided by the annual direct labor costs, C_{labor} , [\$/year]. The corporate overhead rate, OH_C [%], is calculated in a similar manner, except using the annual corporate overhead expenses, c_{OH_C} [\$/year], as the numerator.

The above overhead rates can be further subdivided into individual rates representing labor rates, machine rates, etc..., by using only the total costs of labor, machines, etc..., respectively, as the numerator. For instance, the factory overhead rate attributed to running a particular machine, OH_{F_M} [%], would be computed by dividing the total annual cost of running the machine by the annual direct labor costs, C_{labor} , [\$/year].

Once the appropriate overhead rates have been estimated based on historical cost data, the per-piece cost of overhead required to manufacture the product can be accounted for by adjusting the direct costs by these rates. For instance, Groover calculates the total hourly production cost rate as:

$$\dot{C} = \dot{C}_{\text{labor}} (1 + \text{OH}_{F_L}) + \dot{C}_{\text{mach}} (1 + \text{OH}_{F_M}) \quad (2.3)$$

Where the total hourly cost, \dot{C} [\$/hr], is the sum of the direct labor and machine operation costs, \dot{C}_{labor} , and \dot{C}_{mach} , respectively [\$/hr], each adjusted by their own associated indirect overhead rates. The appropriate overhead rates are the overhead rate for labor, OH_{FL} [%], and the overhead rate for machine operation, OH_{FM} [%].

2.2 – Process Selection and Comparison

Given the desired functional requirements of a product, it can take on several physical embodiments that all more or less perform the required function. It becomes a problem of process selection to choose the better process, given some evaluation metric. In many cases, the metric is simply total cost to manufacture. In this case, a DFM analysis using some sort of cost estimation scheme is utilized to compare and then select an the better process. Two recently developed process selection/comparison methods are discussed below.

2.2.1 – General Process Selection Methods

Esawi and Ashby designed and implemented one such cost-estimation-based process selection tool for use in the early design stages of a product [16]. Their method is based on a hybrid of resource-based modeling and technical cost modeling techniques. The basis of the model involves determining appropriate values for the parameters listed in Table 2.1 and summing their contributions to the total cost using the following generalized equation:

$$c = \underbrace{\left[\frac{mC_m}{1-f} \right]}_{\text{material}} + \underbrace{\left[\frac{C_t}{n} \right]}_{\text{tooling}} + \underbrace{\left[\frac{\dot{C}_L}{\dot{n}} \right]}_{\text{time}} + \underbrace{\left[\frac{\dot{P}C_e}{\dot{n}} \right]}_{\text{energy}} + \underbrace{\left[\frac{A\dot{C}_s}{\dot{n}} \right]}_{\text{space}} + \underbrace{\left[\frac{\dot{C}_i}{\dot{n}} \right]}_{\text{information}} \quad (2.4)$$

Where n [parts] is the production quantity, \dot{n} [parts/hr] is the production rate, and f [%] is the scrap rate. The rest of the terms are defined in Table 2.1.

The parameters in the above equation are found in several ways. For instance, using concepts from technical cost modeling, Esawi and Ashby introduced relative methods for finding the capital cost of any process based on product size and complexity. They found that capital costs and production rate can be adequately described by the following equations:

$$\begin{aligned}
 C_c &= \bar{C}_{co} \left(\frac{m}{\bar{m}} \right)^{x_c} \left(\frac{K}{\bar{K}} \right)^{y_c}, \text{ where } \begin{cases} 0 < x_c < 1 \\ y_c = 0 \end{cases} \\
 C_t &= \bar{C}_{to} \left(\frac{m}{\bar{m}} \right)^{x_t} \left(\frac{K}{\bar{K}} \right)^{y_t}, \text{ where } \begin{cases} 0 < x_t < 1 \\ 0 < y_t < 0 \end{cases} \\
 \dot{n} &= \bar{n}_o \left(\frac{m}{\bar{m}} \right)^{x_p} \left(\frac{K}{\bar{K}} \right)^{y_p}, \text{ where } \begin{cases} -1 < x_p < 0 \\ -4 < y_p = 0 \end{cases}
 \end{aligned} \tag{2.5}$$

Where \bar{C}_{co} [\$], \bar{C}_{to} [\$], and \bar{n}_o [parts/hr] are the capital cost, tooling cost, and production rate of a reference component with a size, \bar{m} , equal to the geometric mean of the size-range associated with that process:

$$\bar{m} = \sqrt{m_L \cdot m_H}$$

Where m_L and m_H are the normal lower and upper limits of component mass that the process can handle, respectively. K [#] is the product's complexity rating on a scale of 1 ("simple") to 5 ("complex"), and \bar{K} is an average complexity value (usually 2). The exponents, x_i and y_i depend on the process and are found by consulting experts and plotting data. Please note that Esawi and Asby do not claim for their model to provide high accuracy, rather it should be intended for comparison purposes to help choose from among over 150 different manufacturing processes early on in the conceptual design stage.

Another process and material selection algorithm was developed by colleagues at the University of Maryland (Gupta et. al.) for use at the product embodiment design stages [60].

The model's approach is to select the most economical manufacturing process for a given embodiment design: "Given design requirements in terms of business, material, and form requirements, this system helps designers in selecting the proper combination of materials and processes to meet design requirements. Various promising process and material options are evaluated using a commercial cost estimation system [SEER DFM]".

Because this thesis is concerned with comparison of two processes rather than choosing an optimal process from a wide selection, none of Esawi and Ashby's theories will be used, outside of the general resource-consumption modeled by Equation 2.4. Similarly, the work of Gupta et. al. will not be directly used in the formulation of the model in this thesis.

2.2.2 – Specific Process Comparison Methods

- Hu and Poli's Process Comparison Model for Molding, Stamping, and Assembly
Aside from general process comparison methods such as Esawi and Ashby's, there are several published methods for comparing specific processes. For example, Hu and Poli have published a DFM cost perspective to help in deciding whether to injection mold, stamp, or assemble a particular product [29], [30]. At the heart of their model lies the assumption of functional equivalence. Functional equivalence means that the same desired function is achieved by two different design embodiments at all levels through some type of feature, including basic features, subsidiary features, and side-action features. Functional equivalence can be achieved through entirely different feature types on different product types. For instance, a rib used for added strength in an injection molded part can be functionally equivalent to an embossing or a wipe form on a sheet metal part.

Through detailed analysis of the stamping, injection molding, and assembly processes, they empirically compared tooling costs, processing and material costs, and total

component costs. Relative costs estimates for these values were obtained by using some of Poli's well-known DFM cost-estimation rules. They arrived at several guidelines regarding total component cost. These guidelines, based on the complexity, size and production volume of the product can help determine whether stamping, injection molding, or assembly are less costly.

While Hu and Poli's specific comparison model will not be directly used in this thesis, some of its general DFM ideas will be used in comparing SMM&A with MMM.

- Kazmer, Karania, and Roser's Case Study for Plastic Forming Processes

A recent study conducted by Kazmer, Karania, and Roser compared both the total costs and lead times for an electrical enclosure product, made from five different plastic forming processes [32]. They used standard DFMA rules and manufacturer's quotes to determine the costs and lead times for eight total variations of the five processes:

- 1) Fused deposition modeling (outsourced)
- 2) Fused deposition modeling (in-house)
- 3) Direct "Tool-Less™" fabrication
- 4) Prototype Injection molding (rush-delivery from ProtoMold, Inc.)
- 5) Prototype Injection molding (standard-delivery from ProtoMold, Inc.)
- 6) Injection molding with modified surplus molds
- 7) Standard injection molding (rush-delivery mold)
- 8) Standard injection molding (standard-delivery mold)

Based on their cost and lead time estimates, they attempted to establish Pareto optimal frontiers for lead time and cost for several production quantities. They concluded that all eight processes are competitive under certain conditions, and therefore it becomes challenging for the designer to choose the optimal process based on market conditions and the application requirements. Furthermore, they concluded "delays in the selection of

manufacturing processes can consume a significant amount of the available development time, thereby artificially forcing the development team towards expensive manufacturing processes with very short lead times”. They suggested that designers consistently use the same manufacturing processes for medium-volume production to avoid delays and uncertainties.

While Kazmer et. al.’s work resulted in some interesting and useful conclusion, it was highly specific to the particular case study of the electrical enclosure. Therefore, it will not be directly used in the development of the cost estimation model proposed in this thesis.

2.2.3 – Injection Molding Process Comparison

The two methodologies described above have been shown to be quite effective in their respective uses. That is, Esawi and Ashby’s model is a good tool for choosing an applicable process from a general set of possible options, while Hu and Poli’s method is useful for choosing between three specific alternatives. In addition to these two models, there are several other ones applicable for helping choose between other sets of processes. Unfortunately, at this time there are no such published methods for comparing SMM with MMM for a particular product and selecting the better method based on some metric. However, there have been some case studies conducted which compare the two process variants, and they will be discussed in Section 2.4.

2.3 – Single Material Molding Cost Estimation

This section covers some of the more commonly used cost estimation techniques for SMM. It begins with an overview of the methods currently practiced in the industry. Then, some contributions from the academic community are discussed. Third, some commercial

cost-estimation software is described. Finally, a concrete example comparing the discussed methods is presented.

2.3.1 – Industrial Techniques

All molders use some form of cost estimation before they commit to a certain production run. In many cases, competing manufacturers all bid on a job and therefore need to get a fast quote out to the customer. These quotes need to be formed quickly and accurately so that the bid is won, and the manufacturer does not lose money on the job (i.e. the actual manufacturing cost must be less than the quoted price). Because of this need, there are several back-of-the-envelope methods that are currently used in the industry to get a representative value for the molding cost of a specific job in the early stages of product design. Most of these methods are rather simple, and only used to get ballpark estimates of the cost. First, two cost estimation methods posed by respected experts in the field are detailed. Then, the methodology used by an actual molding shop is discussed.

2.3.1.1 – Bryce's Method

Based on years of hands-on injection molding experience, Douglas M. Bryce offers a simple empirical, yet effective, way to estimate the cost of an SMM job [11]. His method is used to obtain an estimate of the per-piece molding cost only. It does not account for the capital investment costs of the machines and other equipment. Additionally, Bryce's method does not account for setup costs, tooling costs, operator costs or maintenance costs. Although, these important items are briefly touched upon, they are not explicitly incorporated into the cost estimation equations. According to Bryce, the following input parameters are required for calculating actual injection-molding manufacturing costs:

- | | |
|-------------------------------------|----------------------------------|
| 1) Material Costs, C_{mat} | 10) Setup Charges |
| 2) Raw Material, P_{resin} | 11) Scrap Allowance and Downtime |

- | | |
|--------------------------------------------------------------|-------------------------------------------------------------|
| 3) Recycled Material | Downtime |
| 4) Scrap Allowance, p_{rg} | 12) Number of Cavities in Mold, n_{cav} |
| 5) Estimated Regrind Buildup, V_{gating} | 13) Cycle Time, Per Shot, t_{cyc} |
| 6) Labor Charges (if not included in standard machine rate) | 14) Tooling Charges |
| 7) Straight Time | 15) Initial Mold Costs |
| 8) Overtime | 16) Maintenance Costs |
| 9) Hourly Machine Rate, r_{mach} | 17) Production Volume (for amortization calculations) |

Of the above input variables, the ones with a variable name listed in bold are directly used to calculate the per-piece molding cost. The other variables are mentioned, but not used in any calculations. Bryce's method divides the total cost into material costs and processing costs, namely, the total per-piece cost is the sum of the raw materials cost and the molding cost:

$$c = c_{mat} + c_{proc} \quad (2.6)$$

Where, c [\$/part] is the total cost, c_{mat} is the cost of the materials (resins), and c_{proc} is the processing cost.

- Material Cost

The material cost is the total cost of the resin needed to make one part, including the material used in the sprue and runners. The per-piece material cost is calculated by multiplying the total weight of material used in one injection cycle by the price of the resin, and then dividing this by the number of cavities in the mold (i.e. the number of parts produced per cycle):

$$c_{mat} = \frac{p_{resin} \cdot \gamma \cdot V_{shot}}{n_{cav}} \quad (2.7)$$

Where the price of the resin, p_{resin} [\$/lb], is obtained from the supplier, n_{cav} [parts/cycle] is the number of cavities in the mold, $\gamma = \rho g$ [lb/in³] is the specific gravity of the resin (also obtained from the supplier), and V_{shot} [in³/cycle], is the total volume of the shot, with a correction factor depending on how much regrind can be used. In many cases, the sprue and runners are removed from the ejected part and can be reground and used to make more resin. In all injection molded parts, there is an allowable percentage of this regrind that can be added to the virgin resin. Bryce offers two simple scenarios that account for regrind when calculating shot volume:

- 1) When the percentage of sprue and runner volume (“gating volume”) is less than the allowable regrind percentage then the sprue/runners are “molded for free” and not included in the shot volume.
- 2) When the percentage of gating volume is *more* than the allowable regrind percentage then the excess volume has to be included in the total shot volume.

Hence, the shot volume is calculated as follows:

$$V_{\text{shot}} = \begin{cases} n_{\text{cav}} \cdot V_{\text{part}} & , \text{ if } r_{\text{gating}} \equiv \frac{V_{\text{gating}}}{n_{\text{cav}} \cdot V_{\text{part}} + V_{\text{gating}}} \leq p_{\text{rg}} \\ n_{\text{cav}} \cdot V_{\text{part}} + (r_{\text{gating}} - p_{\text{rg}}) \cdot V_{\text{gating}} & , \text{ if } r_{\text{gating}} > p_{\text{rg}} \end{cases} \quad (2.8)$$

Where the volume of a part, V_{part} [in³/part], and V_{gating} [in³/cycle], the summed volume of the runners and sprue, are both easily calculated from the CAD file, p_{rg} [%] is the acceptable percentage of regrind that can be used, and r_{gating} [%] is the ratio of gating volume to the total shot volume.

- Processing Cost

Bryce’s method calculates the total processing cost as a simple function of the geographically-adjusted machine hourly rate (MHR) and the total cycle time:

$$c_{\text{proc}} = \frac{f_{\text{geo}} \cdot r_{\text{mach}} \cdot t_{\text{cyc}}}{n_{\text{cav}} (3,600 \frac{\text{s}}{\text{hr}})} \quad (2.9)$$

Where the MHR, r_{mach} [\$/hr], is based on the machine clamp tonnage and can be found in a table. The geographical factor, f_{geo} [%], is a factor which changes the actual MHR depending on the location of the machine. This is due to different labor rates, utility rates and other overhead rates in different parts of the world. For example, in the far Western and Northeastern United States, 25%-50% should be added to the MHR, while 15%-25% should be deducted to the MHR for central and Southeastern states [11]. The total gate-to-gate cycle time, t_{cyc} [s/cycle], is based on the nominal part thickness and is also obtained from a table.

The clamp tonnage is a function of the fluid pressure exerted on the walls of the mold. Because the mold must remain closed, the clamp tonnage must be slightly greater than the surface force on the mold due to the injection pressure, yet not too large as to damage the mold. The required clamp tonnage can be calculated as a function of part size and injection pressure as follows:

$$F_{\text{clamp}} = \left[\underbrace{(n_{\text{cav}} A_{\text{proj}} + A_{\text{gating}})}_A \cdot f_{\text{mat}} \right] \left[1 + \frac{1}{10} \text{floor}(d) \right] (1 + f_{\text{safe}}) \quad (2.10)$$

Where F_{clamp} [tons] is the clamp force, A_{proj} [in²] is the total projected area of the part onto the mold surface, and A_{gating} [in²] is the projected area of the sprue and runner system onto the mold surface. f_{mat} [tons/in²] is a material-specific factor between 2 and 8. This factor depends on the viscosity of the injected resin, with higher numbers signifying “stiffer” materials (e.g. polycarbonate has a factor of 5). These values are tabulated for most resins. f_{safe} [%] is a safety factor used to prevent underestimation of the clamp force. Finally, d [in] is the depth of the part, perpendicular to the mold opening direction. The “floor” function is

used to round the depth to the lowest integer value because Bryce states: “For every inch of depth over 1in., the total clamp force must be increased by ten percent”. The value of F_{clamp} obtained from equation 2.10 can be used to find an appropriate machine size and a resultant MHR can be found in a table. Fig. 2.3 illustrates the geometric values to be used in the calculation of F_{clamp} . Please note that Fig. 2.3 does not show the optimal way to mold the part, rather it is only for illustrative purposes. By working backwards through Equations 2.10 through 2.6, along with several tables provided by Bryce, a rough estimate of the per-piece injection molding cost can be calculated.

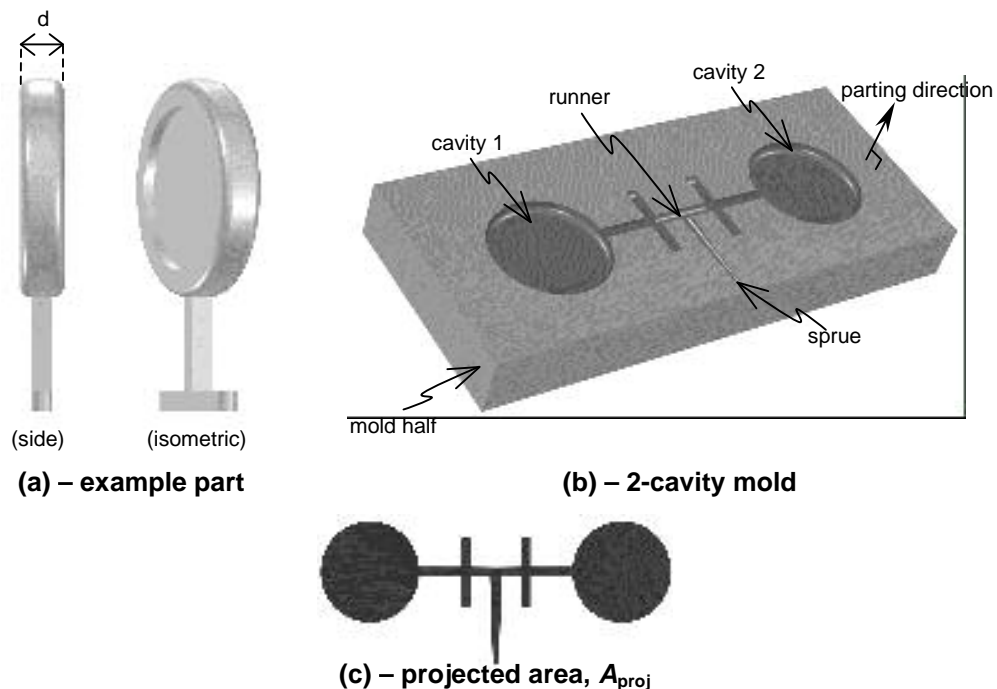


Figure 2.3 – Calculating projected area

- Summary

In summary, Bryce’s method provides a simple way to estimate the per-piece cost of a SM part with a minimal set of input parameters and simple equations. However, some important factors affecting cost are not explicitly accounted for. For instance, Bryce’s method does not include a means for estimating the very important costs associated with the mold and its construction.

Some of the general concepts in Bryce's method, such as computing shot volume and runner percentages, will be adapted into the cost estimation model developed in this thesis.

2.3.1.2 – Rosato's Methods

The Rosato family is perhaps the most respected authority in the fields of injection molding and plastics processing. Their *Injection Molding Handbook* includes comprehensive guidelines for estimating the costs of injection molding [54]. In general, Rosato breaks the cost of molding down into two categories: 1) fixed costs, and 2) variable costs. These are further broken down into the following areas:

<u>Variable Costs</u>	<u>Fixed Costs</u>
1) Material cost	1) Main machine cost
2) Direct labor cost	2) Auxiliary equipment cost
3) Energy cost	3) Tooling cost
	4) Building cost
	5) Overhead labor cost
	6) Maintenance cost
	7) Cost of capital

While it is fairly obvious that all of the above factors do indeed contribute to the total molding cost, it is not readily apparent how to obtain these values and form an estimate of the total cost. Rosato offers some widely used methods for estimating some of the variable cost parameters. These methods are described below.

- “Material Times Two”

The first approximation that can be used simply involves estimating the total cost as a constant multiple of the raw material cost. In many cases, the multiple is two, and Rosato claims the cost is within $\pm 30\%$ of the actual cost [55]. Mathematically, the formula is simply:

$$c = k \cdot c_{\text{mat}} , k > 1 \quad (2.11)$$

Where the material cost, c_{mat} [\$/part] can be obtained through Equation 2.7, or via any another method, and k [#] is some multiple (usually two). Although this method has the advantage of simplicity, it is severely limited due to its neglect of two major parameters: 1) cycle time, and 2) production volume. The next method tries to partially correct the shortcomings of the “Material Times Two” method.

- “Material Cost Plus Shop Time”

One of the most commonly employed techniques adds the costs of processing time to the material costs. Namely, the cost of machine rent is added to the material cost:

$$c = c_{\text{mat}} + r_{\text{mach}} \cdot t_{\text{cyc}} \quad (2.12)$$

Where the machine rent, r_{mach} [\$/s], has to be estimated, usually from historical operating expenses, and the cycle time, t_{cyc} [s/part], has to also be somehow estimated. Given good estimates of the cycle time and machine rent, Rosato claims the cost can be accurately estimated within $\pm 10\%$. Although this method now accounts for the cycle time and is also relatively simple, it still does not account for the production volume. Additionally, it can be difficult to estimate the machine rent and cycle time.

- “Material Cost Plus Loaded Shop Time”

This final technique further refines the previous two techniques by splitting the cost of shop time into a labor element and a direct burden on the labor rate. The cost is estimated by:

$$c = c_{\text{mat}} + [w \cdot (1 + b)] \cdot t_{\text{cyc}} \quad (2.13)$$

Where the labor wage, w [\$/s], is predetermined, and the burden, b [%] is a varying function of the level of machine utilization and production volumes. The advantage of this

technique is that the effect of production volume is finally taken into account, while the equation remains quite simple to evaluate. Unfortunately, the burden function and cycle times are not easily computed, and no method for estimating these quantities is presented.

- Machine Cost

In addition to estimating the variable costs associated with SMM, Rosato offers some guidelines for estimating the fixed machine cost as well. The simplest method involves the total machine investment and the annual quantity of parts produced:

$$c_{\text{mach}} = \frac{I_{\text{annual}}}{q_{\text{annual}}} \quad (2.14)$$

Where the per-part amortized machine cost, c_{mach} [\$/part], is the ratio of the annual investment cost, I_{annual} [\$/yr] and the annual production quantity, q_{annual} [parts/yr]. The annual investment cost can be roughly estimated as the total machine price divided by the number of years it is in service. However, Equation 2.14 is used under the assumption that the equipment is dedicated; that is, utilization is at 100%. For situations in which full utilization is not required or when many different parts are produced on the same machine, Equation 2.14 is not applicable.

A corrected version of this equation involves multiplying the total annual investment by a fraction representing the utilization of the machine:

$$c_{\text{mach}} = \frac{I_{\text{annual}}}{q_{\text{annual}}} \cdot \left(\frac{T_{\text{product}}}{T_{\text{available}}} \right) \quad (2.15)$$

Where T_{product} [hr], is the total time required to make q_{annual} parts, and $T_{\text{available}}$ [hr], is the total time available.

- Cost of Capital

In addition to the fixed machine cost, an equation for explicitly calculating the cost of capital is given. This number accounts for the time value of money and is obtained by the well-known simple-interest capital recovery equation:

$$C = P \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2.16)$$

Where C [\$], is the total cost of capital and i [%], is the fixed interest rate, and n [#], is the number of payments.

- Summary

In summary, Rosato provides a comprehensive list of all of the fixed and variable factors affecting injection molding cost. Each factor is discussed in detail, and several of them have explicit equations. Unfortunately, many of the important factors have no convenient means of calculation or even estimation. Furthermore, the cost estimation guidelines presented are not tied together into one concrete step-by-step method as in Bryce's work.

With the exception of the cost of capital concepts, which aren't unique to his method, none of Rosato's cost estimation models will be used in this thesis.

2.3.1.3 – Space Limited's Method

A custom injection molding company was kind enough to provide this research with valuable insight into how manufacturers bid for and prepare competitive quotes in molding jobs. Space Limited in Baltimore City is a small custom SMM shop that performs most of their tooling and molding in-house, unless sub-contracting proves more cost-effective [10].

They employ a simple and effective method of preparing molding job cost estimates in order to prepare profitable quoted prices to their customers. They subscribe to a constantly updated list of molding jobs which are bid on by competing molding companies.

They select potentially profitable jobs from the list with their process capabilities and plant utilization in mind. After jobs are selected, an experienced engineer carefully analyzes the part drawings and empirically estimates key cost drivers. For example, the maximum part thickness is used to pose an educated guess of the cycle time.

The engineer populates a spreadsheet with the cost-driving parameters gleaned from the drawings and then the various costs are automatically calculated through common costing equations built-in to the spreadsheet. The parameters the engineer must estimate or calculate include:

- | | |
|---------------------------|-----------------------------|
| 1) production quantity | 8) part volume |
| 2) setup costs | 9) tooling costs |
| 3) cycle time | 10) mold surface area |
| 4) # of cavities | 11) side actions [yes/no] |
| 5) reject % | 12) inserts [yes/no] |
| 6) machine size (tonnage) | 13) frame [yes/no] |
| 7) MHR | 14) material cost per pound |

In addition the above parameters, the engineer must also estimate the costs of secondary operations (e.g. finishing or assembly) and the cost of packaging the molded pieces. Finally, they must apply an appropriate mark up percentage in order to ensure profit. It is interesting to note that the engineer estimates most of the cost drivers through experience in stead of applying theoretical or empirical calculations. This is mostly due to the fact that price quotes must be supplied quickly in order to win the bid.

Space Limited's cost estimation method is specifically customized to their business and will not be used in this thesis.

2.3.2 – Academic Work

In an effort to accurately distill the art of injection molding cost estimation down to a concrete methodology, several academic researchers have conducted work in the field. Their research has resulted in some unique cost estimation methods based on advanced variations of the previously discussed industrial techniques. Although loaded with assumptions and generalizations, these methods take into considerations many more factors and can help provide a much clearer picture of the various costs associated with a particular molding job. Two separate academic cost estimation methods will first be discussed and then a third method built as a simpler hybrid of the two will be detailed.

2.3.2.1 – Boothroyd, Dewhurst and Knight's Method

Geoffrey Boothroyd, Peter Dewhurst, and Winston Knight's (BD&K) manual, *Product Design for Manufacture and Assembly*, provides cost estimation techniques to be used during conceptual design for several manufacturing process, including SMM [9]. In particular, they offer separate methodologies for estimating the required molding machine size, the total cycle time, the cost to build the mold, and the optimal number of cavities per mold. These methodologies are detailed below.

- Machine Size

With similar reasoning as Bryce's, BD&K state that the required molding machine size is a function of the required clamp force. This in turn, is a function of both the projected cavity area and the maximum fluid pressure exerted on the mold during the filling stage. Although the projected area of the runner system should be included, they provide a simple method to account for the runners' area as a percentage of the part volume. That is:

$$A = n_{\text{cav}} \cdot A_{\text{proj}} \cdot (1 + p_{\text{run}}) \quad (2.17)$$

Where A [in²] is the total projected area, A_{proj} [in²] is the projected area of one part, and p_{run} [%] is the percentage representing the runner area. This number based on the part volume, and is found in a table.

When the total projected area is calculated, the required clamp force, F_{clamp} [lb], is found using:

$$F_{\text{clamp}} = A \cdot P_{\text{inject}} \quad (2.18)$$

Where the injection pressure, P_{inject} [psi], depends on the resin, and is obtained from a table. BD&K also provide a simple way to estimate the MHR given the clamp force. Based on the national average value of injection molding machine rates, they came up with the following linear relationship:

$$\begin{aligned} r_{\text{mach}} &= k + m \cdot F_{\text{clamp}} \\ k &= (25 \frac{\$}{\text{hr}}) ; m = (4.5 \times 10^{-3} \frac{\$}{\text{h}\cdot\text{lb}}) \end{aligned} \quad (2.19)$$

Because the national average machine rate varies per year, the appropriate values of k and m must be substituted into Equation 2.19. The values provided above were found to be applicable by BD&K at the time of publication (2002). Also, please note that the previous two equations use units of pound-force for simplicity. However, it is usually more natural to work with tons or kilonewtons when dealing with clamp force. The appropriate conversions must be carried out to ensure consistent units before using any of these equations. This method of calculation machine size is very similar to Bryce's, except the calculations are simpler due to some assumptions. For example, this method does not account for part depth, which could affect the required clamp force. One benefit of this method is that the MHR can be computed directly instead of performing a table lookup.

- Cycle Time

BD&K split the total cycle time into three sequential stages: 1) injection time, 2) cooling time, and 3) mold resetting time. The resetting time is the time it takes the mold to get ready for the next shot, i.e. the time it takes to open the mold, eject the part, and then close the mold. The total cycle time, t_{cyc} [s], is expressed as:

$$t_{\text{cyc}} = t_{\text{inject}} + t_{\text{cool}} + t_{\text{reset}} \quad (2.20)$$

Where t_{inject} , t_{cool} , and t_{reset} are the injection, part cooling, and mold resetting times, respectively. The injection time can be estimated as a function of the resin flow rate and the cavity volume. Although the volumetric flow rate during injection is a function that decays over time, the average flow rate, Q_{avg} [in³/s] can be estimated using elementary mechanics as:

$$Q_{\text{avg}} = \frac{\Pi_{\text{inject}}}{2P_{\text{inject}}} \quad (2.21)$$

Where Π_{inject} [lb•in/s] is the power output of the injection unit, and P_{inject} [lb/in²] is the injection pressure. Hence the time it would take to fill the cavity, t_{inject} [s], is given by:

$$t_{\text{inject}} = \frac{V_{\text{shot}}}{Q_{\text{avg}}} = \frac{2P_{\text{inject}} V_{\text{shot}}}{\Pi_{\text{inject}}} \quad (2.22)$$

The mold cooling time can be estimated using a simplified heat transfer analysis of the mold walls and melt temperature. This yields the following equation:

$$t_{\text{cool}} = \frac{h_{\text{max}}^2}{\pi^2 \alpha} \ln \left(\frac{4[T_{\text{inj}} - T_{\text{mold}}]}{\pi[T_{\text{eject}} - T_{\text{mold}}]} \right) \quad (2.23)$$

Where h_{max} [in] is the maximum part wall thickness, T_{inj} [°F] is the recommended resin injection temperature, T_{mold} is the recommended mold wall temperature, T_{eject} is the

temperature at which the part can be safely ejected, and α [in²/s] is the thermal diffusivity coefficient of the resin.

Based on average values for clamp opening and closing times for a wide range of machines, the mold resetting time can be estimated as a function of the part depth as follows:

$$t_{\text{reset}} = (1 \text{ s}) + \frac{7}{4} t_{\text{dry}} \sqrt{\frac{2d + (5 \text{ in})}{L_{\text{stroke}}}} \quad (2.24)$$

Where d [in] is the part depth along the mold opening direction, and the time for the machine to complete a dry run (a cycle without resin), t_{dry} [s], and the maximum stroke of the clamp unit, L_{stroke} [in], are both given by the machine manufacturer. By working backwards through equations 2.18 to 2.14 along with resin-specific and machine-specific tabular data, the total cycle time can be estimated.

- **Mold Cost**

Although it can be quite difficult to predict the total cost of a mold in the early design stages of a part because the exact mold configuration has not been specified, BD&K have posed a method to estimate the total mold cost based on the size and geometric features of the desired part. Their method assumes the mold base will be purchased by a specialized supplier and then the required tooling will be performed in-house by the molder. This includes drilling the cooling lines, and milling pockets to receive the core and cavity inserts. If these assumptions hold, then the total cost of the mold, C_{mold} [\$], is the sum of the mold base cost and the cost of the subsequent machining and finishing all of the cavities:

$$C_{\text{mold}} = C_{\text{base}} + n_{\text{cav}} \cdot C_{\text{tooling}} \quad (2.25)$$

The cost of the mold base was found by Dewhurst and Kuppurajan to be a function of the surface area of the mold base plates and the combined thickness of the cavity and core plates. The cost function was found to be:

$$C_{\text{base}} = (\$1000) + \left(.45 \frac{\$}{\text{cm}^{4/5}} \right) \cdot A_{\text{base}} \cdot h_{\text{plates}}^{2/5} \quad (2.26)$$

Where A_{base} [cm²] is the area of the mold base's cavity plate, and h_{plates} [cm] is the combined thickness of the cavity and core plates in the mold base. Both of these parameters depend on the part size and number of cavities as well as any side-action or threading mechanisms needed to produce the part. BD&K offer some suggestions for calculating the minimum values of both base plate area and core/cavity plate thickness. These guidelines are based on the minimum clearances between adjacent cavities and the minimum thicknesses of the side walls containing the cavities. They recommend a minimum clearance of 7.5 cm. If side actions are to be used, then twice this clearance value should be added to the mold length or width to be used in the area calculation.

Unlike estimating the mold base cost, the tooling cost is much harder to predict. In many cases it is hard to estimate how long the tooling will take for a mold simply based on the part requirements. However, BD&K offer a systematic method of tallying up mold tooling hours, or "points", based on the geometric complexity of the mold cavity. The sum of these points can then be multiplied by an appropriate machining labor rate to get the tooling cost of the mold:

$$C_{\text{tooling}} = r_{\text{tool}} \cdot t_{\text{tool}} \quad (2.27)$$

Where r_{tool} [\$/hr] is the mold tooling labor rate. The mold tooling time, t_{tool} [hr], can be split into the following tasks:

- 1) Ejection system manufacturing time, t_{mes}
- 2) Cavity/core complexity-driven machining time, t_{mcc}
- 3) Cavity/core size-driven machining time, t_{mcs}
- 4) Side-action mechanism manufacturing time, t_{msa}
- 5) Internal lifter mechanism manufacturing time, t_{mil}
- 6) Unscrewing threading core manufacturing time, t_{mtc}
- 7) Surface finishing time, t_{sf}
- 8) Extra machining time required to achieve desired tolerances, t_{tol}
- 9) Surface texturing time, t_{st}
- 10) Parting plane machining time, t_{mpp}

Thus, the total mold tooling time is the sum of these ten manufacturing times:

$$t_{tool} = t_{mes} + t_{mcc} + t_{mcs} + t_{msa} + t_{mil} + t_{mtc} + t_{sf} + t_{tol} + t_{st} + t_{mpp} \quad (2.28)$$

The time required to manufacture the ejection system is approximated as a function of the number of ejector pins required. The number of ejector pins, n_{pins} [#], can roughly be estimated as the square root of the projected part area, A_{proj} [cm²]. It was found that it takes approximately 2.5 machining hours to make one pin. The resulting relationship is:

$$t_{mes} = (2.5 \frac{hr}{cm}) \cdot n_{pins} = (2.5 \frac{hr}{cm}) \cdot \sqrt{A_{proj}} \quad (2.29)$$

The time required to machine the actual mold geometry into both the core and cavity inserts is a function of the part size and geometric complexity. The total core/cavity machining time can be split into two separate times to account for this: 1) t_{mcc} , and 2) t_{mcs} . The geometric complexity is a function of the number of surfaces that need to be machined onto the cavity or core. The relationship between the number of surfaces and machining time was found to be:

$$t_{\text{mcc}} = (5.83 \text{ hr}) \cdot \left[\frac{1}{10} \underbrace{(n_{\text{si}} + n_{\text{so}})}_{n_s} \right]^{1.27} \quad (2.30)$$

Where n_{si} and n_{so} [#] are the total number of surface patches on the inner and outer surfaces of the part, respectively. The inner part surface is the surface in contact with the main core of the mold and the outer part surface is the surface in contact with the cavity side of the mold. All planar and curves surfaces on both sides of the part are simply counted to get the total number of surfaces, n_s .

The time required to machine the mold cavity and core insert based on the part size was found to be:

$$t_{\text{mcs}} = (5 \text{ hr}) + \left(.085 \frac{\text{hr}}{\text{cm}^{8/5}} \right) \cdot A_{\text{proj}}^{6/5} \quad (2.31)$$

The remaining seven tooling times do not have explicit equations that can be used to calculate them. However, approximate times can be found in several tables provided by BD&K. Once the total tooling time is found using Equations 2.23 through 2.26 and the appropriate tables, an estimate of the total mold cost can be found using Equations 2.20 through 2.22.

- **Optimal Number of Cavities**

The effect of the chosen number of identical cavities in a mold can have a dramatic effect on the per-piece part cost as well as the mold tooling cost and required machine size. In general, a tradeoff analysis needs to be conducted to minimize all of these quantities as a function of number of cavities. Using optimizations techniques, the optimal number of mold cavities was found to be:

$$n_{\text{cav}} = \left(\frac{Q \cdot k \cdot t_{\text{cyc}}}{m \cdot C_{\text{tooling}}} \right)^{\frac{1}{m+1}} \quad (2.32)$$

Where Q [#] is the desired production quantity of parts, k is the MHR constant from Equation 2.19, C_{tooling} is the cost of a single-cavity mold from Equation 2.27, and m [#] is the mold tooling index. BD&K suggest using a value of .7 for this variable. Once the appropriate number of cavities has been found, this value can be plugged into Equation 2.25 to get the total mold cost.

- Summary

In summary, BD&K present a novel and systematic approach to estimating the required machine size, cycle time, optimal number of cavities, and most importantly, the mold cost. However, other important cost parameters such as resin cost, processing cost, and capital costs are not addressed.

Many of BD&K's ideas are commonly implemented in various forms in other cost estimation models and commercial software. The theories are well-suited to adaptation to MMM and will be used extensively in the development of the cost estimation model proposed in this thesis.

2.3.2.2 – Poli's Method

Design for Manufacturing, A Structured Approach by Corrado Poli, presents extensive DFM guidelines as well as comprehensive cost-estimation techniques for many popular manufacturing process, including SMM [50]. In fact, compared to the previously described methodologies, Poli's method is the most systematic and detailed, in the sense that it accounts for many more important factors. On the other hand, it is the most complex and lengthy of the methods, requiring more input parameters as well as more detailed computations.

- Total Cost and Relative Costs

According to Poli, the total cost to produce one part, c [\$/part], is a function of the mold tooling cost, the processing cost, and the resin cost as follows:

$$c = \frac{C_{\text{mold}}}{Q} + c_{\text{proc}} + c_{\text{mat}} \quad (2.33)$$

Where C_{mold} [\$] is the cost of the mold, Q [parts] is the production quantity, c_{proc} [\$/part] is the processing costs, and c_{mat} [\$/part] is the material cost. However, the cost to produce the exact same part in different geographical locations or different times or with different equipment can cause the cost to vary significantly. To remedy this, Poli introduces the concept or *relative costs*. Relative costs are simply true costs divided by the costs of a reference part. Similarly, the concept of relative time, length, volume, etc. can be developed. In of all Poli's equations, the reference part was a flat washer with a 1mm thickness and inner/outer diameters of 60mm/72mm, respectively. Hence, χ [#], the per-piece total relative cost becomes:

$$\chi = \frac{c}{c_{\text{ref}}} = \frac{X_{\text{mold}}}{Q} + \chi_{\text{proc}} + \chi_{\text{mat}} \quad (2.34)$$

Where c_{ref} [\$/part] is the total per-piece cost of the reference part. Similar relations hold for all sub-costs (e.g. c_{proc}). The Greek letters χ , X , and τ will be used to signify relative per-piece costs, relative total costs, and relative times, respectively.

- Relative Tooling Cost

The tooling cost relative to the reference part's tooling cost, X_{mold} [#], is a weighted function of the raw die material costs and die construction costs as follows:

$$X_{\text{mold}} = A \underbrace{\left(\frac{C_{\text{mm}}}{(C_{\text{mm}})_{\text{ref}}} \right)}_{X_{\text{mm}}} + (1 - A) \underbrace{\left(\frac{C_{\text{mc}}}{(C_{\text{mc}})_{\text{ref}}} \right)}_{X_{\text{mc}}} \quad (2.35)$$

Where C_{mm} [\$] and C_{mc} [\$] are the mold material cost and mold construction cost, respectively. $(C_{\text{mm}})_{\text{ref}}$ [\$] and $(C_{\text{mc}})_{\text{ref}}$ [\$] are the reference part's mold material cost and mold construction cost, respectively. The weighting value, A [#], is between .15 and .20, and Poli suggests $A=.20$ as a reasonable value. This simply implies that the material cost of the mold is about 20% of the total mold cost. Hence, Equation 2.35 becomes:

$$X_{\text{mold}} = \frac{1}{5} X_{\text{mm}} + \frac{4}{5} X_{\text{mc}} \quad (2.36)$$

The total relative mold construction cost is the product of three complexity/tooling factors and a factor based on the number of identical cavities:

$$X_{\text{mc}} = X_{\text{mc1}} X_{\text{mc2}} X_{\text{mc3}} (.73n_{\text{cav}} + .27) \quad (2.37)$$

X_{mc1} [#] is the approximate relative tooling cost based on size and basic part complexity. This value is a complex function of the following seven characteristics:

- 1) The longest dimension of the part's smallest bounding box
- 2) The number of external undercuts
- 3) The number and location of internal undercuts
- 4) Whether or not the part can be made in only one half of the mold
- 5) Whether or not the dividing surface will be planar
- 6) Whether or not the part's peripheral height from a planar dividing surface is constant
- 7) Whether the part is considered flat or box-shaped (based on dimensions of bounding box)

The above seven characteristics are all obtained with relative ease by inspecting the part geometry. Once they have been determined, the appropriate value of X_{mc1} can be found using a special matrix provided by Poli.

X_{mc2} [#] is a multiplier which accounts for other part complexity factors called subsidiary factors. Basically, the number of nine different types of part features are tallied up and multiplied by an appropriate complexity weight. For example, the total number of circular features and hollow bosses in the part are tallied up as separate quantities. Then the number of circular features gets multiplied by a complexity weight of 2 while the number of hollow bosses gets multiplied by 3 (signifying that hollow bosses are harder to produce than regular circular features). Similar calculations are performed for seven other types of features and then the weighted totals are summed.

This sum, along with the part's maximum bounding box dimension determines whether the mold cavity detail is classified as "low", "moderate", "high", or "very high". The cavity detail level is then cross-referenced in a table with the binary option that a mold will or will not contain external undercuts classified as "extensive" or complex. The value extracted from this table is the complexity multiplier, X_{mc2} .

X_{mc3} [#] is a multiplier which accounts for part surface finish and tolerance issues. This value is obtained from a table by cross-referencing the required surface finish with the binary option of the part requiring either "commercial" or "tight" tolerances.

The relative mold material cost, X_{mm} [#], is the cost of the stock materials needed to fabricate the mold. Therefore, the material cost is a function of the gross part dimensions and the required clearances between adjacent cavities and the mold side walls. X_{mm} can be determined via a series of equations and graphs as detailed below. Please refer to Fig. 2.4 for the notations used for the part and mold dimensions. Also note that the bounding box dimensions of the part, L_b , W_b , and H_b [mm] are used in stead of the true dimensions.

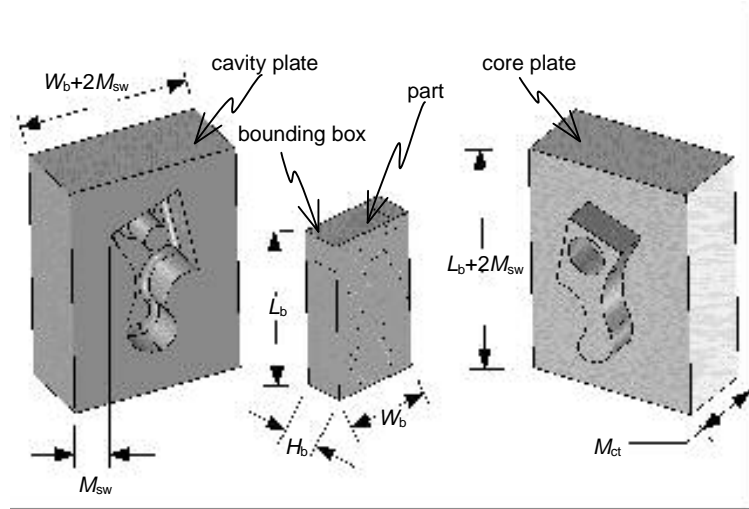


Figure 2.4 – Mold/part notations for Equations 2.38-2.41

First, a part length ratio factor, $k = f(L_b/H_b)$ [mm^{-1}] must be estimated from a graph provided by Poli. This length ratio is then used to determine the minimum clearance between the mold cavity and the sides of the mold, M_{sw} [mm] using the following relationship:

$$M_{sw} = \sqrt[3]{.006k \cdot H_b^4} \quad (2.38)$$

The projected area of the mold base, A_{mb} [mm^2] can then be calculated from the following relationship:

$$A_{mb} = (2M_{sw} + L_b)(2M_{sw} + W_b) \quad (2.39)$$

The core plate thickness, M_{ct} [mm], is a function of the length of the part's bounding box as follows:

$$M_{ct} = (.04 \text{ mm}^{\frac{3}{4}}) L_b^{\frac{4}{3}} \quad (2.40)$$

The total mold thickness is found by adding two core plate thicknesses to the part height as follows:

$$M_t = 2M_{ct} + H_b \quad (2.41)$$

Finally, the total relative mold material cost is estimated from a graph which plots X_{mm} versus A_{mb} for several values of M_t . In summary, Equations 2.30 through 2.36 can be used along with several tables and graphs to systematically estimate the total relative cost of the mold.

- **Relative Processing Cost**

The actual per-piece processing cost, c_{proc} [\$/part], is simply the product of the effective cycle time and the MHR:

$$c_{\text{proc}} = r_{\text{mach}} \cdot \underbrace{\left(\frac{t_{\text{cyc}}}{1 - r_{\text{defect}}} \right)}_{t_{\text{eff}}} \left(\frac{1 \text{ hr}}{3600 \text{ s}} \right) \quad (2.42)$$

Where r_{mach} [\$/hr] is the appropriate MHR, and the effective cycle time, t_{eff} [s], is the actual cycle time divided by the production yield. The production yield is the fraction of parts considered acceptable or non-defective; hence it is the inverse of the defect rate, r_{defect} [%].

The relative processing cost, χ_{proc} [#], can hence be defined as the ratio of the actual part processing cost to the part processing cost of a reference part:

$$\chi_{\text{proc}} = \frac{c_{\text{proc}}}{(c_{\text{proc}})_{\text{ref}}} = \frac{r_{\text{mach}} \cdot t_{\text{eff}}}{(r_{\text{mach}})_{\text{ref}} \cdot t_{\text{ref}}} = \underbrace{\left(\frac{r_{\text{mach}}}{(r_{\text{mach}})_{\text{ref}}} \right)}_{\rho_{\text{mach}}} \underbrace{\left(\frac{t_{\text{eff}}}{t_{\text{ref}}} \right)}_{\tau_{\text{cyc}}} \quad (2.43)$$

Where $(r_{\text{mach}})_{\text{ref}}$ [\$/hr] and t_{ref} [s] are the MHR and cycle time for the reference part, respectively.

- **Relative Material Cost**

Similar to the relative processing cost, the relative material (resin) cost is simply the cost of the resin needed to make one part divided by the cost of the resin for a reference part:

$$\chi_{\text{mat}} = \frac{c_{\text{mat}}}{(c_{\text{mat}})_{\text{ref}}} = \frac{V_{\text{part}} \cdot p_{\text{resin}}}{(V_{\text{part}})_{\text{ref}} \cdot (p_{\text{resin}})_{\text{ref}}} = \underbrace{\left(\frac{V_{\text{part}}}{(V_{\text{part}})_{\text{ref}}} \right)}_{\nu_{\text{part}}} \underbrace{\left(\frac{p_{\text{resin}}}{(p_{\text{resin}})_{\text{ref}}} \right)}_{\pi_{\text{resin}}} \quad (2.44)$$

Where V_{part} and $(V_{\text{part}})_{\text{ref}}$ [mm³] are the volumes of the part and the reference part, respectively, and p_{resin} and $(p_{\text{resin}})_{\text{ref}}$ [\$/mm³] are the prices of the resin for the part and the reference part, respectively. Please note that this method does not account for the volume of the sprues and runners or the fact that defects will be produced. Additionally, the use of regrind is not considered.

- Relative Total Cycle Time

The relative cycle time, τ_{cyc} [s], is defined as the total cycle time divided by the cycle time of a reference part. It can be expressed by the following relationship:

$$\tau_{\text{cyc}} = (\tau_{\text{b}} + \tau_{\text{e}})\tau_{\text{p}} \quad (2.45)$$

Where τ_{b} [#] is the base cycle time depending on the maximum wall thickness and geometry of the part, τ_{e} is the additional time required for metal inserts or internal threads (i.e. “insert molding”), and τ_{p} is a penalty factor resulting from specified surface finishes and tolerances.

The base cycle time is a complex function involving the wall thickness and a number of geometric factors. The following information is needed to estimate τ_{b} :

- 1) Whether or not the part is partitionable into a set of “elemental plates”
- 2) Whether or not the part is considered “slender” or “non-slender” (based on the bounding box dimensions)

- 3) Whether or not any elemental plates contain significant ribs and/or bosses, and the locations/orientations of such ribs/bosses
- 4) Whether the part is considered “easy to cool” or “difficult to cool” based on geometry and mold cooling line issues
- 5) The maximum wall thickness for each elemental plate

These factors are relatively easily determined for each elemental plate (if the part is partitionable) and then a base cycle time is found using a special matrix developed by Poli. The maximum base cycle time among all elemental plates is used as the parts minimum base relative cycle time.

The additional time, τ_c , is determined from a simple 4-celled table by cross referencing whether or not the part has internal threads and/or metal inserts.

Finally, the surface penalty factor, τ_p , is also determined from a simple table based on the wall thickness, whether the surface finish requirements are considered “low” or “high”, and whether the tolerances are considered “difficult to hold” or “not difficult to hold”.

- Summary

In summary, Poli provides a comprehensive and systematic quantitative methodology for *relative* cost estimation of a SMM job. Many important cost parameters, such as the relative mold tooling cost, are considered in his method. However, it is important to remember that these values are all relative; that is they must be compared against a reference part. If the costs associated with the reference part are well known, then it may be possible to obtain accurate values for absolute costs. Compared to BD&K’s method, Poli’s method is more comprehensive, but more involved as well. The relative nature of the calculations may yield more accuracy when a reference part’s cost estimate accurate.

Although the relative comparison theories of Poli’s method seem well suited to a relative cost estimation/comparison model, they will not be used in this thesis. This is because his method is rather complicated, highly empirical, and difficult to adapt due to its highly numerical and tabular structure.

2.3.2.3 – *Fagade-Kazmer’s Method*

Adekunle Fagade and David Kazmer (F&K) present a simple and effective approach to SMM cost estimation in their article “Early Cost Estimation for Injection Molded Components” [18]. Most notably, they offer simple empirical equations to predict the cost of the mold and the lead time required to manufacture the mold. Additionally, they present methods for material and processing cost estimation . Their methods are detailed below.

- Total Cost

As with most authors, F&K agree that the total per-piece cost of injection molding, c [\$/part], is the sum of three separate factors:

$$c = c_{\text{mat}} + \frac{c_{\text{proc}}}{y} + \frac{C_{\text{mold}}}{Q} \quad (2.46)$$

Where c_{mat} [\$/part], c_{proc} , and C_{mold} [\$] are the familiar values of the material cost, processing cost, and mold cost, respectively. Q [#] is the desired production quantity, and y [#] is the yield, or the ratio of good parts produced to defective ones.

- Mold Cost and Lead Time

Along with BD&K and Poli, F&K agree that the mold cost is a directly correlated to the part’s complexity. However, unlike the previous authors, F&K’s definition of “complexity” is much simpler. In stead of going through multiple and sometimes ambiguous steps in determining a part’s complexity, F&K’s method uses the following five complexity-determining input values in their cost estimation method:

- 1) Number of unique dimensions needed to define the part, n_{dim}
- 2) Volume of part bounding box, $V_b=L_b \cdot H_b \cdot W_b$
- 3) The number of actuators required (e.g. side cores), n_{act}
- 4) Whether or not the mold requires a “high polish finish”, S_{high}
- 5) Whether or not the mold requires a “high tolerances”, T_{tight}

n_{dim} [#] is simply the number of unique dimensions required to unambiguously define the part and can be enumerated by hand or calculated by any commercial parametric CAD modeler. The volume of the bounding box, $V_b=L_b \cdot H_b \cdot W_b$ [cm³], determines the basic part size. The number of actuators, n_{act} [#], is a count of the number of separate actuators needed for side cores in order to produce undercuts and/or threads on the part. S_{high} [0 or 1] is simply a binary factor accounting for whether the part requires a high surface finish. In this case, a “high” surface finish ($S_{\text{high}}=1$) is one with a surface finish specification of SP1 A1, A2, or A3 on more than 25% of their entire surface area. T_{high} [0 or 1] is another binary factor accounting for whether or not the part has tolerances considered “tight”. In this case, a part is considered to have “tight” tolerances ($T_{\text{tight}}=1$) if the absolute percentage tolerance per unit length was less than or equal to .07%.

F&K systematically measured these relevant parameters for 30 different single-cavity molds and tried to find a correlation with these values and the average of over 75 actual quotes supplied by mold makers. Based on the data, they posed the following regression results:

$$C_{\text{mold}} = (\$22,500) + (.82 \frac{\$}{\text{cm}^3})V_b + (\$30)n_{\text{dim}} + (\$2940)n_{\text{act}} + (\$7630)S_{\text{high}} + (\$5470)T_{\text{tight}} \quad (2.47)$$

$$R^2 = .911 \text{ (@ 95\% confidence level)}$$

In this case, the sample coefficient of multiple determination, $R^2=.911$, is quite accurate when using a 95% confidence interval. However, please note that this equation does not allow for multiple-cavity molds. Additionally, F&K state that a different regression equation should be used for aluminum molds. For comparison purposes, F&K compared their mold cost estimation method with BD&K’s method and Poli’s method. The results are reproduced in Table 2.2:

Table 2.2 – Comparison of Three Cost-Estimation Techniques (reproduced from [18])				
Technique	Part 1: “End Cap”		Part 2: “Top Housing”	
	estimate	relative error	estimate	relative error
<i>mean quoted price</i>	\$17.3K	-	\$38.5K	-
BD&K	\$5.43K	+69%	\$17.52K	+54%
Poli	\$14.69K	+15%	\$47.2K	-23%
F&K	\$30.6K	-77%	\$39.9K	-4%

According to F&K, the BD&K underestimates the mold costs and under-predicts the relative sensitivity between the two different designs. The Poli model exhibits greater range than the observed mold quotes, but is likely the best estimator for these two test parts. F&K’s proposed model over-predicts the mold cost and doesn’t exhibit adequate sensitivity. F&K point out however, that their method is the simplest, requiring only several easy-to-obtain input parameters.

Besides just supplying an estimation method for mold cost, F&K also present a similar analysis for estimation the total lead time it would take to receive the mold from the manufacturer. The following relationship was based on the 75 data points for the 30 single-cavity molds:

$$t_{\text{mold}} = (13 \text{ weeks}) + (5.5 \times 10^{-5} \frac{\text{weeks}}{\text{cm}^3})V_b + (7 \times 10^{-3} \text{ weeks})n_{\text{dim}} \quad (2.48)$$

$$R^2 = .7 \text{ (@ 95\% confidence level)}$$

Although the .7 value for R^2 is not as desirable as the cost-estimation value from Equation 2.48, it still provides a decent ballpark estimate for the lead time. This has not been attempted by any of the previously described methods.

- Material Cost

Similar to the previous material cost estimation methods, F&K provide a simple equation:

$$c_{\text{mat}} = \frac{V_{\text{part}} \cdot p_{\text{resin}} \cdot \rho}{1 - f} \quad (2.49)$$

Where V_{part} [in^3] is the part volume, and the resin price, p_{resin} [\$/lb], and density, ρ [lb/in^3], are both provided by the material supplier. f [#] is a factor accounting for the sprue/runner volumes and recycled material. F&K suggest using a conservative value of $f = 10\%$.

- Processing Cost

Similar to the previous processing cost estimation methods, F&K provide a simple equation:

$$c_{\text{proc}} = \frac{r_{\text{mach}} \cdot t_{\text{cyc}}}{(3600 \frac{\text{s}}{\text{hr}})y} \quad (2.50)$$

They also provide a simple relation that closely agrees with BD&K's to estimate the MHR based on the clamp force:

$$r_{\text{mach}} = (31.33 \frac{\$}{\text{hr}}) + (.725 \frac{\$}{\text{hr} \cdot \text{ton}})F_{\text{clamp}} \quad (2.51)$$

Where the clamp force, F_{clamp} , is measured in tons.

- Summary

In Summary, F&K provide a simple and straightforward method for estimating the cost of an injection molding job as well as a simple estimate for the mold manufacture lead time. However, their method does not take into account multiple cavity molds and was shown to be less than accurate for two test parts when compared with other available cost estimation models.

Although F&K’s method can be quite useful for obtaining a rough cost estimate in the early design stages, it is rather simple and empirical. Additionally, it would be difficult to directly adapt these theories to MMM cost estimation, hence they will not be used in this thesis.

2.3.3 – Software-Based Models

Many of the SMM cost estimation methods discussed above have at least partially been implemented into some form of software. Some of these programs are available in the public domain while others are commercial suites. Three such programs are discussed below.

2.3.3.1 – Injection Molding Cost Estimator

Dr. David Kazmer designed a small online Java applet, “Injection Molding Cost Estimator” (IMCE), which provides rough injection molding cost estimates with a minimal set of inputs [33]. Kazmer developed the tool based on his own experience in the molding industry and claims it is as accurate as any other available tool, including both proprietary and public programs as well as internal corporate spreadsheets. The programs inputs and outputs are listed below:

Table 2.3 – Inputs/Outputs for IMCE	
<u>Inputs</u>	<u>Outputs</u>
1) material type*	1) ejection time
2) production quantity	2) injection pressure
3) # of cavities	3) clamp tonnage
4) part complexity**	4) tool cost
5) basic dimensions: l×w×h×t	5) MHR
	6) material cost (per pound)

	7)	per-part processing cost
	8)	per-part material cost
	9)	per-part-tooling cost
	10)	TOTAL per-part cost
* - 5 available classes, e.g. "lower commodity" or "upper engineering"		
** - low, medium, or high		

The advantage of this program is that it quickly produces a cost estimate without considering any of the parts geometry outside of its basic envelope dimensions and wall thickness. Unfortunately, there aren't a wide range of options, and most of the input parameters must be selected from a limited list rather than input exactly (e.g. the production quantity is input via a drop-down list with only six choices ranging from 5K-500K cycles).

Fig. 2.5 shows a screen capture of the IMCE's user interface.

The screenshot shows the IMCE user interface. On the left, a bracket labeled 'output' points to a table of cost estimates. On the right, a bracket labeled 'user input' points to a form with various input fields. A 3D wireframe model of a part is visible in the center-right area.

Process Cost	\$0.35
Materials Cost	\$0.22
Tooling Cost	\$9.83
Total Cost	\$11.4

DIRECTIONS:
Click the up and down arrows at right to scroll through this scrollable window. Define your application's parameters in the fields below. As you enter data, this window will provide information regarding your selection. The cost estimates and part geometry will also be updated automatically. For additional details on the cost estimates, click

Material Type	Lower Commodity
Mold Production	5000 Cycles
#Cavities per Mold	1
Part Complexity	Low
Length	20.0 in === 508.0 mm
Width	12.0 in === 304.799999 mm
Height	8.0 in === 203.2 mm
Thickness	0.1 in === 2.54 mm

Figure 2.5 – Screen capture of Kazmer's IMCE

Source: <http://www.ecs.umass.edu/mie/faculty/kazmer/imcost/imcost.html>

2.3.3.2 – Manufacturing Advisory Service

The Manufacturing Advisory Service (MAS) is another public domain Java applet developed at Berkeley. Using theory similar to the process selection methodology of Esawi

and Ashby (Section 2.3), the MAS is used to select feasible process/material combinations and then estimates the costs associated with manufacturing [6].

The user selectively inputs a set of eleven common (process non-specific) part parameters called “facets” and then the seven material parameters. Provided enough facets are defined, a ranked list of possible material and process combinations is output. The user can then select a combination and perform a process-specific cost estimate by inputting more parameters. For injection molding, the following inputs and outputs are given, implementing a version of Boothroyd’s cost estimation method:

Table 2.4 – Inputs/Outputs for MAS’s IM module			
General Facet Inputs	Material Inputs	SMM Parameter Inputs	Outputs
1) Batch size	1) process	1) projected area	1) injection time
2) Shape type*	2) per-pound cost	2) draw height	2) cool time
3) Bounding box dims.	3) density	3) volume	3) reset time
4) Material	4) yield strength	4) # surface patches	4) TOTAL cycle time
5) dimensional tols.	5) thermal expans.	5) # holes/depression	5) per-piece material cost
6) surface roughness	6) elastic modulus	6) # side actions	6) per-piece processing cost
7) wall thickness	7) hardness	7) # internal undercuts	7) TOTAL per-piece cost
8) production rate		8) # threaders	8) mold tooling cost
9) setup time		9) parting surface type**	9) mold tooling time
10) setup cost		10) texturing	10) TOTAL cost
11) per-part cost		11) learning curve %	
		12) markup %	

* - 7 types (e.g. prismatic, freeform drape, thin wall, etc...)
 ** - 4 types (e.g. flat or curved surface with steps)

While the MAS is still quite simple to use, it does allow a considerably greater range of inputs, and hence provides more detailed output. However, once the material and injection molding process are specified, the cost estimation utility is really nothing more than a simplified version of Boothroyd’s method.

Fig. 2.6 shows a typical example of input and output for the MAS.

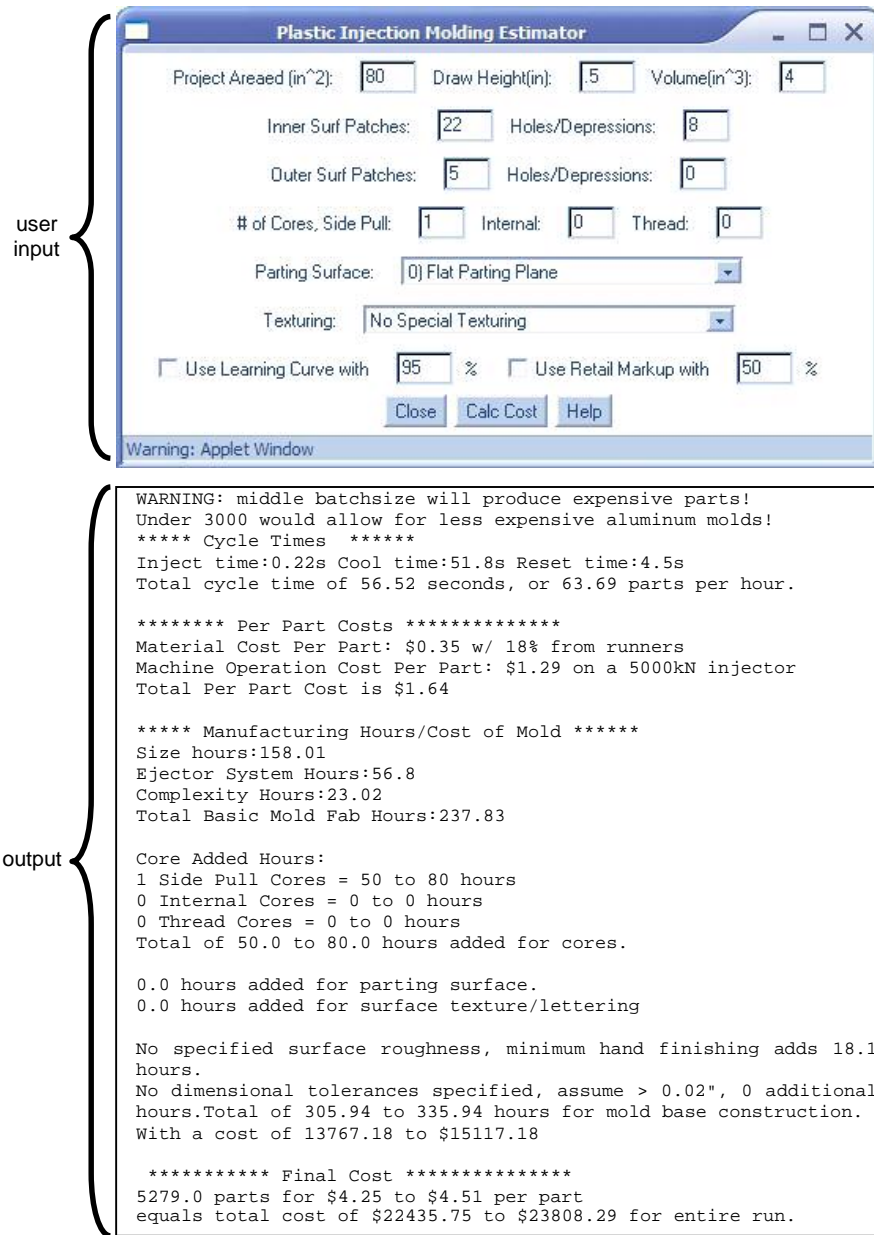


Figure 2.6 – Example input/output for MAS

Source: <http://cybercut.berkeley.edu/mas2/html/applet/index.html>

2.3.3.3 – SEER DFM

Galorath Software publishes SEER DFM, a commercial software suite that “... is an estimation and analysis tool that lets you identify, evaluate and manage the complex array of cost, labor, assembly, process, part design, material, and production variables that affect manufacturing operations.” [23]. SEER DFM contains a set of modules, each tailored for a specific domain of manufacturing (e.g. machining, sheet metal bending, assembly, etc...).

One such module is dedicated to SMM cost analysis. The software allows the user to input ranges of manufacturing input variables (in stead of fixed quantities) and will output a cost estimate based on some proprietary internal computations.

Although SEER DFM accounts for a considerable array of input variables, it neglects many key part geometry parameters that are required for an accurate estimate, especially for estimating tooling costs. For instance, the software does not account for part complexity or number of undercuts. Realistically, the software is more oriented towards a rough estimation of a whole product which requires assembly of many components made with many different processes. As a dedicated injection molding cost estimator, it seems rather limited.

2.4 – Multi-Material Molding Cost Estimation

Currently, there is very little public information regarding MSM, let alone cost estimation methods for any of the MMM process. Unlike the widely available SMM cost estimation models (Boothroyd, Poli, SEER DFM, etc...), there are no customized techniques dedicated to MSM. However, a few specialists in the MMM industry have shared their knowledge in the form of various rudimentary technical papers. Two such publications involve case studies comparing various forms of SMM and MSM in terms of product cost and function. The results of these two studies will be discussed below.

2.4.1 – Case Study I: “Trio Knob”

In the book, *Multi-Material Injection Moulding*, authors Goodship and Love recount a 1996 case study performed by SMT Multi-Shot in Devon, England [24]. The case study involved producing the same product, a 2-colored knob with printed graphics (see the inset of the graph in Fig. 2.7), using three different injection molding variations:

- 1) **Traditional:** Molding the two separate components (the knob and colored cap), then assembling them together and printing a graphics label on it.
- 2) **2-Shot:** Molding the knob and cap together in the same mold and then printing the graphics label on it.
- 3) **3-Shot:** Molding the knob, cap, and graphics all in the same mold.

Table 2.5 is a reproduction of the cost breakdown for each of the three molding methods:

Cost Element *	Molding Process		
	Traditional	2-Shot	3-Shot
cycle time	21+21 s	21 s	21 s
tool cost	£8,500	£12,000	£19,000
run cost	£.01241/part	£.00657/part	£.00695/part
material cost	£.00345/part	£.00365/part	£.00385/part
assembly + print cost	£.01650/part	£.00825/part	£0/part
part cost	£.03236/part	£.01847/part	£.01080/part
* - measured in 1996 British Pounds			

From the table, it is readily apparent that although the tooling cost for both MS processes is greater than for traditional molding, the per-part cost is reduced significantly. However, it is more instructive to look at the total cost as a function of batch size. Fig. 2.7 plots the total cost of each process as a function of batch size. The equation plotted was:

$$C_{\text{total}}(q) = C_{\text{tool}} + q \cdot c_{\text{part}} \quad (2.52)$$

Where the total cost, C_{total} [£], is the sum of the tool cost, C_{tool} [£], and the product of the production quantity, q [parts], and the per-piece cost, c_{part} [£/part]. From Fig. 2.7, it becomes evident that the cheapest production method depends on the production quantity. In this case, traditional molding costs the least until about 2,500,000 pieces, when 2-shot molding becomes the cheapest until about 9,000,000 pieces, where 3-shot molding finally becomes the most economical process.

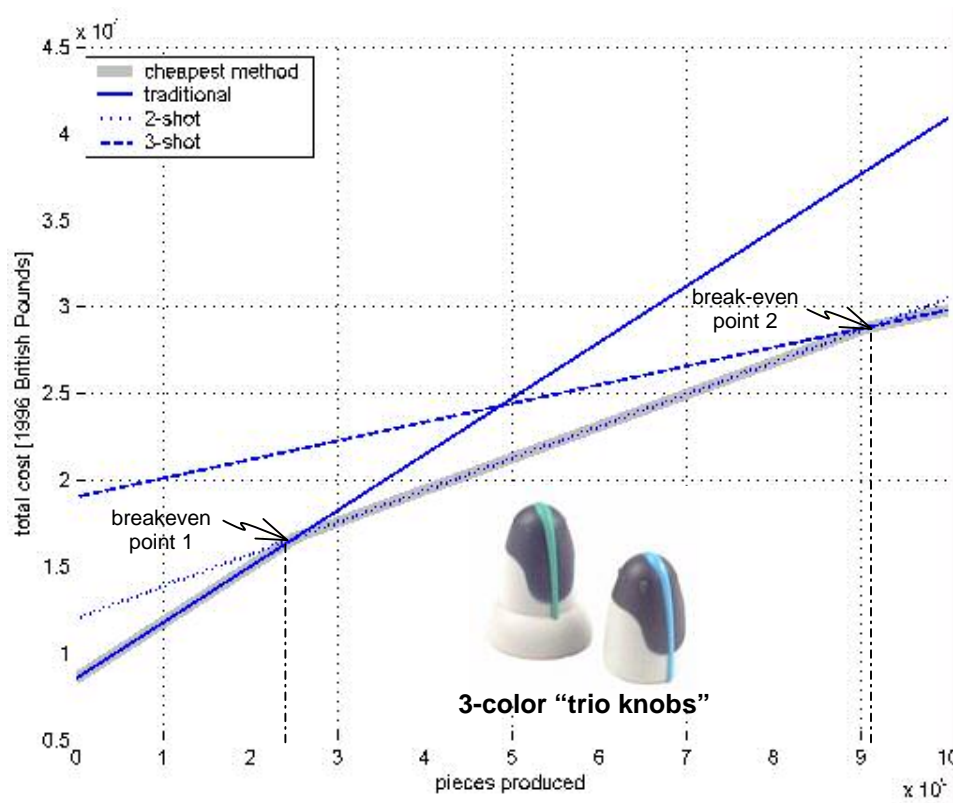


Figure 2.7– Cost comparison plot for tri knob case study

Although the real-world scenario is probably more complex in terms of total costs and factory logistics, this simple exercise shows how each mold process has its economic advantages and drawbacks dependent on the production demands. This implies that if the product quality and functionality is the same for all processes, there is no “best” process choice for all scenarios.

Goodship and Love’s work is really a survey rather than cost estimation model. Consequently, there are no theories of use for adaptation into the cost estimation model developed in this thesis.

2.4.2 – Case Study II: “Concept Part”

John Hahn of MGS Enterprises conducted a case study on the hypothetical concept part shown in Fig. 2.8 [26]. The case study compared the total costs associated with producing that part using six different variations of MSM. Each variation used a

combination of different equipment and MSM techniques. The six variations studied were as follows:

- 1) Robotic part transfer between separate molds on a single dual-injection unit press
- 2) Rotary platen with side actions in mold
- 3) Rotary platen with retracting sleeves (“core toggles”) in mold
- 4) Rotary platen with a shutoff style mold
- 5) Rotating stripper (“index plate”) in the mold
- 6) Retracting sleeve (“core toggle”) in the mold

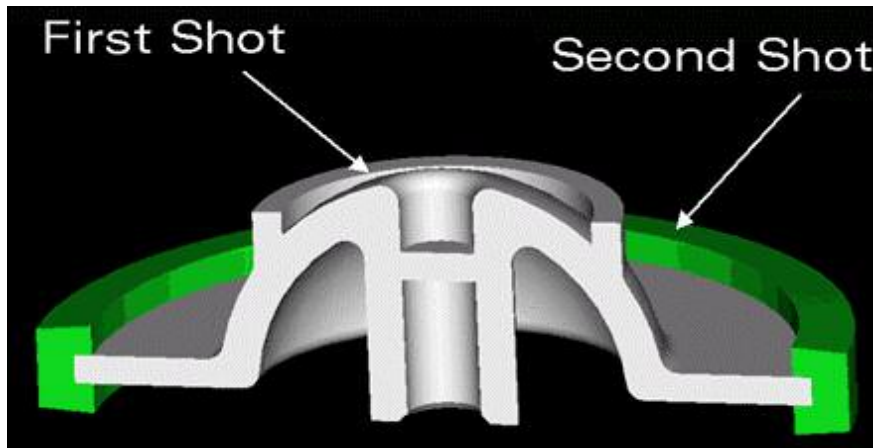


Figure 2.8 – X-section of concept Part for Case Study II
 Source: http://www.multishot.com/data/version_concept.htm

Please note that while every variation produced a part similar to the concept part illustrated in Fig. 2.8, they were not all identical in geometry. That is, the geometry of the interface between both materials would be different in some of the variations. These small geometric differences could affect the functional requirement of the product in some cases.

The cost breakdown of each variation is reproduced in Table 2.6 below:

Table 2.6 – Cost Comparison for Concept Part Case Study (reproduced from [26])						
Cost Element	Molding Process Variation					
	1	2	3	4	5	6
cycle time	26 s	24 s	24 s	24 s	24 s	28 s
press cost	\$360,085	\$380,085	\$360,085	\$360,085	\$360,085	\$320,085
Tooling cost	\$146,500	\$234,000	\$186,700	\$175,000	\$186,700	\$186,700
robot cost	\$80,690	-	-	-	-	-
vision system cost	\$12,250	-	-	-	-	-
rotary platen cost	-	\$57,000	\$57,000	\$57,000	\$57,000	-

total capital cost	\$599,525	\$671,085	\$603,785	\$592,085	\$603,785	\$506,785
part cost (per million)	\$95	\$91	\$91	\$91	\$91	\$73

From Table 2.6, we see a similar scenario as in the first case study. That is, some processes require lower capital investments while causing a higher per-piece cost and vice versa. However, in this case study, the retracting sleeve (variation #6) clearly is cheaper in terms of capital investment and per-piece part cost.

However, these numbers do not reflect the fact that variation #6 produces the part with the most dissimilar geometry to that of the desired case study part. Fig. 2.9 illustrates the mold required for this variant, and the resultant modified geometry of the part. This potential tradeoff between cost and product functionality seems to suggest that no one process variation is “best” in terms of cost and performance. This agrees with the conclusions of the case study: “The part’s functional requirement will ultimately decide which option of tooling and manufacturing can be chosen.” [26].

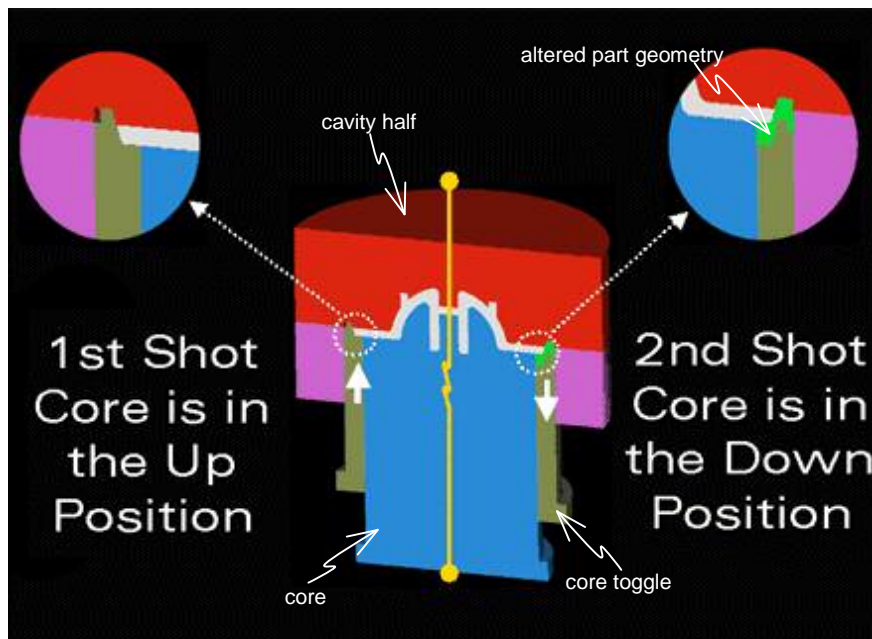


Figure 2.9 – Molding Variant #6 for Case Study II
Source: http://www.multishot.com/data/version_7.htm

Although Hahn does not explain how he arrived at the numbers in Table 2.6, it is the author's opinion that he used a combination of experience and direct quotes to obtain these his cost values. While the data is insightful, there are no theories useful to the development of the cost estimation model proposed in this thesis.

2.5 – Summary

In summary of this chapter, a broad range of work relevant to MMM cost estimation was reviewed. More specifically, this included general cost accounting practices, generic cost modeling and estimation methods, and specific cost estimation and process selection theories. The key points of each major theory were identified, and the ideas which are directly borrowed and/or adapted into the proposed cost estimation model were noted.

CHAPTER 3 – COST ESTIMATION

This chapter presents a cost estimation model that compares the total manufacturing costs associated with both multi-material molding and single-material molding and assembly for functionally-similar products. The model is based on original work as well as some of the single-material cost estimation methods reviewed in Chapter 2. First, the purpose of the model is stated, including the type of real-world scenario where such a model may be applicable and useful. The mechanics and assumptions of the model are then posed before a brief example scenario is illustrated. Finally, the technical discussion and justifications are presented.

3.1 – Introduction

This section lays the groundwork needed for understanding and utilizing the model. The purpose, scope, and assumptions underlying the model are explained. An example scenario where such a model might be used is also presented.

3.1.1 – Model Purpose

The purpose of the model is to provide product designers a tool with which to help them compare two manufacturing processes using a cost-based metric. The specific manufacturing alternatives are MMM and SMM&A. The model will calculate the total per-piece manufacturing cost of the product for both processes, allowing the designers and other decision makers to compare and choose the appropriate options.

Consider the following generic scenario: A company interested in manufacturing a new product has narrowed down the final design to two variants, one made using SMM&A,

the other using MMM. Because this is a new product line, the company does not yet have the capital equipment (e.g. molding presses) required to make either variant, and therefore must decide which technology to invest in. However, from just looking at the engineering drawings and CAD models of the product, it is unclear which one will cost less to produce.

The company would use the proposed model to determine which process is economically superior. The input to the model would be the geometric and material characteristics of the product (preferably automatically via a CAD model), as well as other variables representing the company's process capabilities and economic trends (e.g. machining accuracy, utility rates, labor requirements, etc...). The model would then perform a series of analytical calculations based on the input for both manufacturing scenarios. It would output the total costs, broken down into several categories, for both processes. The designers could then choose the cheaper alternative or revise the product design and run the model again.

3.1.2 – Model Embodiment

The model is designed to estimate manufacturing costs through evaluation of an ordered sequence of analytical and semi-empirical formulas in conjunction with tabular data. The equations require input values of a number of relatively low-level physical characteristics dependent on the desired product form/function, and chosen materials. For example, parameters such as part volume, wall thicknesses, and surface finishes need to be known in addition to such parameters as resin cost, density and melting temperature.

Additionally, several manufacturer-specific process-capability variables also need to be input. This includes such things as dimensional tolerances provided by particular milling equipment, material removal rates, assembly times, and labor rates.

In many cases the equations are left in a generic symbolic form so that the model can be tailored specifically for the user. This requires input of several manufacturer-specific constants that must be determined in order for the formulas to output actual numerical results. These parameters are usually determined through analysis of the company's historical records. For example, each machine shop might have different hourly labor rates, utility costs, etc..., as well as different process capabilities. A “black box” view of the model is illustrated in Fig. 3.1.

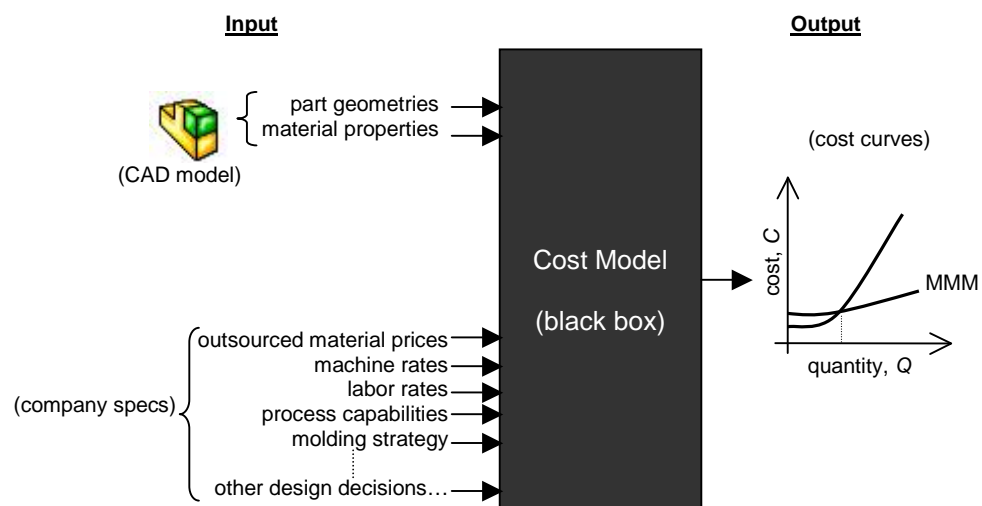


Figure 3.1 – Black box view of cost model

Because the model simply computes the total costs based on equations and table-lookups, it could quite easily be implemented into some type of software. In fact, the eventual goal is to incorporate an automated version of this model into a mold design software suite concurrently being developed. Conceivably, the user would simply input the CAD model along with other important parameter values and the total molding cost would be estimated along with other functions such as fully automated mold design, flow simulations, etc...

The model is structured as a tree of equations (Fig. 3.2), which must be successively evaluated from the bottom layer up, in order to arrive a value for total cost (the top of the

tree). The second-highest level contains the most generic and limited equations, with terms that are decomposed into lower-level relations on the next level down. Working down the tree, each quantity is broken down into simpler (or more easily-obtainable) constituents until it cannot be further dissected, or the scope of the model is exceeded. At the bottom level of each branch (e.g. “ $p_c^{a,b}$ ” in Fig. 3.2) are simple quantities that must be input by the user to allow the symbolic equations to be evaluated, trickling up to the topmost level of the tree.

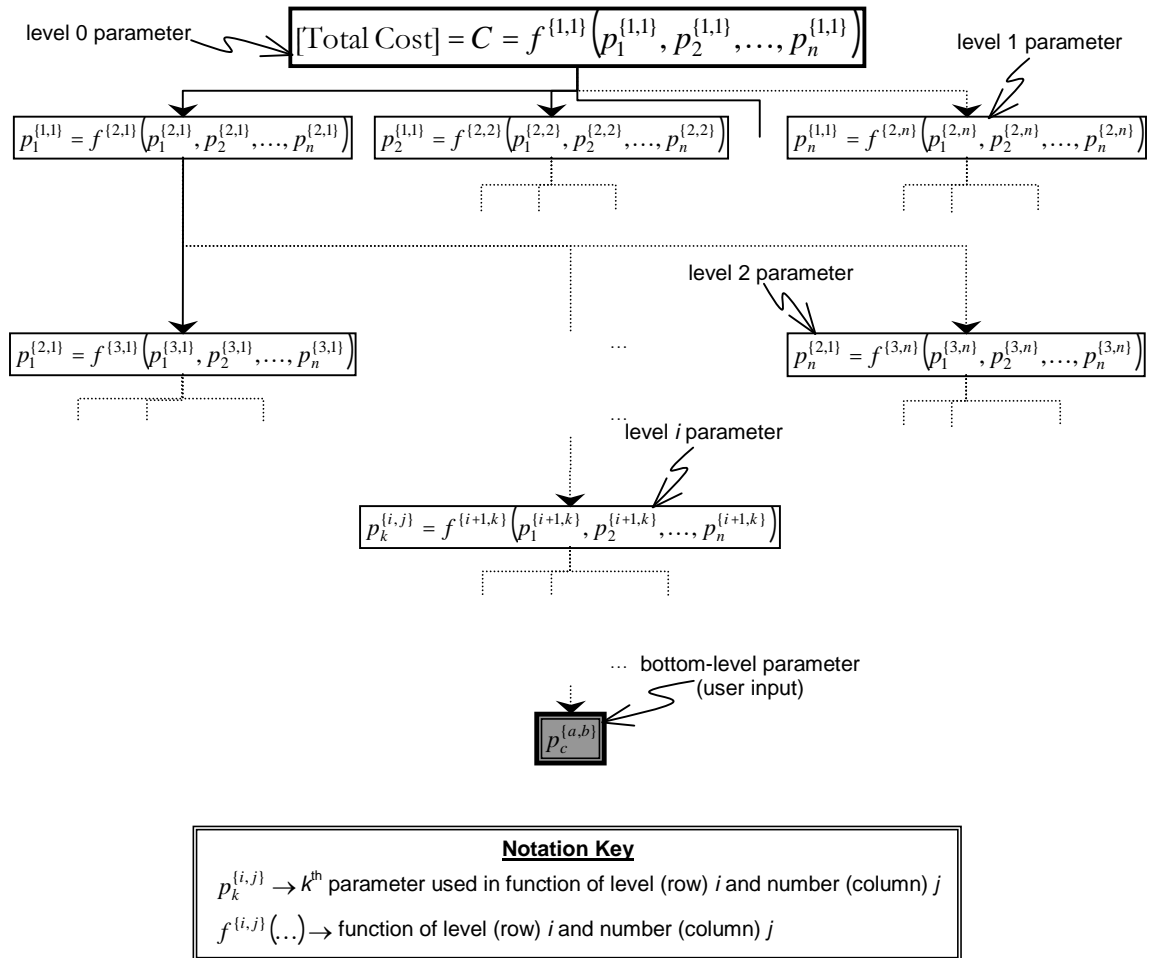


Figure 3.2 – Generalized layout of model’s tree structure

Figure 3.4 in Section 3.2.2.3 illustrates a more specific roadmap of the model in a similar form as Figure 3.2 above.

3.1.3 – Model Scope and Assumptions

For the sake of keeping the model tractable, several assumptions constraining the scope of the model must be made. These simplifications are discussed below.

3.1.3.1 – *Input Parameters and Absolute/Relative Accuracy*

Obviously the ideal goal of the model is to provide cost estimates of the highest accuracy, reliability and repeatability. Provided all the input data to the model is completely accurate, the model output should be accurate as well. However, as is the case with most models, the principle of “garbage in, garbage out” also applies here. That is to say, that the model results are only as good as the underlying input.

Unfortunately, in many cases it is infeasible or simply not possible to obtain all the correct values for the myriad of input parameters. This is especially true at the early design stages, where only the CAD model of the desired product is available. However, when this is the case, the model can still be used to provide accurate cost values in a comparative sense.

In fact, the main purpose of the model is to compare two process variants, so relative costs between these variants will still be quite useful in aiding decision-making. In light of this, the model was designed to emphasize the differences in cost-drivers for both processes in order to produce accurate relative cost estimates when absolute costs cannot be reliably produced from the available input data. The idea is that any inaccuracies caused by input data will be propagated into cost estimates for both process variants, so that they will, in effect, cancel each other out. Thus, when comparing cost values, error caused by bad input values will be present in both variants’ estimates.

As an example, consider the following scenario: say an inaccurate set of material properties for one resin was input into the model, causing the expected cooling time to be off by a value of $x\%$. This would cause the cycle time to be erroneously calculated. Since

the same material properties would be used for both process variants, this input error would cause the total cost estimate to be off by some $y\%$ for both the SMM&A and the MMM cost estimates. So although this input error could have a great effect on the absolute cost, it wouldn't affect the accuracy in a relative sense.

As the model is derived throughout this chapter, this principle of relative accuracy will be emphasized, especially in noting parameters in which inaccuracy will have the same relative effect on both variants' estimated cost.

3.1.3.2 – Process Capability Assumptions

The model assumes that all direct manufacturing operations (i.e. molding and assembly) are performed in-house. It is assumed the products are completely manufactured in a single in-house facility, going from raw material to their final embodiment, including packaging. This assumption requires that all of the proper capital equipment be purchased. The model will account for the cost of the capital equipment.

It is also assumed that all the mold cavity/core tooling and surfacing is performed in-house by a fully-capable machine shop. Additionally, the mold ejector systems and cooling systems will be manufactured in-house. The capital cost of the machining equipment (e.g. milling machines, etc...) will not be included in the model.

Aside from the product manufacturing and mold tooling, it is assumed that everything else is subcontracted out. This includes the purchasing of raw materials (i.e. raw plastic resin and fasteners) as well as the mold base (prior to machining cavities, cooling lines, ejectors, etc...).

3.1.3.3 – Molding Process and Equipment Assumptions

This model is restricted to comparing only two specific manufacturing processes: 1) separate single-material molding with assembly operations, and 2) multi-material molding via

the MS rotary platen technique. These two process variants were chosen based on their industry popularity and relative simplicity compared with other variants. It should be noted that, without much difficulty, it would be possible to expand the model to accommodate other MS processes besides the rotary platen technique. On the other hand, substantial modifications to the model would be required to accommodate other MMM process such as co-injection molding.

The two applicable molding processes are detailed below.

- Single Material Molding with Assembly Operations

In the proposed model, SMM&A involves separately molding both components and then manually assembling them together (using the required fasteners/adhesives) to form the desired product. The individual components are made using standard injection molding described in Section 1.2.1. It is assumed that any fasteners needed to assemble the separate components are simply purchased from outside manufacturer. Furthermore, it is assumed that each component is inspected before assembly, and defective pieces are removed and prevented from creating a defective assembly. The defective units can later be reground and recycled into raw plastic stock. Finally, the finished assemblies are packaged and ready for shipment.

For this model, the capital equipment considered is limited to:

- 1) The two separate injection molding presses, including the required injection units and resin feed systems (i.e. hoppers, etc...)
 - 2) The two separate molds with required subsystems
 - 3) The assembly station and its required tools
 - 4) Auxiliary equipment such as resin dehumidifiers
- Multi-Material Molding via the Multi-Shot Rotary Platen Technique

In the proposed model, MMM involves only the rotary platen variant of MSM. The whole product will be assembled in-mold on a single MS capable molding press fitted with a

rotary platen, as described in Section 1.2.2.4. After the finished product is ejected from the mold, it will be collected and packaged if it passes manual inspection and discarded if it fails. This is necessary due to the fact that defective assemblies cannot be reground and recycled because it is usually too difficult to separate them into their single material components.

For this model, the capital equipment considered is limited to:

- 1) The multi-shot capable molding press, including both separate injection units
- 2) The multi-shot mold with its required subsystems
- 3) The rotary platen
- 4) Auxiliary equipment such as resin dehumidifiers

It should also be noted that it will be assumed that a hot runner system will be employed in the MMM variant because they are almost always required for rotary platen molding. The cost of the rotary platen will be considered a sub-cost of the tooling.

3.1.3.4 – Factory Dynamics and Labor Assumptions

This model will take a simplistic approach to analyzing the dynamics of the production systems under consideration. Specifically, it is assumed that all processes in the production line are constantly running at full speed with 100% utilization (no unscheduled interruptions). The system will be treated as deterministic with no queuing and quantities such as WIP and capacities will be neglected. In essence, the system will be treated as a simplified batch production line, where batches of products traverse uninterruptedly through sequential operations until completion. Furthermore, it is assumed that each station will have access to essentially unlimited quantities of raw materials. This ensures that the previous assumption of 100% utilization is fulfilled; that is, at no time are there inactive stations (e.g. the molding machine has an unlimited supply of resin so that it can continue to produce parts at all times). These assumptions allow the production quantities and cycle times for each station –key factors in production costs – to be computed in a simple manner.

In terms of labor, the same assumption of 100% utilization will hold. The exact labor strategy is not constrained in this model, allowing as many or as few laborers assigned to the production line as the company sees fit. However, more complex factors such as worker scheduling, learning curves, inconsistent production times, and the like will not be considered.

3.1.3.5 – Product Restrictions

For conciseness and simplicity, the proposed model has been developed to only handle bi-material products, not including fasteners in the SMM&A variant. Fortunately, two-shot molding is the most common in the industry, with three or more shot molding seeing very limited use. Regardless, the model could quite naturally be expanded to incorporate n materials. Similar reasoning used to develop the current model would be used to arrive at analytical cost-estimation expressions for more than two material products.

In terms of product geometry or physical embodiment, there are no specific restrictions per-se, as long as the proposed geometry is physically realizable for the process. It is assumed that all of the applicable DFM rules have been applied with good judgment during the design of both product variants. In other words, it is assumed that both product variants under consideration are indeed manufacturable by their respective processes. For example, because the rotary platen MSM process requires the core side of the mold to be geometrically identical for all shots, this needs to be taken into consideration because it could potentially limit the geometry of the MM variant.

In terms of material selection, the proposed model imposes no restrictions provided the product is properly designed so that the two materials will remain attached at their intended interface. This can be accomplished via using compatible materials, adhesives or

fasteners, and/or macroscopic interfaces. As long as the proper DFM and DFA rules have been considered, the proposed model will work for any material combination choice.

3.1.3.6 – Mold Tooling Assumptions

For the purposes of this model, it will be assumed that the final cavity and core sections of the mold are fabricated using only CNC machining. Although in practice most molds are actually tooled via a combination of machining and electrical discharge machining (EDM), standard numerically-controlled machining, especially milling, will be the only tooling processes accounted for in this model. This assumption is not as limiting as it might at first seem, because up until recently, CNC machining was the primary method used to machine the core/cavity geometry. Most mold cavity geometries may be realized through machining, although there are some limiting factors. For example, all internal corners will have to be rounded (filleted) due to the finite positive diameter of milling cutters. Usually however, this is not an issue because most DFM rules recommend rounding corners wherever possible.

The model could be readily expanded to incorporate other mold tooling processes such as EDM, although the mold process planning would have to be more completely specified. This may be difficult in the early design stages, where this model would be most applicable and beneficial.

A final important simplifying assumption that this model will make use of is that all molds will be made out of standard quality steel suitable for most mid-sized molding runs (under 5 millions parts). In practice, most moldmakers will build their molds out of different metals, depending on the production requirements. More durable and costlier materials are used for high-volume runs, and cheaper materials are used for low-volume runs. This ensures the molds will be able to last throughout the entire production run without needing

excessive retooling or complete rebuilding. This model will not take into account the wear induced on molds due to high-volume runs, and hence only one material (steel) will be considered for the tooling cost estimation.

3.1.3.7 – Other Assumptions

There are several other assumptions formed throughout this thesis, regarding various aspects of the two process variants. These assumptions are quite specific and will be introduced in their respective sections of relevance.

3.1.4 – Model Application Example

The following example presents an applicable scenario where such a model would be beneficial to both the designers and other decision makers in a company.

A captive molding company is interested in manufacturing a new product which consists of a simple two-piece plastic box with a translucent lid and opaque base. They currently have not invested in any capital equipment which could produce such a product, and want to figure out what manufacturing process would be most economical for this particular product. They have narrowed the possible processes down to two choices: 1) SMM&A, or 2) Rotary Platen MMM.

Based on the two possible manufacturing processes, the designers have produced two product variants, both of which are shown in Fig. 3.3. While both variants may appear identical at first glance, there is one crucial difference: The SMM&A variant (Fig. 3.3a) has the lid and base coupled via a metal hinge pin while the MMM variant (Fig. 3.3b) has no such pin; rather, the base material (“material A”) forms the hinge itself. Because the precision of the hinge is not an issue with this simple assembly, both variants perform the intended product function equally well.

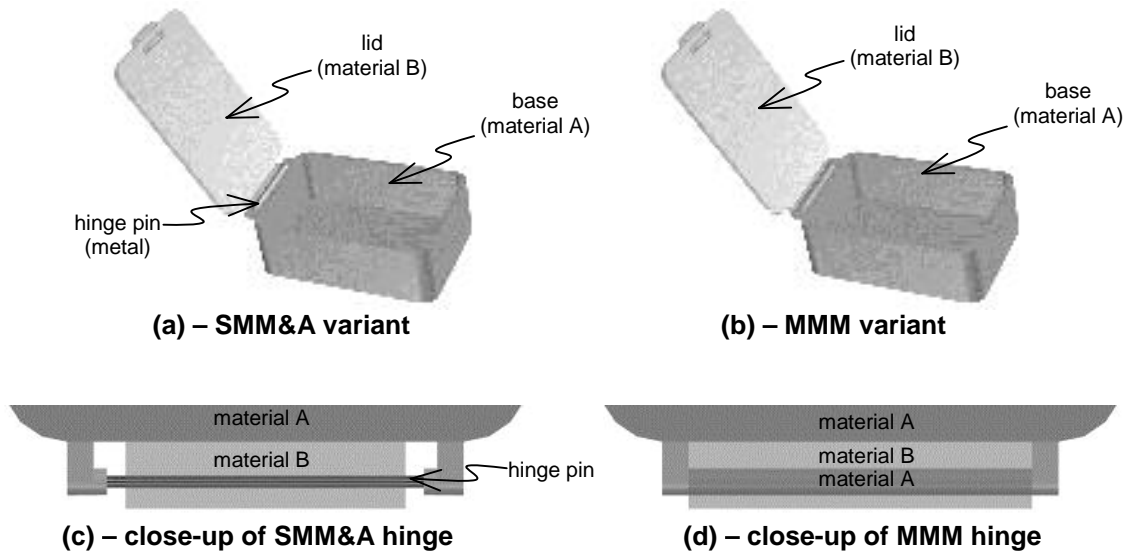


Figure 3.3 – Two variants of the hinge box

Of course the action of the hinge would be slightly different. The SMM&A version would tend to rotate smoother but also exhibit some lateral wobble due to slight dimensional mismatch between the pin and plastic sections. The MMM hinge would tend to be tighter overall, including rotation and lateral movement. However, the only real important difference between the two variants is the manufacturing process, and hence total manufacturing cost.

The SMM&A variant would be manufactured by injection molding the lid and base separately and then manually (or robotically) assembling the base, hinge pin, and lid. This would be accomplished by first inserting the pin into the lid and then snapping the ends of the pin into small holes on the base. This would require a slight deformation at the ends of the hinge section on the base piece in order for the pin to fit inside.

The MMM variant would be manufactured by first injecting the base (material A), reconfiguring the mold via rotary platen, and then injecting the lid (material B), which would form around the hardened base, producing the hinge in the process.

In order to select the most economical variant, the designers could use the proposed model by inputting all of the relevant physical parameters and process capabilities related to both variants. The model would output the total cost of producing each variant (as a function of production quantity). Then the designers would choose to go ahead with the cheaper variant and purchase all of the required capital equipment for manufacturing their chosen product.

3.2 – Model Formulation

This section will develop the equations used in the model from a top-down perspective. All relevant quantities and relations are defined along with explanations and justifications.

3.2.1 – Notation Scheme

For the sake of consistency, a new notation scheme has been developed for this model, rather than adhering to one or more described in Chapter 2. Every time an equation with new terms is introduced, a table will directly follow it listing the new variables and the appropriate units. For example:

$$E = Cx + Dy \quad (\text{<equation \#>})$$

<variable name>	<i>E</i>	[<units>]
<variable name>	<i>C</i>	<units>]
<variable name>	<i>x</i>	<units>]
<variable name>	<i>D</i>	<units>]
<variable name>	<i>y</i>	[<units>]

The tables' columns, from left to right, list the variables name, the symbol, and the units. If a variable's row is not shaded (i.e. white) like *y* in the above example, it denotes that the variable is a function of other variables which will be defined later in the model formulation. If a row is shaded light grey like *C* in the above example, it denotes that it is a

company-specific quantity (e.g. utility rates, labor rates, etc...) that must be determined and input. Finally, if a row is shaded dark grey like x in the above example, it denotes that it is an input variable which must be supplied by the model user.

A further distinction that should be clarified is in denoting variables with respect to their particular material shot. For this model, only 2-material products are considered, so the letters “A” and “B” will be used to refer to the two separate materials respectively. For example, “part A” refers to the component made of the first material (“material A”), and “part AB” refers to the final assembly of both components A and B.

With this naming scheme in mind, variables specifically pertaining to either parts A, B, or AB will have the appropriate subscripts. For example, if we were calculating the weight of the final assembly, we would use the following relation:

$$w_{AB} = w_A + w_B + \sum w_{\text{fasteners}}$$

Weight of assembly AB	w_{AB}	[oz]
Weight of part A	w_A	[oz]
Weight of part B	w_B	[oz]
Total weight of fasteners	$\sum w_{\text{fasteners}}$	[oz]

Which simply states that the weight of the final assembly (“part AB”) is the sum of the weights of part A, part B, and all of the fasteners required. A similar notation is used when referring to other material-specific or part-specific quantities.

For the sake of brevity, the subscript, i , is sometimes used to denote a variable that could pertain to either material A or B. For example, an equation for calculating the weight of either part A or B could be written as:

$$w_i = V_i \rho_i$$

Weight of part i	w_i	[oz]
Volume of part i	V_i	[in ³]
Density of material i	ρ_i	[oz/in ³]

Where the subscript i would be replaced with either an “A” or “B” when referring to a specific material. Sequential equation numbers will only be assigned to the major formulae directly used in evaluation of cost.

3.2.2 – Overall Cost Equations

3.2.2.1 – Case Switching

The variable, ϕ , will be used as a switch in the following model to account for using either MMM or SMM&A. This simply allows certain terms to switch on and off in several equations. This way one equation can be used to represent either manufacturing process.

$$\phi = \begin{cases} 0, & \text{case I : SMM \& A} \\ 1, & \text{case II : MMM} \end{cases} \quad (3.1)$$

3.2.2.2 – Generic Per-Piece Costs

For a foundation, we first start with the most generic per-piece manufacturing cost as suggested by Esawi and Ashby’s resource-based modeling [16], [17]:

$$c = c_M + c_T + c_O + c_E + c_S + c_I$$

$$c = \underbrace{\left[\frac{c_M}{Q} \right]}_{\text{Material}} + \underbrace{\left[\frac{C_T}{Q} \right]}_{\text{Tooling}} + \underbrace{\left[\frac{\dot{C}_O}{\dot{Q}} \right]}_{\text{Overhead (time)}} + \underbrace{\left[\frac{\dot{E}\hat{C}_E}{\dot{Q}} \right]}_{\text{Energy}} + \underbrace{\left[\frac{A\tilde{C}_S}{\dot{Q}} \right]}_{\text{Space}} + \underbrace{\left[\frac{\dot{C}_I}{\dot{Q}} \right]}_{\text{Info}}$$

Total per-piece cost	c	[\$/part]
Per-piece material cost	c_M	[\$/part]
Per-piece tooling cost	c_T	[\$/part]
Per-piece overhead cost	c_O	[\$/part]
Per-piece energy cost	c_E	[\$/part]
Per-piece space cost	c_S	[\$/part]
Per-piece info cost	c_I	[\$/part]

Tooling cost	C_T	[\$]
Overhead rate	\dot{C}_O	[\$/hr]
Power consumption	\dot{E}	[kW]
Energy cost	\hat{C}_E	[\$/(kW•hr)]
Area	A	[ft ²]
Space cost	\tilde{C}_S	[\$/(ft ² •hr)]
Info rate	\dot{C}_I	[\$/hr]
Production quantity	Q	[parts]
Production rate	\dot{Q}	[parts/hr]

Here the total per-piece cost is split into six categories: 1) material, 2) tooling, 3) overhead or time, 4) energy, 5) space, and 6) information. The total cost's units of dollars per piece are kept consistent by dividing each resource by an appropriate rate. For example, the overhead per-piece cost is found by dividing the per-hour cost of overhead by the hourly total assembly production rate. The above equation is intended to be used for a *single process* rather than a manufacturing system such as SMM&A or MMM production lines with multiple stations (e.g. molding, assembly, inspection, etc...).

The previous equation can be rearranged into three terms as follows:

$$c = [c_M] + \frac{1}{Q} [C_T] + \frac{1}{\dot{Q}} \left[\underbrace{\left(\dot{C}_{BO} + \frac{C_C}{f_L t_{WO}} \right)}_{\dot{C}_O} + \dot{E} \hat{C}_E + A \tilde{C}_S + \dot{C}_I \right]$$

"gross overhead" term

Basic overhead rate	\dot{C}_{BO}	[\$/hr]
Total capital cost of equipment	C_C	[\$]
Load factor	f_L	[%]
Capital write-off time of investment	t_{WO}	[hr]

The three terms represent the three essential contributions to cost per unit: 1) a material cost (independent of batch size or production rate), 2) a dedicated production cost (inversely proportional to batch size), and 3) a “gross overhead cost” (inversely proportional to production rate).

- **Material Cost**

The material cost is simply the cost of the raw materials that go into producing one unit (e.g. resin, fasteners, adhesives, etc...). This cost is usually quite easily calculated by determining how much material goes into each product and multiplying it by its respective cost from the supplier. For example, in injection molding, the total volume of a part can be used to determine how much resin is needed, which is then used to determine the cost based on a supplier’s resin price. The material cost calculations are discussed in Section 3.2.4.

- **Dedicated Production Cost**

The dedicated production cost (or “tooling cost”) is basically the cost of the specialized equipment (e.g. molds) required to manufacture the product, amortized over the total production volume. For example, if a \$500,000 mold is used to make a total of 5 million products before it is retired, the mold itself is contributing a cost of \$0.10 to each product. For injection molding, the tooling includes the mold base, the machined cavities, the machined cooling system, the ejector system, and any other special features such as side actions. The cost of each of these items must be accurately calculated and summed to get the total tooling cost, which can then be divided by the production quantity. The production cost calculations are discussed in Section 3.2.5.

- **Gross Overhead Cost**

The gross overhead is split into five terms: 1) basic overhead, 2) capital cost, 3) energy cost, 4) space cost, and 5) information cost. These all relate to the fact that the

manufacture of any product requires the consumption of all of these five kinds of “resources” (e.g. labor, capital equipment, power for running equipment, factory space, and designer’s time, respectively).

The reason that the cost of capital equipment is amortized over the production rate (instead of the production quantity as with the tooling cost), is because capital equipment (such as an injection molding machine) is typically used to manufacture many different product lines, rather than dedicated to a single product. Therefore, it is customary to amortize such capital costs over a period of time rather than a production quantity.

The above equation splits the overhead rate into two terms: 1) a basic overhead rate which covers the cost of labor and other fuzzy expenses, and 2) a total capital cost which is amortized over a specified write-off time, t_{wo} , (usually in years, but expressed in hours for unit consistency). The write-off time is time is how long the capital cost of equipment takes to be recovered or paid off, and depends on the conditions of the loan. There is an additional term contributing to the overhead rate representing the fraction of time over which the equipment is actually being productively used. This load factor depends on the factory conditions and which production lines utilize the equipment. For the purposes of this model, the load factor and capital write-off time must be specified by the user. This is because these terms are completely dependent on the financing practices of the company and cannot be estimated analytically. The remaining overhead cost terms, namely the basic overhead rate and total capital cost, are discussed in Section 3.2.6.

- Final Cost Equations

Although every term in the above equation is important, having the potential to drastically influence the overall cost, two terms in the gross overhead expression will be dropped for this model. The first, the cost of energy, will actually be absorbed into the basic

overhead rate. This is because the primary energy consumption is caused only by the operation of the injection machines and any auxiliary equipment. These will all have their own associated run costs based on their power consumption and other factors. The other term, information cost, while having important contributions to overall cost, is outside of the scope of the model. It relates to more administrative cost factors rather than direct manufacturing costs. While this may seem like gross oversight, it should not have a large effect in a relative sense, since this value should be a constant independent of either process variant.

3.2.2.3 – Total Manufacturing Costs

While the per-piece cost of the following equations is a valid and useful measure for cost estimation purposes, it may be more informative to see how the total cost varies with the production quantity. This is because in many cases (e.g. the case study in section 2.4.1) the optimal process in terms of total cost, depends on the amount of units made. For this reason, we will look at total cost as a function of the total production quantity, allowing us to plot quantity-cost curves and identify break-even points and chose the proper variant based on estimated production quantity. To emphasize the most influential factors on cost, the total cost equation can be expressed as a sum of five terms:

$$C = C_M + C_T + C_{BO} + C_{CI} + C_S \quad (3.2)$$

Total manufacturing cost	C	[\$]
Total material cost	C_M	[\$]
Total tooling cost	C_T	[\$]
Total basic overhead cost	C_{BO}	[\$]
Total capital investment cost	C_{CI}	[\$]
Total cost of plant floor space	C_S	[\$]

In summary, Eq. 3.2 will serve as the top-level equation of the model. It simply states that the total cost is estimated as the sum of:

- 1) Material costs (Section 3.2.4)
- 2) Tooling costs (Section 3.2.5)
- 3) Basic overhead costs (Section 3.2.6)
- 4) Capital investment costs (Section 3.2.7)
- 5) Plant floor space costs (Section 3.2.8)

Fig. 3.4 below illustrates a high-level roadmap of the cost estimation model, with some of the terms from Eq. 3.2 expanded. Below each expression are the corresponding section and equation numbers, respectively.

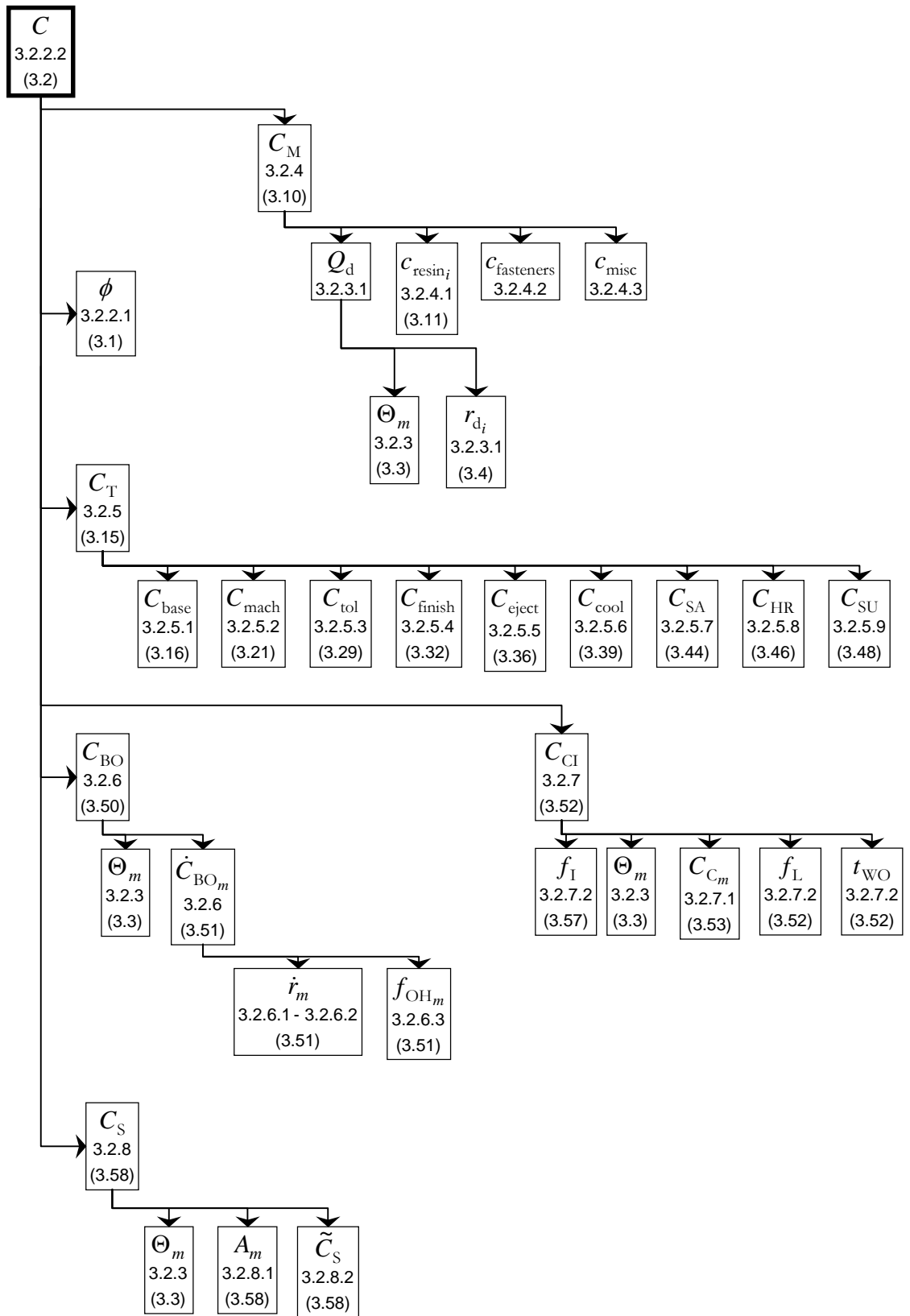
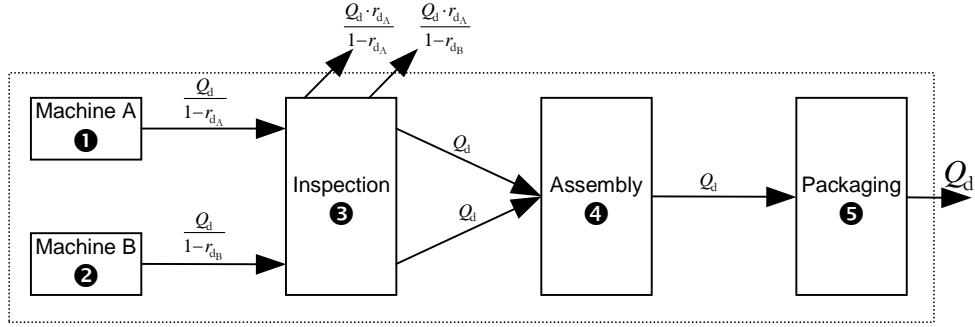


Figure 3.4 – Condensed roadmap for cost estimation model

All of the equations used in this section were borrowed from Ashby's work, with only the terms relabeled and rearranged. They are considered to be valid for all manufacturing processes because they are generic and include all relevant cost drivers. They will need to be adapted to accommodate the specific molding processes under consideration. Particularly, the terms involving production quantities and rates need special expansions to properly account for the numerous workstations needed for production.

3.2.3 – Production Parameters

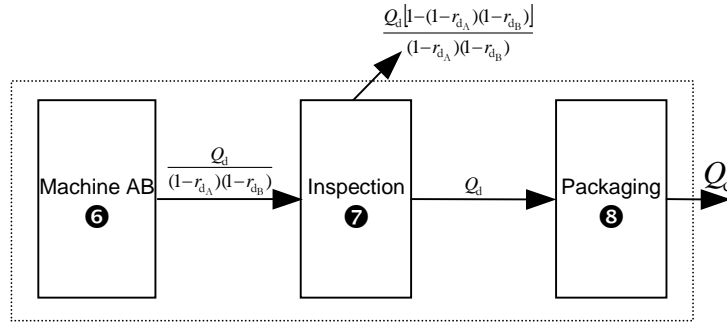
The production parameters relate to the volume and speed of production. That is, they quantify the number of products produced, and the rate of production. These parameters directly affect all of the five cost parameters of Eq. 3.2. Fig. 3.5 graphically represents the production line layout for both variants. It shows the flows of production quantities (Q_m), and rates (\dot{Q}_m) for each station in the line. This figure will be referred to frequently throughout this section.



$$Q_1 = \frac{Q_d}{1-r_{dA}} ; Q_2 = \frac{Q_d}{1-r_{dB}} ; Q_3 = Q_d + Q_d ; Q_4 = Q_5 = Q_d$$

$$\dot{Q}_1 = \frac{n_{cav} \cdot \left(\frac{\text{parts}}{\text{shot}}\right)}{t_{moldA}} ; \dot{Q}_2 = \frac{n_{cav} \cdot \left(\frac{\text{parts}}{\text{shot}}\right)}{t_{moldB}} ; \dot{Q}_3 = \frac{1}{t_{inspA} + t_{inspB}} ; \dot{Q}_4 = \frac{1}{t_{assm}} ; \dot{Q}_5 = \frac{1}{t_{pack}}$$

(a) – SMM&A production line



$$Q_6 = \frac{Q_d}{(1-r_{dA})(1-r_{dB})} ; Q_7 = Q_8 = Q_d$$

$$\dot{Q}_6 = \frac{n_{cav} \cdot \left(\frac{\text{parts}}{\text{shot}}\right)}{t_{moldAB}} ; \dot{Q}_7 = \frac{1}{t_{inspAB}} ; \dot{Q}_8 = \frac{1}{t_{pack}}$$

(b) – MMM production line

Figure 3.5 – Production parameters for both variants

From Fig. 3.5, it can be seen that there are eight separate stations that need to be accounted for. Each station has an associated index, m , ranging from 1 to 8. In the proceeding sections, this index will be used to indicate the station to which a variable corresponds. For example, when referring to the production rate, \dot{Q}_m , the variable \dot{Q}_7 would refer to the output rate [parts/hr] of the MMM inspection station.

For convenience of notation, the following relation is defined to represent the total time spent producing parts at a particular station:

$$\Theta_m \equiv \left(\frac{1 \text{ hr}}{3600 \text{ s}} \right) \frac{Q_m}{\dot{Q}_m}, \quad m = 1, 2, \dots, 8 \quad (3.3)$$

Effective production time of station m	Θ_m	[hr]
Quantity produced at station m	Q_m	[parts]
Production rate at station m	\dot{Q}_m	[parts/s]

3.2.3.1 – Production Quantities

The desired production quantity, Q_d , is the total number of assemblies that need to be made. This actual number could depend on a customer's order size or anticipated demand of the product. It is used as the independent variable for plotting the cost-quantity curves.

The individual production quantities, Q_m , represent the total number of units processed at each station. For example, Q_2 denotes the total number of part B's molded at machine B. In order to ensure that enough assembly AB's are produced to meet the production demand, Q_d , the actual production quantity has to be scaled higher to account for defects. Taking this into account, and referring to Fig. 3.5, the production quantities can be expressed as:

$$Q_1 = \frac{Q_d}{1-r_{dA}} \quad ; \quad Q_2 = \frac{Q_d}{1-r_{dB}} \quad ; \quad Q_3 = 2Q_d \quad ; \quad Q_4 = Q_5 = Q_d$$

$$Q_6 = \frac{Q_d}{(1-r_{dA})(1-r_{dB})} \quad ; \quad Q_7 = Q_8 = Q_d \quad (3.4)$$

Quantity produced at station m	Q_m	[parts]
Desired production quantity	Q_d	[parts]

Expected defect rate of part A	r_{dA}	[%]
Expected defect rate of part B	r_{dB}	[%]

Eqs. 3.4 ensures that Q_d is achieved by adjusting the production quantities at each molding machine (Q_1, Q_2 , and Q_6). This emphasizes how the defect rates affect the variants differently; namely, the chances of a defective assembly are higher in MMM because there is no intermediate inspection and removal of defective components.

- Defect Rates

The defect rates, expressed in a percentage of bad parts to good ones, are a result of random errors in the manufacturing process which result in unacceptable components. These could be caused by any number of reasons such as fluctuations in the controlled parameters (e.g. melt temperatures and pressures), human errors, or mold malfunctions. These numbers have to be estimated from historical data and an understanding of each molding machine's characteristics. However, each molding job is different, with different part geometries producing different defect rates. Typically, conservative average defect rates (based on the plant's production capabilities and adjusted for any geometric issues) must be substituted into Eq. 3.7.

It should be stated, that because the state of today's manufacturing technology, (including molding machines) has significantly reduced defect rates, the defect rates used in the above equation will be rather low (less than 5%). However, it should be notated that because MMM is both more complex than traditional molding, and the technology is less mature, there will most likely be higher defect rates associated with the MMM variant. This is an important difference that is especially emphasized by the structure of Eq. 3.4.

The production quantity and defect rate equations have all been verified as valid through consultation of several molding experts. They serve to correctly adjust the production quantity to account for the inevitable production of defective components.

3.2.3.2 – Production Rates

The individual production rates are defined as the inverse of the total processing time at each corresponding station. For instance, the production rate of the assembly station is the inverse of the assembly time, i.e.: $\dot{Q}_4 = 1/t_{\text{assm}}$. Each \dot{Q}_m depends on the station type as well as the individual parameters governing the station's operation. Referring to Fig. 3.5, the production rates can be expressed via the following equations:

$$\dot{Q}_1 = \frac{n_{\text{cav}} \cdot \left(\frac{\text{parts}}{\text{shot}}\right)}{t_{\text{mold}_A}} ; \dot{Q}_2 = \frac{n_{\text{cav}} \cdot \left(\frac{\text{parts}}{\text{shot}}\right)}{t_{\text{mold}_B}} ; \dot{Q}_3 = \frac{1}{t_{\text{insp}_A} + t_{\text{insp}_B}} ; \dot{Q}_4 = \frac{1}{t_{\text{assm}}} \quad (3.5)$$

$$\dot{Q}_5 = \frac{1}{t_{\text{pack}}} = \dot{Q}_8 ; \dot{Q}_6 = \frac{n_{\text{cav}} \cdot \left(\frac{\text{parts}}{\text{shot}}\right)}{t_{\text{mold}_{AB}}} ; \dot{Q}_7 = \frac{1}{t_{\text{insp}_{AB}}}$$

Production rate at station m	\dot{Q}_m	[parts/s]
Molding time for part i	t_{mold_i}	[s/shot]
Molding time for part AB	$t_{\text{mold}_{AB}}$	[s/shot]
Number of cavities per mold	n_{cav}	[#]
Assembly time	t_{assm}	[s/part]
Inspection time for part i	t_{insp_i}	[s/part]
Inspection time for part AB	$t_{\text{insp}_{AB}}$	[s/part]
Packaging time	t_{pack}	[s/part]

The term in the parentheses is included for unit consistency. It effectively allows n_{cav} to remain dimensionless, which will be convenient in later equations. The above equation makes the simplifying assumption that batch processing is employed throughout the production line. This means that each station is constantly kept busy by working on

batches of the product in various stages of completion. This eliminates the problem of bottlenecks, and makes the production rates simpler to compute. It is important to note that the labor times used in Eq. 3.5 (e.g. t_{pack}) are the times required for one worker to complete the task. If there is more than one worker at any station, although this would increase the corresponding station's effective production rate, it would also increase the hourly labor cost of the station. For instance, if there are two assemblers, the assembly production rate would double, but so would the hourly wages paid to the workers. This would cancel out the effect of the number of laborers on the total cost. Hence, the actual labor distribution is disregarded in this model.

In Eq. 3.5, the molding and assembly times are the most important, because they typically dominate the total cycle time. Analytical expressions for these terms are discussed in more detail below.

- Inspection, and Packaging Times

The inspection, and packaging times must both be estimated based on historical data and reasonable assumptions about the difficulty of such tasks based on the product geometry. For example, a simple box-shaped part would require only a brief look-over by an inspector, while a complicated part with many features might require several seconds of inspection. Similar reasoning should be applied to the packaging term.

- Molding Time

The total molding time is the time the product is spent in the injection molding machine. For the SMM&A variant, although both separate pieces could conceivably be manufactured simultaneously on different machines (in fact, this would be the preferred method), they still require dedicated use of both injection machines, which has an associated cost. Therefore, the molding time for this variant will be the sum of processing times for

parts A and B. On the other hand, the MMM variant only makes use of one machine. Although the molding operation involves the injection and cooling of two separate shots, the actual associated molding time will be only the maximum of the two molding times. This is because, after the machine has reached steady state, one finished part AB is ejected from the mold after the required injection and cooling times. This essentially causes the MMM variant to have consistently less molding times than the SMM&A variant. In an effort to emphasize this key difference, the molding time are defined as:

$$\begin{aligned}
 t_{\text{mold}_i} &= t_{\text{inj}_i} + t_{\text{cool}_i} + t_{\text{reset}_i} \\
 t_{\text{mold}_{AB}} &= \max\{t_{\text{mold}_A}, t_{\text{mold}_B}\} + t_{\text{reset}_{AB}}
 \end{aligned}
 \tag{3.6}$$

Total molding time for part i	t_{mold_i}	[s/shot]
Total molding time for part AB	$t_{\text{mold}_{AB}}$	[s/shot]
Injection time for shot i	t_{inj_i}	[s/shot]
Cooling time for shot i	t_{cool_i}	[s/shot]
Mold resetting time for mold i	t_{reset_i}	[s/shot]
Mold resetting time for mold AB	$t_{\text{reset}_{AB}}$	[s/shot]

The molding time for the i^{th} shot is defined as the time it takes for the part to be injected, cooled, and ejected along with the mold resetting time.

- Injection Time

The injection time can be approximated using the injection pressure and power relation provided by BD&K's pressure/power relation (Eq. 2.22)

$$t_{\text{inj}_i} = \frac{V_{\text{shot}_i}}{Q_{\text{avg}_i}} = \frac{2P_{\text{inj}_i} V_{\text{shot}_i}}{\Pi_{\text{inj}_i}}
 \tag{3.7}$$

Injection time for shot i	t_{inj_i}	[s/part]
Volume of shot i	V_{shot_i}	[in ³]

Injection pressure for shot <i>i</i>	P_{inj_i}	[lb/in ²]
Injection power for shot <i>i</i>	Π_{inj_i}	[lb•in/s]

The injection pressure is set depending on the size of the shot and the mold filling requirements. The power of the injection unit depends on its size, and is obtained from the manufacturer's data. The method for finding the appropriate injection unit size is discussed in Section 3.2.7.1. Calculation of the shot volume is discussed in Section 3.2.4..

- Mold Cooling Time

Perhaps the most accurate method to estimate the mold cooling time is through CAD cooling simulations such as C-Mold or Pro/E's mold analysis tools. If this is not feasible, there are two simpler methods of calculation the cooling time as described below.

The mold cooling time may be estimated based on the maximum wall thickness of the part. This can be done either by Poli's table-lookup method based on elemental plates and part complexity (Section 2.3.2.2), or by using the simple analytical cooling equation (Eq. 2.23). If the simple cooling equation is sufficient, it has to be slightly modified to accommodate MMM:

$$t_{cool_i} = \frac{\tau_{max_i}^2}{\pi^2 \alpha_i} \ln \left(\frac{4[T_{inj_i} - T_{mold_i}]}{\pi[T_{eject_i} - T_{mold_i}]} \right) + t_{extra_i} \quad (3.8)$$

Cooling time for shot <i>i</i>	t_{cool_i}	[s/part]
Maximum wall thickness for shot <i>i</i>	τ_{max_i}	[in]
Thermal diffusivity coefficient for resin <i>i</i>	α_i	[in ² /s]
Required injection temperature for shot <i>i</i>	T_{inj_i}	[°F]
Required mold wall temperature for shot <i>i</i>	T_{mold_i}	[°F]
Safe part ejection temperature for shot <i>i</i>	T_{eject_i}	[°F]
Additional time (safety factor)	t_{extra_i}	[s/part]

Here the maximum wall thickness is obtained from a simple part analysis (or automatically through CAD algorithms). The additional cooling time is simply a factor added to ensure that the part is rigid enough for injection. However, in some MMM cases, this number can actually be *negative*. This is because it may be desirable for the first shot to be only partially cooled to promote bonding between it and the subsequent shot. The remaining four quantities are material-specific and must be obtained through material data provided by the resin supplier.

- Mold Resetting Time

The mold resetting times (t_{reset_i} , and $t_{\text{reset}_{AB}}$) are the time it takes for the mold readied for the next cycle. This includes both the times required for closing as well as the operation of any side-actions and/or the rotary platen (for MMM only). In addition to being affected by the presence of a rotary platen or side actions, the reset time is greatly affected by the part height in the direction of the mold opening. This value should be estimated based on the specifics of the molding press.

A good estimate for the reset time for a SM mold with no side-actions can be obtained by using BD&K's mold reset time equation (Eq. 2.24). The values obtained from this equation have to be augmented by an appropriate time required to reset any side actions the mold contains. The additional time required for the reset of the rotary platen is a function of the size of the platen and how quickly it can rotate 180° to prepare for subsequent shots. This value can be obtained from the platen manufacturer's specifications.

- Assembly Times

The assembly time specifically refers to the total time required to assemble the SMM&A variant of the product. This includes both the handling and insertion times of

both material components as well as any fasteners/adhesives required to secure them. The generic assembly time equation can be written as:

$$t_{\text{assm}} = t_{\text{handle}_A} + t_{\text{handle}_B} + t_{\text{insert}_B} + \sum_{j=1}^{n_{\text{fast}}} (t_{\text{handle}_j} + t_{\text{insert}_j}) \quad (3.9)$$

Assembly time	t_{assm}	[s/part]
Handling time for part i	t_{handle_i}	[s/part]
Insertion time for part i	t_{insert_i}	[s/part]
Handling time for j^{th} fastener	t_{handle_j}	[s/part]
Insertion time for j^{th} fastener	t_{insert_j}	[s/part]
Total number of fasteners	n_{fast}	[#]

Eq. 3.9 assumes the well-known convention as seeing assembly as a series of two types of operations: 1) handling/positioning, and 2) insertion. The times required for these operations are dependent on the part complexity as well as other factors such as workers' skill and the specifics of the assembly station (such as tools and layout/space considerations). There are many detailed works dedicated to estimating assembly times that can be used to accurately find these input parameters. Please refer [8], [9].

If these references are unavailable, or a quick and rough estimate for assembly times are desired, simple reasoning can be used to arrive at reasonable times. This is especially true because the model only allows for simple two-component assemblies with fasteners. In general, any required assembly operations will be very straight forward and brief, requiring at most, a few seconds. In fact, many plastic assemblies are designed to make use of simple mating techniques such as snap-fits and other mechanical locks in order to completely avoid fasteners. If this is the case, then the entire assembly operation would consist of holding one component in each hand, orienting them, and snapping together. Poli offers a simple

“assembly advisor” which can be used to estimate assembly times based on simple criteria [50][50]. These guidelines are reproduced in Table 3.1:

Table 3.1 – Poli’s “Assembly Advisor” for Estimating Assembly Times (reproduced from Poli, [50])				
		← Insertion →		
		Easily Aligned and Easily Inserted*	Not Easily Aligned or Not Easily Inserted*	Not Easily Aligned and Not Easily Inserted*
↑ Handling ↓	Easily Grasped/Manipulated	4.0 s ("good")	8.0 s ("poor")	13.0 s ("costly")
	Not Easily Grasped/Manipulated	7.5 s ("poor")	11.5 s ("costly")	16.5 s ("most costly")
* - "not easily inserted" includes difficulties due to obstructed view and/or access, parts jamming and/or difficulties due to lack of chamfers or part geometry, etc. Resistance to insertion due to press and snap fits is not to be included here				

The total assembly time can be computed by estimating the assembly time of each component and fastener (via Table 3.1) and summing the results. In most real 2-component SMM&A scenarios, the assembly times should be on the lower side of those numbers suggested by Poli (provided adequate use of DFA strategies).

It is of value to emphasize the fact that the assembly time only applies to SMM&A, thus causing a potentially significant difference in the cycle times between SMM&A and MMM. Even if the estimated assembly times have some inaccuracy, their addition to the cycle time will help to differentiate the cost values output by the model.

The equations developed in this section have all been shown valid through consultation with molding experts and comparing with the widely-accepted literature. All new equations were either modified from first principles to incorporate MMM or account for a larger number of cost drivers than their initial versions. In particular, the computation of the cycle time, while not the only way to account for the cost of time, is the most relevant

in terms of the injection molding processes under consideration. It accounts for all of the important time-consuming tasks in the products' production cycles.

3.2.4 – Material Cost

The material cost accounts for all of the separate components of a product, including resins, fasteners/adhesives, labels, and packaging materials. The material cost of a product is given by:

$$C_M = (1 - \phi) [Q_1 c_{\text{resin}_A} + Q_2 c_{\text{resin}_B} + Q_d c_{\text{fasteners}}] + \phi [Q_6 (c_{\text{resin}_A} + c_{\text{resin}_B})] + Q_d c_{\text{misc}} \quad (3.10)$$

Total Material Cost	C_M	[\$]
Cost of resin for shot i	c_{resin_i}	[\$/part]
Cost of fasteners and/or adhesives	$c_{\text{fasteners}}$	[\$/part]
Miscellaneous material costs	c_{misc}	[\$/part]

Where the material cost has been broken down into a sum of resin costs, fasteners cost (SMM&A only), and miscellaneous costs (e.g. packaging, labels, etc...).

3.2.4.1 – Resin Cost

The resin cost is dependant on the amount of resin used in making one part and the resin supplier's price. The total cost is simply calculated as follows:

$$c_{\text{resin}_i} = \frac{V_{\text{shot}_i} \gamma_i}{n_{\text{cav}}} \cdot p_{\text{resin}_i} \quad (3.11)$$

Cost of resin for shot i	c_{resin_i}	[\$/part]
Total volume of shot i	V_{shot_i}	[in ³]
Specific gravity of plasticized material i	γ_i	[lb/in ³]
Supplier's price for resin i	p_{resin_i}	[\$/lb]

Where both the specific gravity of the resin and the price per pound are supplied by the resin manufacturer.

- Shot Volume

The shot volume is the total amount of material that is plasticized and ejected from the mold after injection. This includes the cavity images themselves (the desired molded part geometry), as well as the hardened sprue, runners and gating required to fill the cavity.

$$V_{\text{shot}_i} = n_{\text{cav}} \cdot V_{\text{part}_i} + (1 - \phi)(r_{\text{gating}_i} - f_{\text{rg}_i}) \cdot V_{\text{gating}_i} \quad (3.12)$$

$$r_{\text{gating}_i} \equiv \frac{V_{\text{gating}_i}}{n_{\text{cav}} \cdot V_{\text{part}_i} + V_{\text{gating}_i}}$$

Total volume of shot <i>i</i>	V_{shot_i}	[in ³]
Volume of part <i>i</i>	V_{part_i}	[in ³]
Volume of gating (sprue + runners + gates) for shot <i>i</i>	V_{gating_i}	[in ³]
Ratio of gating volume to total volume for shot <i>i</i>	r_{gating_i}	[%]
Percent of allowable regrind used in resin <i>i</i>	f_{rg_i}	[%]

Here, the total shot volume is the volume of the part plus the volume of the gating (including the sprue, runners, and cavity gates) adjusted for the percentage of allowable regrind. Regrind use is only feasible with SMM&A because most rotary platen MSM utilizes a hot runner system, which keeps virtually all of the resin in a molten state inside the gating system. This is accomplished through special heating channels in the mold, and allows easy rotation of the platen between shots. This effectively sets the shot size to just the cavity volume times the number of cavities. The percentage of allowable regrind is a material property and depends on the desired plastic quality. A conservative value is usually less than 10%. The actual cost of regrinding plasticized resin will not be considered in this model.

- Part Volume

The part volumes (V_{part_A} or V_{part_B}) are the actual volume of plastic needed to make each component (part A or part B) of the final assembly, part AB. These values can be

automatically calculated from the CAD models of the parts. These volumes are the exact volumes, and should not be confused with the bounding box volumes of the parts.

- Gating Volume

The gating volume accounts for the additional material consumed by the resin which solidifies inside the sprue, runners and gates. In most molding situations, the volume of the gate into the cavity is insignificant compared to the volume of the runners and sprue. Because of this, the gate volume will be omitted from the total gating volume calculations. Furthermore, the gate volume is typically included in the cavity volume, so in those cases, this assumption is accurate. Therefore, the term “gating volume” will henceforth refer to the combined volume of the runners and the sprue. Hence the total gating volume can be expressed as the sum of these two volumes:

$$\begin{aligned}
 V_{\text{gating}_i} &= V_{\text{sprue}_i} + V_{\text{runners}_i} \\
 V_{\text{gating}_{AB}} &= 0
 \end{aligned}
 \tag{3.13}$$

Total gating volume for mold <i>i</i>	V_{gating_i}	[in ³]
Total gating volume for mold AB	$V_{\text{gating}_{AB}}$	[in ³]
Volume of sprue for mold <i>i</i>	V_{sprue_i}	[in ³]
Volume of runners for mold <i>i</i>	V_{runners_i}	[in ³]

Please note that although the gating volume for mold AB is set to zero in the above equation. This is because the rotary platen MSM process requires the use of hot runners in the mold, which effectively sets the gating volume to zero. Because hot runners are only optional for SMM&A, Eq. 3.13 allows for non-zero gating volumes. Of course, if hot runners are used in one or both of the SMM&A molds, then the associated gating volume would also be set to zero.

The exact values of these gating volumes depend on the required flow conditions, which in turn, depend on the material properties, number of cavities, and the cavity arrangement itself. Although exact values are difficult to obtain at an early design stage (through only analysis of the part geometry), several guidelines can be used to obtain reasonable estimates. For example, it is well known that the runner diameter should be larger than the part's nominal wall thickness without being excessively high. The actual diameter depends on how far the resin must travel (runner length) as well as how many sharp turns it must take to get to the cavity. Another guideline states that the largest cross-sectional area of the sprue should be greater than the sum of the cross sectional areas of all the runners. There are additional guidelines for determining the appropriate sprue geometry and gating requirements (see [12]).

This model assumes the volume of the gating is known. This requires the mold gating layout to be completely specified. The preferred method of designing near-optimal gating systems involves using specialized CAD software (such as C-Mold or Moldflow) to analyze the mold filling requirements and suggest a runner/gating strategy. From this, the total volume can readily be calculated. However, if this software is not available, or deemed too time-consuming to run, a representative value for gating volume can be estimated from the part geometry and dimensional guidelines. The simplest method assumes that the total gating volume will be some fraction of the total part volume. This would take the following form:

$$V_{\text{gating}_i} \approx f_{\text{vol}_i} V_{\text{part}_i} \quad (3.14)$$

Volume of gating (sprue + runners + gates) for shot i	V_{gating_i}	[in ³]
Gating volume's percentage of total shot volume	f_{vol_i}	[%]

Where the gating's volume is assumed to be some conservative percentage of the part's volume. This value should be chosen based on the part's size and cavity layout cross-referenced with historical data of part-to-runner volume percentages. For example, a large, thin part made in a two-cavity mold would typically have a much lower gating volume than a small, thick part made in an eight-cavity mold (requiring long runners with bends). For the first part, a value of $f_{vol_i} = 10-15\%$ may be reasonable, whereas the second part might require $f_{vol_i} = 30-60\%$ because of the extensive runner system and part thickness. These are just representative values – the actual percentages depend on the gating strategy as well as material considerations. More accurate number should be chosen based on the part's specifics and historical experience.

3.2.4.2 – Fasteners Cost

In some SMM&A scenarios, some sort of fasteners must be used to secure the separate molded pieces together. This could include screws, pins, clips, and/or adhesives. The fastening method is entirely dependent on the product design and should be avoided where possible. For example, a common DFM/DFA technique is to use snap-fit connections to avoid additional parts in the form of fasteners.

If the use of fasteners is unavoidable, the type and number of them must be determined for each SMM&A variant of a product design and then priced according to supplier's rates.

3.2.4.3 – Miscellaneous Material Costs

The miscellaneous costs represent consumable materials such as packaging, labels and the like. As with the fasteners, each design must be evaluated on a case-by-case basis to determine the packaging, labeling, and other miscellaneous material requirements and then price them accordingly.

The material cost equations presented in this section are all adapted from existing literature to include MMM. They are based on first principles and are valid versions of the equations commonly used to account for material cost.

3.2.5 – Tooling Cost

The tooling cost refers specifically to the total cost of the mold, including mold base material costs, cavity machining/finishing costs, and the added costs for manufacturing the cooling system, ejector system, and any side actions and/or hot-runner systems. Additionally, the mold has an associated setup cost. The total tooling cost can then be expressed as a sum of these various costs drivers:

$$C_T = C_{\text{base}} + C_{\text{mach}} + C_{\text{tol}} + C_{\text{finish}} + C_{\text{eject}} + C_{\text{cool}} + C_{\text{SA}} + C_{\text{HR}} + C_{\text{SU}} \quad (3.15)$$

Total tooling cost	C_T	[\$]
Mold base/s costs	C_{base}	[\$]
Core/cavity machining costs	C_{mach}	[\$]
Tolerance costs	C_{tol}	[\$]
Surface finishing costs	C_{finish}	[\$]
Ejector system costs	C_{eject}	[\$]
Cooling system costs	C_{cool}	[\$]
Side actions costs	C_{SA}	[\$]
Hot runner system costs	C_{HR}	[\$]
Mold setup costs	C_{SU}	[\$]

3.2.5.1 – Mold Bases Cost

The mold base is the unfinished set of steel (or aluminum) plates that will house all of the mold components, including the cavities/cores, the gating system, the ejector system, and etc... It is typically bought from a specialized dealer, built to the specifications of the molding job. Then the molder finishes manufacturing the mold by machining and adding the required mold components into the base. The base itself can be rather costly due to its

complexity and precision. The number and type of mold bases, and hence total cost, depend on the molding process being used:

$$C_{\text{base}} = (1 - \phi)(C_{\text{base}_A} + C_{\text{base}_B}) + \phi C_{\text{base}_{AB}} \quad (3.16)$$

Total mold bases cost	C_{base}	[\$]
Mold base cost for mold i	C_{base_i}	[\$]
Mold base cost for mold AB	$C_{\text{base}_{AB}}$	[\$]

Where the switching variable, ϕ , is used to switch between using two separate mold bases for SMM&A and one combined mold base for rotary platen MSM.

The cost of an individual mold base was empirically found by Dewhurst and Kuppurajan to vary linearly with its size [9]:

$$C_{\text{base}_i} = \alpha_{\text{base}} A_{\text{base}_i} h_{\text{base}_i}^{2/5} + \beta_{\text{base}} \quad (3.17)$$

$$C_{\text{base}_{AB}} = \alpha_{\text{base}} A_{\text{base}_{AB}} h_{\text{base}_{AB}}^{2/5} + \beta_{\text{base}}$$

Mold base cost for mold i	C_{base_i}	[\$]
Linear mold base cost constant 1, intercept	β_{base}	[\$]
Linear mold base cost constant 2, slope	α_{base}	[\$/\text{in}^{(4/5)}]
Mold base area for mold i	A_{base_i}	$[\text{in}^2]$
Mold base height for mold i	h_{base_i}	[in]
Mold base cost for mold i	$C_{\text{base}_{AB}}$	[\$]
Mold base area for mold i	$A_{\text{base}_{AB}}$	$[\text{in}^2]$
Mold base height for mold i	$h_{\text{base}_{AB}}$	[in]

- Mold Base Cost Constants

The mold base cost constants, β_{base} and α_{base} , depend on historical price data from the mold base manufacturer. Each manufacturer will offer different prices for the same job, and these prices will also fluctuate over long periods of time (due to inflation and other

external factors). Dewhurst found the costs constants to be (\$1000) and (\$.045/in^{4/5}), respectively. For better accuracy, these values should be determined for each individual mold base manufacturer. However, if accurate values of these constants cannot easily be estimated, the model will still work as a relative cost comparator between SMM&A and MSM because both mold base cost expressions (Eqs. 3.17) use the same values for these constants, and hence will provide consistent values.

- **Mold Base Dimensions**

The mold base dimensions depend directly on the part size as well as any special mold features such as side actions. They can be calculated based on the part's bounding box dimensions by using a modified version of Poli's equations (Eqs. 2.38-2.41):

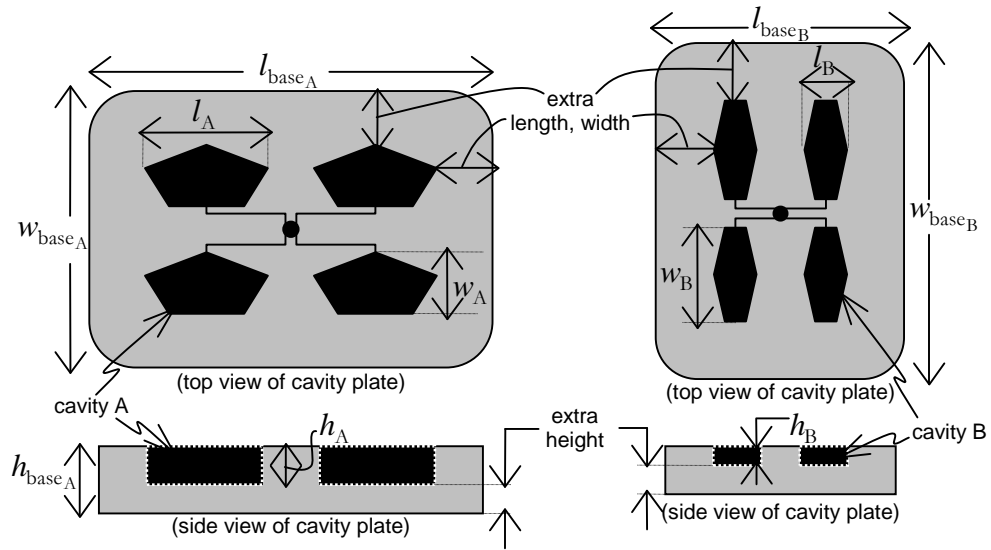
$$\begin{aligned}
 A_{\text{base}_i} &= l_{\text{base}_i} w_{\text{base}_i} = n_{\text{cav}} (l_i w_i)(1 + f_A) + A_{\text{SA}_i} \\
 A_{\text{base}_{AB}} &= l_{\text{base}_{AB}} w_{\text{base}_{AB}} = 2n_{\text{cav}} \cdot \max\{l_A w_A, l_B w_B\}(1 + f_A) + A_{\text{SA}_{AB}}
 \end{aligned}
 \tag{3.18}$$

Mold base area for mold <i>i</i>	A_{base_i}	[in ²]
Mold base length for mold <i>i</i>	l_{base_i}	[in]
Mold base width for mold <i>i</i>	w_{base_i}	[in]
Length of bounding box for part <i>i</i>	l_i	[in]
Width of bounding box for part <i>i</i>	w_i	[in]
Mold wall clearance factor, area	f_A	[%]
Additional mold base area for side actions in mold <i>i</i>	A_{SA_i}	[in ²]
Mold base area for mold AB	$A_{\text{base}_{AB}}$	[in ²]
Mold base length for mold AB	$l_{\text{base}_{AB}}$	[in]
Mold base width for mold AB	$w_{\text{base}_{AB}}$	[in]
Additional mold base area for side actions in mold AB	$A_{\text{SA}_{AB}}$	[in ²]

$$\begin{aligned}
 h_{\text{base}_i} &= h_i(1 + f_h) + h_{\text{SA}_i} \\
 h_{\text{base}_{AB}} &= h_{AB}(1 + f_h) + h_{\text{SA}_{AB}}
 \end{aligned}
 \tag{3.19}$$

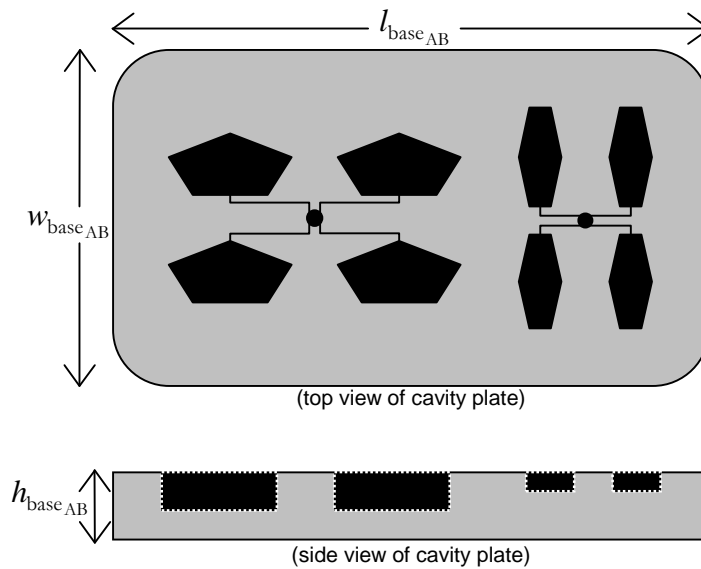
Mold base height for mold i	h_{base_i}	[in]
Height of bounding box for part i	h_i	[in]
Mold wall clearance factor, height	f_h	[%]
Additional mold base height for side actions	h_{SA_i}	[in]
Mold base height for mold AB	$h_{\text{base}_{\text{AB}}}$	[in]
Height of bounding box for part AB	h_{AB}	[in]
Additional mold base height for side actions in mold AB	$h_{\text{SA}_{\text{AB}}}$	[in]

The dimensions defined above are illustrated in Fig. 3.6. Please note that the figure is highly simplified and is not intended to closely resemble any actual molds. The mold base area is the total projected area ($l \times w$) of the entire mold base. It is calculated above by summing the required area for housing all of the cavities and then allowing for the additional area to accommodate side actions and/or other mold accessories. Additionally, extra length and width (resulting in extra area) should be added to the mold base dimensions to allow adequate spacing between the cavities and the edges of the mold base as well as each other. This gives the mold base enough rigidity to resist clamping force and injection pressure as well as allowing for cooling channels. Similar reasoning is used to calculate the total mold base thickness.



(a) – SMM&A, mold A

(b) – SMM&A, mold B



(c) – MMM, mold AB

Figure 3.6 – Notations for mold base dimensioning

- Mold Wall Clearance Factors

The mold wall clearance factors, f_A & f_h , represent the additional percentage of the cavity size that should be added to the mold area and height, respectively. These factors depend on the required mold strength which is a function of the mold material, part size, and injection pressure. They must be conservatively chosen so as to ensure safe mold operation while not requiring excessive mold size. If this method is not convenient or the

factors are difficult to determine, a simple constant length representing the minimum wall thickness can be added between adjacent cavities and between cavities and the walls of the mold. For example, Boothroyd et. al. recommend a minimum of 7.5 cm clearance between cavities and mold walls.

- Additional Area and Height Required for Side Actions

The additional mold base area and height required for housing the side actions or other accessories depends on the nature of the device and must be appropriately chosen. However for estimation purposes, a constant length factor can be added onto the mold at the appropriate location. For example, Boothroyd et. al. recommend doubling the outer wall thickness of the mold base on each side wall that will contain a side action. For example, if a mold would normally require 3" of clearance between the cavity and outer walls, and side actions were to be used on two opposite sides of the mold, both corresponding side wall thicknesses should be increased to 6", increasing the total mold length (or width) by 6".

- Part Bounding Box Dimensions

The part bounding box dimensions are simply the maximum cavity length, width, and height corresponding to the respective dimensions of the mold base. These dimensions can be automatically extracted from the CAD model of the part, after its orientation relative to the mold base has been chosen. Of course an attempt to minimize the bounding box dimensions should be made by appropriately orienting the cavities. This should be done to reduce the mold base size and resultantly, cost.

For use later on, we can define the part's projected areas and volumes as the following quantities:

$$A_i = l_i w_i \quad ; \quad V_i = A_i h_i \quad (3.20)$$

$$A_{AB} = \max\{l_A w_A, l_B w_B\} \quad ; \quad V_{AB} = A_{AB} h_{AB}$$

Projected area of part i	A_i	[in ²]
Bounding box volume of part i	V_i	[in ³]
Projected area of part AB	A_{AB}	[in ²]
Bounding box volume of part AB	V_{AB}	[in ³]

Again, it should be noted that these quantities should not be confused with the exact part areas and volumes (e.g. $A_i \neq A_{\text{part } i}$). The exact areas and volumes can be calculated directly from the CAD files.

The mold base cost equations presented above are expanded versions of Boothroyd's cost equations, which were shown to be valid in industrial cost estimation. The modified equations can be set to coincide with Boothroyd's originals through proper selection of the linear cost constants, and will hence maintain at least the same validity as Boothroyd's original work.

3.2.5.2 – Mold Machining Cost

Assuming the mold cores and cavities are machined into the mold base in-house, the total cost of the required machining operations can be estimated as the product of total machining time and the machine shop's hourly tooling rate:

$$C_{\text{mach}} = \dot{r}_{\text{mach}} \left[\underbrace{(1 - \phi)(t_{\text{mach}_A} + t_{\text{mach}_B}) + \phi \cdot t_{\text{mach}_{AB}}}_{t_{\text{mach}}} \right] \quad (3.21)$$

Core/cavity machining costs	C_{mach}	[\$]
Hourly machining rate	\dot{r}_{mach}	[\$/hr]
Total mold machining time	t_{mach}	[hr]
Total mold machining time for mold i	t_{mach_i}	[hr]
Total mold machining time for mold AB	$t_{\text{mach}_{AB}}$	[hr]

Where for simplicity, it is assumed that the various costs of all the various machining operations will be rolled into one representative hourly rate. This can be accomplished by averaging the rates of all possible processes (milling, grinding, EDM, etc...), or some more complex weighting system. Although this seems quite simplified and potentially inaccurate, if the original assumption of using only end milling still holds, the machining rate will correspond to the milling rate and hence be exact.

- Machine Shop Hourly Rate

The actual machining rate depends on the process capabilities of the machine shop and must be specified based on historical job data. If this rate is difficult to determine, an appropriate value can be estimated based on current national averages (for example, at the time of this writing, a quick internet search of “machine shop rates” returned values between \$40/hr to \$80/hr).

- Total Mold Machining Time

The total mold machining time is the sum of the individual machining times required for cores, cavities, and gating:

$$t_{\text{mach}_i} = n_{\text{cav}} (t_{\text{cavity}_i} + t_{\text{core}_i}) + t_{\text{gating}_i} \tag{3.22}$$

$$t_{\text{mach}_{AB}} = n_{\text{cav}} (t_{\text{cavity}_A} + t_{\text{cavity}_B} + 2t_{\text{core}_{AB}}) + t_{\text{gating}_{AB}}$$

Total mold machining time for mold i	t_{mach_i}	[hr]
Total mold machining time for mold AB	$t_{\text{mach}_{AB}}$	[hr]
Time for machining one cavity of type i	t_{cavity_i}	[hr]
Time for machining one core of type i	t_{core_i}	[hr]
Time for machining one core of type AB	$t_{\text{core}_{AB}}$	[hr]
Time for machining the gating for mold i	t_{gating_i}	[hr]
Time for machining the gating for mold AB	$t_{\text{gating}_{AB}}$	[hr]

As is customary for most molds, it will be assumed here that the cores and cavities are embodied as *inserts* which are secured into pockets of the mold base. This facilitates machining, mold repair, and even potentially allows some mold bases to be reused with different core/cavity insert sets. Therefore, the various core/cavity machining times listed in the tables and equations above represent the times required to machine an appropriate core/cavity insert.

- Cavity and Core Insert Machining Time Calculations

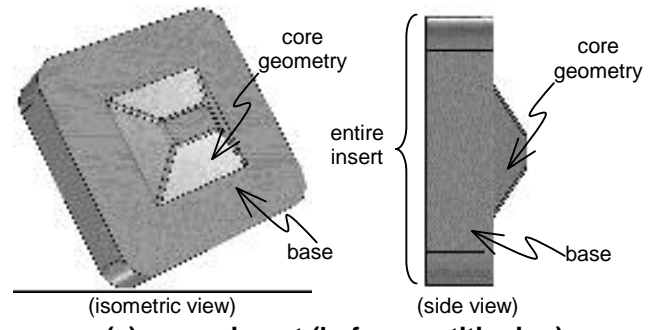
The times required for machining the core and cavity inserts of the mold are complex functions of the gross part size, part geometry/complexity, and machining process capabilities. If the exact mold design is completely specified along with the process planning, the machining time can accurately and easily be predicated through CAM simulations. Unfortunately, in the early stages of design the exact mold configuration has most likely not been determined. This is because there are many somewhat arbitrary ways to configure the geometry of the core and cavity inserts of the mold bases.

However, there exists specialized mold design software that can automatically generate the necessary core and cavity geometry given a CAD model of the desired part. Using this software, the mold can be partitioned into appropriate core and cavity segments and then the manufacturing time for each piece can accurately be estimated through performing a machining simulation [15], [36], and [52]. This model assumes that the gross core and cavity insert geometry has been specified either manually by the designers, or automatically through such software. Once both the core and cavity geometry have been specified, it may be advantageous to further decompose their gross shapes into several

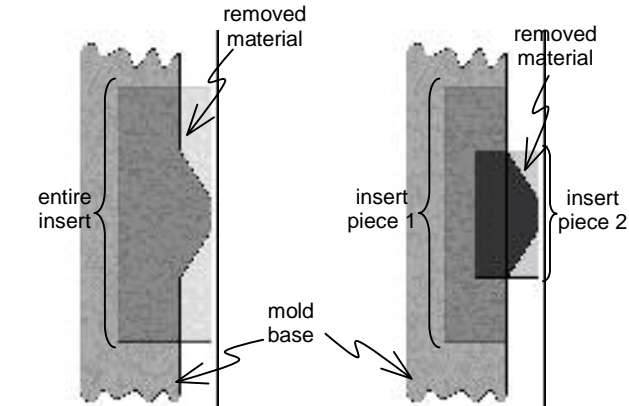
simpler pieces that can be machined separately and then assembled. This could potentially reduce both machining times and costs as discussed below.

The cavity geometry is usually just a negative image of the part to be produced, and hence the cavity insert is typically made by milling the appropriately-shaped pocket out of a block of stock material. This usually results in a relatively simple, one-piece cavity insert. Therefore, the machining process planning for the cavity is quite straightforward, and can be simulated as a series of simple material-removal operations from a single workpiece. This can easily be done in any cutter path generation or verification software; given the cavity geometry (which is simply the same as the inverse of the part's gross shape), the CNC milling cutter path program can automatically be generated and verified to obtain the estimate for cavity machining time, t_{cavity} . Using Pro/Manufacture for example, the milling time of a complex cavity with free-form surfaces can easily be estimated as a series of volume-removal and surface-cutting operations.

Unlike the cavity, the core insert usually has to be partitioned into several pieces to avoid excessive milling of the various core protrusions. Fig. 3.7 illustrates a simple two-piece partitioning of the core insert. The core insert (Fig. 3.7a) simply consists of the core geometry (a tapered and rounded block protrusion) and a base for alignment with the pocket in the mold base. If it is not partitioned into separate pieces, it will have to be machined from a single stock piece, resembling the layout of Fig. 3.7b. However, if it is portioned into two pieces (the base and the protrusion) as in Fig. 3.7c, it would require less machining.



(a) – core insert (before partitioning)



(b) – non-partitioned (b) – partitioned
Figure 3.7 – Partitioning the core insert

This core partitioning needs to be completed before machining time can be estimated. Unfortunately, it is hard to predict the final core insert design based on the part geometry itself, making it difficult to estimate the core insert machining time. If the partitioning cannot be easily specified at the early design stage, the core machining time can be conservatively estimated by assuming there will be no partitioning.

Once the core insert has been decomposed into a set of pieces, the individual machining times for each section must be assessed by performing a milling simulation via CAM software such as Parametric’s Pro/Manufacture. Each piece should be treated as a set of material removal sequences on appropriately sized stock workpieces.

More specifically, the total machining time for a single core or cavity is calculated by summing the machining time needed for each piece forming the insert. These individual

machining times can be estimated by performing simulations in which the insert geometry is obtained by a material-removal process from an appropriately-sized stock workpiece.

The most accurate method of estimating the core and cavity machining times would be to have specialized automated mold design software automatically generate the cavity and core geometry for the part (including core partitioning), and then run a CNC milling simulation on the results to get the cutter paths and resultant machining times. However, if the specialized mold generation and partitioning and/or milling simulation software is not readily available, rough estimates for the machining time can still be estimated based on either part complexity or simple volumetric calculations. The machining time can be estimated based on any of the methods discussed in Section 2.3, such as Kazmer's dimension-driven method, or Boothroyd's complexity-driven method. However, these methods can become quite involved.

If both automated techniques and popular techniques described in the literature are infeasible or too involved, simple volume-based geometric reasoning can be used. While less accurate than the more involved cost estimation procedures, this can still give reasonable cost estimates for process comparison purposes. The simplest method involves approximating machining time by dividing the amount of material needed to be removed by an appropriate material-removal rate:

$$t_{\text{mach}_A} + t_{\text{mach}_B} \approx n_{\text{cav}} \left(\frac{V_{\text{mill}}}{\dot{V}_{\text{mill}}} \right) + t_{\text{gating}_A} + t_{\text{gating}_B} \quad (3.23)$$

$$t_{\text{mach}_{AB}} \approx n_{\text{cav}} \left(\frac{V_{\text{mill}}}{\dot{V}_{\text{mill}}} \right) + t_{\text{gating}_{AB}}$$

Total mold machining time for mold i	t_{mach_i}	[hr]
----------------------------------------	---------------------	------

Total mold machining time for mold AB	$t_{\text{mach}_{AB}}$	[hr]
Total volume removed for one assembly (parts A and B)	V_{mill}	[in ³]
Average material removal rate	\dot{V}_{mill}	[in ³ /hr]

Here the times for machining cavities and cores have been replaced by a single expression involving total volume removed and a removal rate. The first approximation lies in the fact that it is assumed that material is removed at a constant (or averaged) rate. This average material removal rate is completely dependant on the machine shop's process capabilities. More specifically, it depends on acceptable feed rates/spindle speeds as well as tool sizes/geometries. If multiple tools are to be used (as is customary), the average material removal rate should be a weighted average based on attainable removal rates for all of the tools. It should be noted that this number may seem extremely low (e.g. less than .1 in³/hr of material removal). This is because the mold core/cavity milling process is usually very slow in order to achieve the desired geometric complexity and dimensional accuracy. This variable should not be viewed as an accurate machining capability, rather it is simply a representative value used to form a rough estimate of machining time based on minimal input. It should be sufficient in a relative comparison sense, but it is highly recommended to estimate the machining times via more accurate methods.

The total volume removed from the mold base (or more specifically, the inserts) depends on the part geometry, and is the sum of the volumes removed in forming both the cores and cavities:

$$V_{\text{mill}} = V_{\text{cav}_A} + V_{\text{cav}_B} + (1 - \phi)(V_{\text{core}_A} + V_{\text{core}_B}) + \phi \cdot 2V_{\text{core}_A} \quad (3.24)$$

Total volume removed for one assembly (parts A and B)	V_{mill}	[in ³]
Volume removed in machining one cavity for mold i	V_{cav_i}	[in ³]
Volume removed in machining one core for mold i	V_{core_i}	[in ³]

Assuming no partitioning is done on the core or cavity inserts (a worst-case scenario in terms of cost), the individual core/cavity volumes can be calculated simply through analysis of the CAD model. Given any freeform part, it is simple to generate its bounding box, and its convex/concave portions relative to the parting direction. The dimensions of these volumes can then be used to calculate the machining volumes. Fig. 3.8 illustrates these geometric quantities. The total volume of the part can be expressed by:

$$V_{\text{part}_i} = V_{\text{convex}_i} - V_{\text{concave}_i} \quad (3.25)$$

Total volume of part i	V_{part_i}	[in ³]
Convex portion's volume for part i	V_{convex_i}	[in ³]
Concave portion's volume for part i	V_{concave_i}	[in ³]

Where the convex portion of the part (or sometimes “convex hull”) is the volume of the solid generated by removing all concave features (indentations) of the part that are facing the core side of the mold. The convex portion of the part is the volume of the solid generated from the concave features of the part that are facing the core side of the mold.

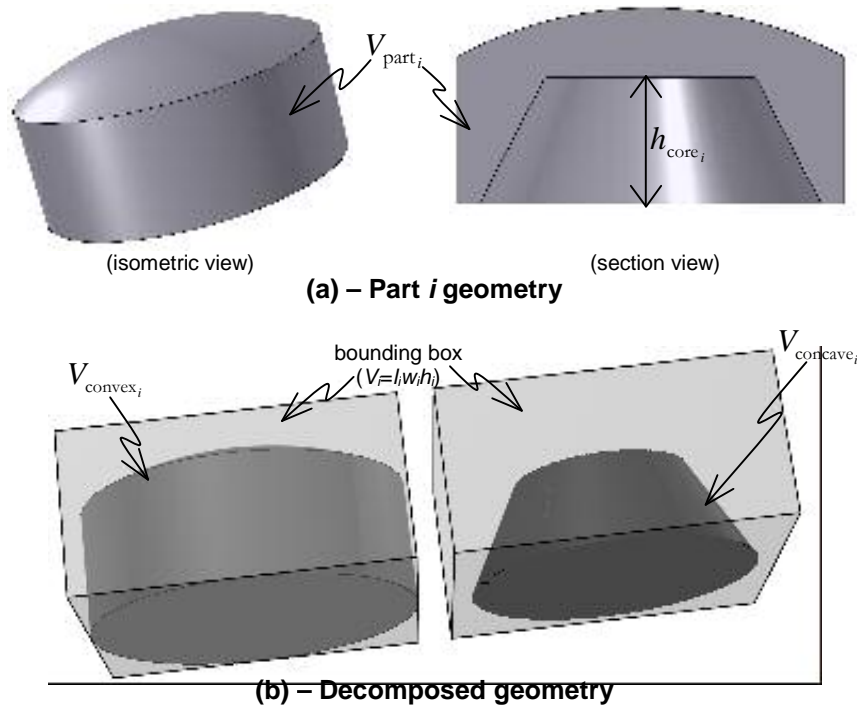


Figure 3.8 – Example volume decomposition for material removal estimation

The volume of material removed from the cavity is simply equal to the convex volume of the part adjusted for shrinkage:

$$V_{cav_i} = V_{convex_i} (1 + f_{shrink_i}) \quad (3.26)$$

Volume of cavity for part i	V_{cav_i}	$[\text{in}^3]$
Shrinkage factor for material i	f_{shrink_i}	$[\%]$

Here a shrinkage factor is introduced to account for the fact that the resin tends to shrink away from the cavity towards the core as it hardens. This means the actual volume of the cavity should be slightly larger than the desired part in order to compensate and obtain the desired dimensions. The shrinkage factor depends on the specific resin as well as the processing conditions. Accurate values can be obtained from the resin supplier.

The volume removed in machining the core can be calculated by subtracting the total volume of the core (which is equal to the concave portion of the part, $V_{concave_i}$) from an

appropriate bounding box volume which is calculated based on the total projected part area and core height:

$$V_{\text{core}_i} = h_{\text{core}_i} [A_i(1 + f_A)] - V_{\text{concave}_i} \quad (3.27)$$

Volume removed in machining one core for part i	V_{core_i}	[in ³]
Height of core for part i	h_{core_i}	[in]

Where the height of the core is obtained through the CAD model as with the concave/convex volumes. The term in the brackets represents the total area needed for one cavity, including the extra area clearance factor (cavity spacing) as discussed in Section 3.2.4.1. Please note that the above equations assume the cavity insert has rectangular cross-section and a resulting box-shaped volume ($b \times l \times w$), which is the most common form. If for some reason the core insert has a different shape (such as cylindrical), Eq. 3.27 must be modified to obtain the correct volume.

- Gating Machining Time Calculations

As well as the machining required to produce the desired cores/cavities in the mold base, additional machining is needed for the mold gating system. In an ideal situation, the completely-specified cavity layout (as discussed in Section 3.2.4.1) would be input into a cutter path generation program to obtain the total milling time in a similar manner to predicting the core/cavity milling times. If this is not possible, a rough estimate can still be obtained through volumetric considerations similar to those for the core/cavity machining time estimation of Section 3.2.5.2:

$$\begin{aligned}
t_{\text{gating}_A} + t_{\text{gating}_B} &\approx \left(\frac{V_{\text{gating}_A} + V_{\text{gating}_B}}{\dot{V}_{\text{mill}}} \right) \\
t_{\text{gating}_{AB}} &= \left(\frac{V_{\text{gating}_{AB}}}{\dot{V}_{\text{mill}}} \right) = \left(\frac{(0 \text{ in}^3)}{\dot{V}_{\text{mill}}} \right) = 0
\end{aligned}
\tag{3.28}$$

Where the gating volumes are determined as discussed in Section 3.2.4.1. Notice that if the expression for $V_{\text{gating}_{AB}}$ in Eq. 3.13 is substituted in Eq. 3.28 above, the machining time for the gating system of mold AB goes to zero. This is actually consistent with the use of hot runner systems because the runner is embedded in the hot runner rather than machined into the mold base. The purchase cost of the hot runner (discussed in Section 3.2.5.8) accounts for the cost of runners in molds of type AB.

The mold machining cost equations were developed based on first principles and consultation with machine shops and molding shops. They were shown to coincide with machining time/cost estimation procedures commonly employed.

3.2.5.3 – Tolerance Costs

“Tolerance costs” refer to the costs associated with achieving the required dimensional tolerances specified in the plastic components’ design. Obviously it will cost more to mold a part that has tight tolerances, because the tooling used to produce it must have tight tolerances itself. We will account for this added cost by estimating the additional machining time required to achieve the desired tolerances in the core and cavity inserts of the mold.

Before we can develop our tolerance cost estimation model, we must first specify what tolerancing exactly entails. We will assume that desired core/cavity dimensional tolerances are produced by additional precision milling operations. Typically, any milling process is performed in a series of increasingly precise (but slower) machining steps, using

smaller and smaller tools. The initial steps are referred to as “roughing” operations and the final step is referred to as a “finishing”, or here, “tolerancing” operation. A typical machining sequence is as follows:

- 1) Several rough milling operations are conducted at relatively fast feed rates to remove the bulk of the material from the workpiece for the core or cavity insert. These operations are considered as volume-removal operations, as they typically cut large volumes of material from the stock workpiece. (The associated machining costs were discussed above in Section 3.2.5.3).
- 2) The final roughing operation is conducted, leaving some material to be removed by the subsequent tolerancing operations. The roughing operation is performed at an acceptable feed rate and provides a certain dimensional tolerance value, specific to the milling machine, tool size, and feed rate.
- 3) If any of the dimensions produced by the rough milling are outside of the specified tolerances required by the part drawings, tolerancing operations are performed. These operations are considered as surface-milling operations, where a tool makes a series of shallow material-removal passes along the surfaces of the core or cavity. The tolerancing operation is performed at a relatively slow feed rate, and provides a certain dimensional tolerance value which should be less than or (at most) equal to the tolerances specified in the part drawings.

We can estimate the machining time and resultant cost associated with performing these surface-milling operations by relating the material removal rates and the amount of material removal necessary to obtain the desired tolerances. If there are n_{tol} such surfaces requiring tolerancing operations, we can relate the total additional machining time required as the sum of these individual times. Then we can find the corresponding cost by multiplying this total machining time by its associated hourly rate, as we have done with other machining operations (Section 3.2.5.2):

$$C_{tol} = n_{cav} \dot{r}_{tol} t_{tol} = n_{cav} \dot{r}_{tol} \underbrace{\left(\sum_{j=1}^{n_{tol}} t_{tolj} \right)}_{t_{tol}} \quad (3.29)$$

Total cost of tolerance machining operations	C_{tol}	[\$]
Hourly rate associated with tolerance machining	\dot{r}_{tol}	[\$/hr]
Machining time required to achieve tolerances for all surfaces in one core or cavity	t_{tol}	[hr]

Machining time required to achieve desired tolerances for surface j	t_{tol_j}	[hr]
Number of mold surfaces requiring tolerancing	n_{tol}	[#]

- Hourly Tolerance Machining Rate

The hourly machining rate applied to tolerancing operations is similar to the other hourly rates previously discussed. It is a representative hourly cost that accounts for the labor and machine tools (milling machines) used to perform the tolerancing. The actual value depends on the rates charged by the particular machine shop and should readily be calculated based on historical machining data. If desired, the same general machining rate, \dot{r}_{mach} , can be used.

- Number of Surfaces Requiring Tolerancing

The number of surfaces requiring tolerancing are simply the number of part surfaces that have specified dimensional tolerances that are tighter than those provided by regular rough machining. Each one of these surfaces has a corresponding surface in the core or cavity insert of the mold. The number of each of these surfaces must be tallied, and assigned a unique index number, j (in order to match with a corresponding area, A_j). The counting is done by noting whether each surface is internal (core side) or external (cavity side) and then using the following formula:

$$n_{tol} = (1 - \phi) [n_{tol_A} + n_{tol_B}] + \phi [n_{tol_{AB-cavA}} + n_{tol_{AB-cavB}} + 2n_{tol_{AB-core}}] \quad (3.30)$$

Total number of mold surfaces requiring tolerancing	n_{tol}	[#]
Number of surfaces requiring tolerancing in mold i (core and cavity sides)	n_{tol_i}	[#]
Number of surfaces requiring tolerancing in mold AB, cavity i	$n_{tol_{AB-cavi}}$	[#]
Number of surfaces requiring tolerancing in mold AB, common core	$n_{tol_{AB-core}}$	[#]

The above equation allows for different specified tolerances in both core and cavity sides for both variants. This is because it is typical to specify looser tolerances for MM parts

because there is no required assembly; rather, the subsequent shots form essentially perfect fits on top of the previous shots. Regardless, this allows for different tolerances between variants for both parts A and B. Each surface requiring tolerancing should be assigned a consecutive index value and the associated surface area and required tolerance should share this same index value.

▪ Individual Surface Tolerancing Time Calculation

If a given surface of area A_j in the core or cavity insert requires additional machining to achieve a tighter tolerances of value d_j , we can estimate the required machining time with the following formula:

$$t_{tolj} = \frac{A_j (d_{rough} - d_j)^{\alpha_{tol}}}{i_{tol} \beta_{tol}} \quad \text{where } 1 \leq j \leq n_{tol} \quad (3.31)$$

Machining time required to achieve desired tolerances for surface j	t_{tolj}	[hr]
Surface area of surface j	A_j	[in ²]
Dimensional tolerance provided by rough milling	d_{rough}	[in]
Dimensional tolerance required for surface j	d_j	[in]
Average feed rate for surface milling	i_{tol}	[in/hr]
Tolerancing time normalization constant 1, exponent	α_{tol}	[# = x]
Tolerancing time normalization constant 2, denominator	β_{tol}	[in ^($x+1$)]

- Surface Area

The surface area term in Eq. 3.31 is the total area on the core or cavity's surface that possesses the tolerance value trying to be obtained. The entire surface typically has to be engaged by the finishing tool, increasing the total machining time. These surface area values are readily obtained from the CAD model and are required inputs to the model.

- Dimensional Tolerance Levels

Both dimensional tolerance variables in Eq. 3.31 relate to the differences in tolerances achievable by rough machining and finishing. d_{rough} is the dimensional tolerance achievable through the final rough machining pass and depends on the process capabilities of the machine shop. It is highly dependent on the machine quality and accuracy as well as the cutting tool and feed rates used. It must be input based on known machine and tool data (and/or from machine manufacturer specifications). d_j is the desired dimensional tolerance of surface j and is obtained from the engineering drawings of the part.

- Surface Milling Feed Rate

The tolerancing feed rate is also a process-specific input variable and is obtained in a similar manner as the regular volumetric feed rate used in rough machining (Eqs. 3.28). This value depends on the milling operation and can be obtained from a machinist's handbook [44]. The actual feed values are typically much lower speeds than regular machining feed rates, and are based on the process capabilities and tools of the individual milling machine.

- Normalization Constants

The tolerancing time normalization constants, α_{tol} and β_{tol} , serve to fit an appropriate time estimation curve to the process data, as well as produce appropriate units of time when evaluating Eq. 3.31. They may at first appear as abstract and arbitrary quantities, but their physical significance can be envisioned as representing scaling factors that adjust the equation by a certain number of extra machining passes. These extra passes are required to remove all of the material at the specified feed rate and machining conditions. These values are highly dependent on the machine shop's process capabilities and must be input to the model based on historical tolerancing data.

- Relative Accuracy of Estimated Tolerancing Times

The tolerancing time is estimated based on empirical equations, and admittedly may not be completely accurate depending on the actual constants used in the above equations. However, they should serve to provide relatively reasonable estimates for cost comparison purposes in a sense that any absolute errors are present in both variants' estimates. The relative differences of these cost estimates then arise solely from the inherent process differences. Therefore, this model should still serve its intended purpose of relative process comparison and selection.

The actual forms of the equations suggested for tolerancing costs were obtained through discussions with experts in both academic and industrial fields. Provided the right constants are substituted, the equations should all hold to be valid.

3.2.5.4 – Surface Finishing Costs

Surface finishing costs will here refer the combined cost of two separate actions: 1) hand polishing the mold to produce the desired appearance on the part's surface, and 2) incorporation of textures onto the mold surfaces. These two operations are performed independently, but they are both carried out to enhance the surface texture of the part, so are rolled into one cost as follows:

$$C_{\text{finish}} = n_{\text{cav}} [C_{\text{polish}} + C_{\text{texture}}]$$

$$= n_{\text{cav}} \left[\dot{r}_{\text{polish}} \underbrace{\left(\sum_{j=1}^{n_{\text{polish}}} t_{\text{polish}_j} \right)}_{t_{\text{polish}}} + \dot{r}_{\text{texture}} t_{\text{texture}} \right] \quad (3.32)$$

Total cost for mold surface finishing operations	C_{finish}	[\$]
Cost of hand polishing operations for one core/cavity set	C_{polish}	[\$]
Cost of texturing operations for one core/cavity set	C_{texture}	[\$]
Hourly rate associated with hand polishing	\dot{r}_{polish}	[\$/hr]

Total mold polishing time operations for one core/cavity set	t_{polish}	[hr]
Polishing time for surface j	$t_{\text{polish } j}$	[hr]
Number of surfaces requiring polishing	n_{polish}	[#]
Hourly rate associated with texturing	\dot{r}_{texture}	[\$/hr]
Total mold texturing operations for one core/cavity set	t_{texture}	[hr]

Here, the two types of costs are broken down into products of a mold finishing time and a corresponding hourly rate, as with other tooling costs previously discussed. Furthermore, the mold polishing time is split into n_{polish} separate times, each corresponding to an individual surface. This is analogous to the tolerancing cost Eq. 3.29.

- Hourly Rates of Mold Polishing and Texturing

As with the other tooling operations such as machining and tolerancing, both types of surface finishing operations have associated hourly rates that deal with the costs of labor and equipment operation throughout the tooling process. These values are company-specific and are input to the model based on historical tooling cost data. The only difference here is that since mold texturing is usually outsourced to specialized companies, the hourly rates can be directly quoted from them. Because hand polishing is usually done in-house, the hourly rate of this operation is obtained from historical polishing cost data, in a similar manner to other hourly rates.

- Mold Polishing Time

Mold polishing is a costly operation, performed by hand on the mold core and cavity surfaces. Typically, a special type of sand paper is used to buff the mold surface until the desired finish is produced. The total time required for this action is proportional to the surface area, part complexity, and desired surface finish. Surface finishes are typically divided into seven distinct categories, each with an associated Society of Plastics Engineers (SPE) grade. These seven finishes are listed below in Table 3.2:

Table 3.2 – Mold Surface Finishes (Adapted from Boothroyd, [9])				
model's surface code	resin translucency	surface appearance	SPE grade	typical tooling time % increase
0	opaque	not critical (used for surfaces to be textured)	-#6 - #4	10%
1	opaque	standard	#3	15%
2	transparent	standard (internal flaws or waviness permitted)	-	20%
3	opaque	High gloss	#2	25%
4	transparent	high quality	-	30%
5	opaque	Highest gloss	#1	(not listed)
6	transparent	optical quality	-	40%

The first column in Table 3.2 serves to uniquely identify each surface type for estimating costs. The final column lists representative cost increases obtained from Boothroyd, and should only be used as a rough guide, as actual surface finishing times can vary greatly for each molder.

Although the actual polishing time depends greatly on the part complexity as well as surface area, we will take a simple approach similar to the one used for estimating tolerancing costs (Section 3.2.5.3). Specifically, we will fit a time estimation curve based on the surface area and level of surface finishing required. First we must count the number of surfaces in the core and cavity that need to be polished and assign a unique index value to each surface. We will also have to keep track of each surface's area as well as the required surface appearance. This procedure is identical to the one used above in counting the number of surfaces requiring tolerances. The equation used is of the same form as Eq. 3.30:

$$n_{\text{polish}} = (1 - \phi) [n_{\text{polish}_A} + n_{\text{polish}_B}] + \phi [n_{\text{polish}_{AB-\text{cav}_A}} + n_{\text{polish}_{AB-\text{cav}_B}} + 2n_{\text{polish}_{AB-\text{core}}}] \quad (3.33)$$

Total number of mold surfaces requiring polishing	n_{polish}	[#]
Number of surfaces requiring polishing in mold i (core and cavity sides)	n_{polish_i}	[#]
Number of surfaces requiring polishing in mold AB, cavity i	$n_{\text{polish}_{AB-\text{cav}_i}}$	[#]
Number of surfaces requiring polishing in mold AB, common core	$n_{\text{polish}_{AB-\text{core}}}$	[#]

The above equation allows for different surface finishes in both the core and cavity sides of parts A and B for the two process variants. Please note that in many cases, surfaces that won't be visible in the final assembly (e.g. the cavity side of part A) will usually have low surface finish requirements, unless they require articulated movement between the components. If relative movement is required between parts A and B at their adjoining interfaces, smoother surfaces may be required to allow smoother movement.

The time required to polish an individual surface of area A_j to surface with a code s_j can be estimated as:

$$t_{\text{polish } j} = \frac{A_j (s_j)^{\alpha_{\text{polish}}}}{\dot{A}_{\text{polish}} \beta_{\text{polish}}} \quad \text{where } 1 \leq j \leq n_{\text{polish}} \quad (3.34)$$

$$s_j = \{0,1,2,3,4,5,6\}$$

Polishing time for surface j	$t_{\text{polish } j}$	[hr]
Surface area of surface j	A_j	[in ²]
Surface area code (from Table 3.2)	s_j	[#]
Average surface area polishing rate	\dot{A}_{polish}	[in ² /hr]
Polishing time normalization constant 1, exponent	α_{polish}	[#]
Polishing time normalization constant 2, denominator	β_{polish}	[#]

- Surface Areas

Each individual surface that requires polishing has an associated surface area that must be input to the model. This value is readily calculated from the CAD models of the parts.

- Surface Area Codes

The surface area codes are simply integers ranging from 0 to 6 that correspond with the surfaces described in Table 3.2. They must be input to the model and are obtained from the engineering drawings of the parts.

- Average Surface Area Polishing Rate

The actual speed that the surface area can be polished varies throughout the job, and depends on the surface complexity (e.g. small, hard to reach surfaces take longer to polish). Also, since the polishing is usually done by hand, it depends on the individual person who is in charge polishing. However, an averaged rate for all surface finishes, mold surfaces, laborers, and etc. should be readily calculated from historical polishing time data. This company-specific value must be input to the model. This averaged value will then be transformed by the normalization constants.

- Polishing Normalization Constants

Both normalization constants are company-specific parameters that serve to fit an appropriate curve correlating surface area and code to polishing time. They transform the integer value of s_j to a corresponding hourly time based on the relative difficulty in achieving the specified finish. The actual values of these constants depend on the specifics of the company, including the mold polisher and must be input based on historical data.

- Relative Accuracy of Estimated Polishing Times

The same argument used to justify the use of the empirical tolerancing equations will be used to justify the polishing cost estimate model used here. Namely, any inaccuracies will tend to cancel each other out in a relative sense, and differences in cost estimates between variants will be a direct result of the process differences.

- Mold Texturing Time

While the mold texturing time could possibly be estimated using similar reasoning as that for the tolerancing and polishing times, it will not be done here because there are many specialized textures, each with their own associated application processes and costs. To obtain any degree of accuracy, a new governing cost equation would have to be developed

for each individual texture type. Furthermore, tolerancing is typically outsourced to a third party, which will directly provide the cost quotes for a particular texture application.

With that said, texturing costs are still proportional to the total surface area that requires texture. Fortunately, texturing costs are small in a relative sense, when compared with the total cost of the mold. Boothroyd simply suggests that adding 5% to the basic cavity machining costs provides a “fairly good estimate” of the texturing costs. This is a simple approach, and we will use it here. Our texturing time can then simply be expressed as some percentage of the total machining time:

$$t_{\text{texture}} = f_{\text{texture}} t_{\text{mach}} \quad (3.35)$$

Total time for adding surface textures to a core/cavity set	t_{texture}	[hr]
Texturing time factor related to machining time	f_{texture}	[%]

Eq. 3.35 takes the machining time previously calculated in Section 3.2.5.2, and sets the texturing time as some fraction of this total time. The value of f_{texture} can be estimated from historical texturing price quotes, or a reasonable value (such as Boothroyd’s 5%) can be used. In terms of cost comparison, this only serves to multiply the machining cost by a constant (and small) value for both process variants, not affecting the total costs in a relative sense.

3.2.5.5 – Ejector System Costs

The process of preparing the mold base to receive the ejector system is a lengthy (and costly) task, and unfortunately, very difficult to predict in the early product design stages. This makes the total cost of ejector system hard to estimate with any certainty. According to Boothroyd, although the cost is directly related to the number of ejector pins, which in turn, is dependent on the part size, core depth, rib geometry, and other part-complexity features, no strong mathematical relationships between these factors and cost

could be established [9]. He suggested using a simple relationship based on projected area to estimate the number of ejector pins (Eq. 2.29). We will use an adapted version of Boothroyd's equation to model the cost of ejector systems.

First, we propose another linear equation relating the cost of the ejector system to the number of ejector pins needed:

$$C_{\text{eject}} = \alpha_{\text{pins}} n_{\text{pins}} + \beta_{\text{pins}} \quad (3.36)$$

Total ejector system cost	C_{eject}	[\$]
Number of ejector pins	n_{pins}	[#]
Ejector pin linear cost constant 1, slope	α_{pins}	[\$/pin]
Ejector pin linear cost constant 2, intercept	β_{pins}	[\$]

Here we have assumed that the cost of the ejector system is another generic linear function of the number of ejector pins. This is similar to Boothroyd's method, where it is assumed that manufacturing time of ejector pins is linearly related to the number of pins, except we are relating the number of pins directly to cost in stead of time.

- Ejector Pin Linear Cost Constants

The linear cost constants in Eq. 3.36 are company-specific and depend on the process capabilities of the machine shop manufacturing the ejector system. As with all specific constant parameters, these have to be input directly to the model based on historical pin manufacturing data. For reference, Boothroyd used the following values:

$\alpha_{\text{pins}} = (2.5 \text{ hrs}) \cdot \dot{r}_{\text{mach}} ; \beta_{\text{pins}} = 0$. In other words, he assumed it takes 2.5 hours to manufacture one pin, so this time is multiplied by the associated hourly machining rate.

- Number of Ejector Pins

The total number of ejector pins required for either variant can be expressed as:

$$n_{\text{pins}} = n_{\text{cav}} \left((1 - \phi) [n_{\text{pins}_A} + n_{\text{pins}_B}] + \phi [2n_{\text{pins}_A}] \right) \quad (3.37)$$

Total number of ejector pins	n_{pins}	[#]
Number of ejector pins for part i	n_{pins_i}	[#]

The above equation accounts for the fact that the SMM&A variant uses two different molds which can have completely different ejector pin layouts, whereas MMM uses only one mold, forcing the ejector system to be the same for both shots (namely, the ejector system used for the core side of shot A).

We will use an expanded version of Boothroyd’s area-based model to predict the number of ejector pins required for a particular shot. Specifically, we will adapt Eq. to 2.29 to incorporate a linear multiplier and exponent other than $1/2$:

$$n_{\text{pins}_i} = \text{ceil} \left(\alpha_{\text{area}} A_i^{\beta_{\text{area}}} \right) \quad (3.38)$$

Number of ejector pins for part i	n_{pins_i}	[#]
Pin number cost constant 1, multiplier	α_{area}	[in ^{-2x}]
Pin number cost constant 2, exponent	β_{area}	[# = x]

Here the “ceil” function is used to ensure that an integer number of pins is output by rounding the calculated value up. The calculation of the projected area, A , was discussed in Section 3.2.5.1.

Again, the two cost constants are company-specific and depend on the practices of the shop manufacturing the ejector pins. They serve to fit an appropriate curve relating the typical number of ejector pins to the part’s projected area. For reference, Boothroyd used the following values: $\alpha_{\text{area}} = (1)$; $\beta_{\text{pins}} = \left(\frac{1}{2}\right)$.

- Relative Accuracy of Estimated Ejector System Costs

The equations used above should have little effect on the total cost of both variants in a relative sense. In fact, the only real difference is embodied in Eq. 3.37 and arises for the fact that the SMM&A variant can have two different ejector systems while the MMM variant can only have one. As long as consistent use of the above equations and required cost constants is used, any errors in the actual costs will be present in both variants' estimates and hence, tend to cancel each other out.

The ejector system cooling cost equations were developed as a simple extension to Boothroyd's model. If desired, the input parameters can be set so that the equations match Boothroyd's original model, and will become as valid as the existing work.

3.2.5.6 – Cooling System Costs

Most typical molds employ a cooling system which is simply a series of connected cylindrical channels that run throughout the mold, close to the cavity and core surfaces. These channels circulate cold water during the cooling phase of injection molding, helping cool the molten resin. There are other specialized cooling devices that can be built into molds in order to help meet special cooling requirements and reach difficult mold areas. Some such devices are baffles and water jets. For simplicity, these specialized cooling devices will be neglected and only the more commonly used cooling channels will be considered in this model.

Cooling channels are usually machined into the molds as a series of deep drilling operations. Then certain channels are plugged on one or both ends to create a closed circuit. A simple example of this is illustrated in Fig. 3.9. From the schematic, it can be seen that the holes are drilled near where cooling is required on the part, and are plugged in certain locations to create one closed path where the coolant circulates. The cost of these plugs is insignificant in relation to the total mold cost, so they will be neglected.

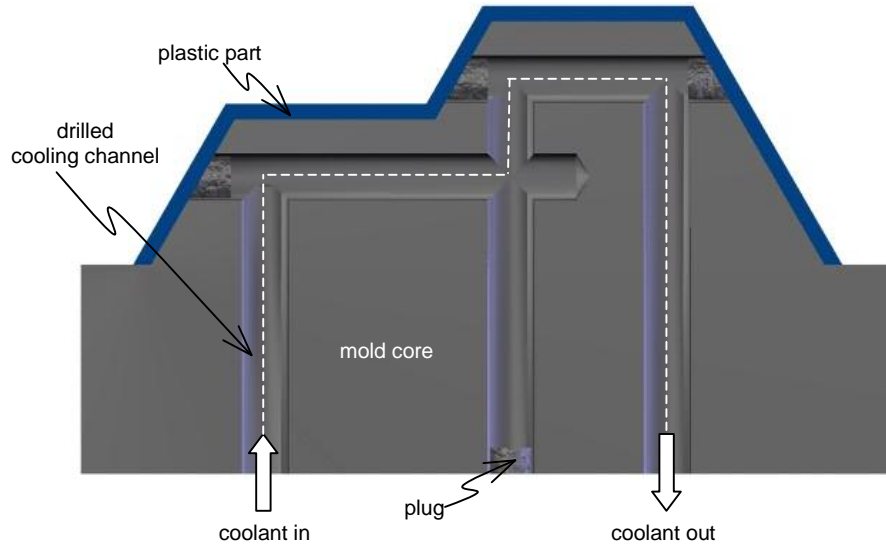


Figure 3.9 – Typical drilled cooling channels in a mold core

A simple way to calculate the machining costs of these drilled holes is by realizing that the cost is directly proportional to the machining time. Keeping this in mind, a cost equation relating the drilling time and an associated machining rate can be used. This results in the following expression, which is analogous to the core/cavity machining times of Section 3.2.5.2:

$$C_{\text{cool}} = \dot{r}_{\text{drill}} t_{\text{drill}} \quad (3.39)$$

Cooling channel drilling costs	C_{cool}	[\$]
Hourly machining rate (for drilling)	\dot{r}_{drill}	[\$/hr]
Total channel drilling time	t_{drill}	[hr]

- **Drilling Hourly Shop Rates**

The hourly cost of drilling is just another hourly machine shop cost associated with the operation of drill presses and the associated labor costs. The actual value depends on the specific shop and must be input to the model along with the other hourly machining rates (e.g. \dot{r}_{mach} in section 3.2.5.2).

- **Drilling Time**

The time required for drilling the holes is directly proportional to the channel size, which in turn, is directly proportional to their length and diameter. Because drilling is a relatively straightforward operation, the drilling time can be written as a simple function involving channel length and a drilling rate:

$$t_{\text{drill}} = \frac{l_{\text{cool}}}{\dot{i}_{\text{drill}}} \quad (3.40)$$

Total channel drilling time	t_{drill}	[hr]
Total length of drilled cooling channels for one core/cavity set	l_{cool}	[in]
Drilling feed rate	\dot{i}_{drill}	[in/hr]

- **Drilling Speed**

The drilling feed rate, or speed relates how fast holes can be drilled, that is, how fast the drill can travel through the mold core and cavity plates per unit time. This value is highly dependent on the hole diameter, mold material (typically steel), and most importantly, the machine shop's drilling equipment and capabilities. This value is readily computed from historical machine shop data, and must be directly input to the model by the user. Additionally, representative feed rates can be obtained from a machinists handbook.

- **Cooling Channel Length**

The total cooling channel length is the most important parameter in terms of cooling system cost and is also, unfortunately, the most difficult to determine at an early design stage. This is because just from looking at the CAD model of the part, it may be difficult to determine the best cooling strategy. Although there are many widely available tools that can be used to analyze and optimize cooling systems after they have been designed, there is relatively little work involving the automated design of cooling channels based on the CAD model of the plastic parts. However, C.L. Li has developed a feature-based approach to

cooling system design [37]. His algorithm recognizes certain geometric features and parametrically assigns custom cooling channel and/or baffle designs based on proven cooling strategies. The cooling channel geometry output by his algorithm can then be verified and optimized in traditional mold analysis software such as C-Mold or MoldFlow.

While Li's algorithm and other related cooling channel design tools have been proven quite successful in helping design optimal cooling systems for traditional single-material molds, there haven't been any published methods specifically tailored to automatically designing MMM cooling channels. This is a potential problem because the cooling process for the MM variant of a product can be significantly different from the SM variant. This is caused by the fact that MMM requires the second material to cool onto the first material, and may have different cooling requirements than the individual parts in the SMM&A variant. In reality, it could be quite possible that the MS mold incorporates a completely different (and more complex) cooling system than its related single material variant due to the inherent greater mold complexity associated with MMM.

Fortunately, our fundamental assumption that the MMM variant is strictly the rotary platen MSM method slightly simplifies the cooling channel considerations because both shots have the same core, and hence, the same cooling channels in the core side of the mold. In terms of the cavity side of the mold, we can also assume the cooling channel layout for both cavities A and B will be the same in either process variant. Because the cavities should be nearly identical in the SM mold and the MS mold, this assumption is justified. These assumptions reduce the total number of unique cooling channel layouts to four, as listed below and illustrated in Fig. 3.10:

- 1) A layout for the core side of mold A, and the common core side of mold AB
- 2) A layout for the cavity side of mold A. and the cavity side of mold AB - shot A

- 3) A layout for the core side of mold B
- 4) A layout for the cavity side of mold B and mold AB, shot B

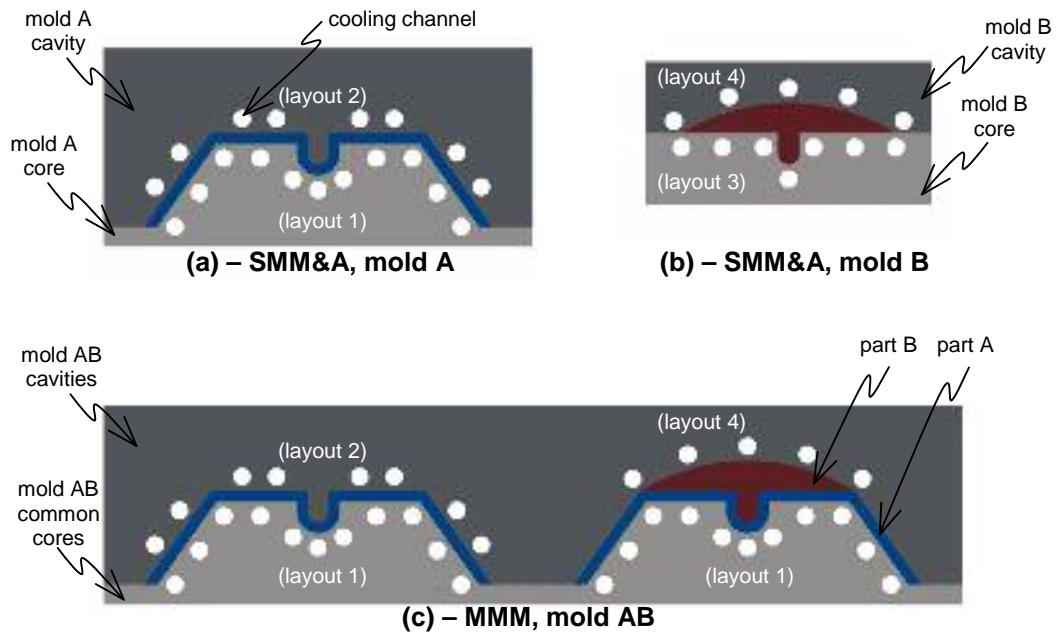


Figure 3.10 – Four unique channel layouts required between MMM & SMM&A

Fig. 3.10 attempts to emphasize the differences between the four different cooling channel layouts required for MMM and SMM&A. Namely, the major difference between the two variants is that layout 3 cannot be used for the MMM variant due to the common core requirement. Because of this, channel layout 4 will be responsible for most of the cooling of material B in mold AB. The effect of the cooling channels on part B will be minimal because part A will be in between part B and the core side channels, hampering heat transfer in that direction. From here on, it will be assumed that the cooling channel systems are designed using the four unique layouts as discussed above. This simply means that the SMM&A variant will have four different cooling channel layouts to design, and the MMM variant will use three of the four of these layouts as well

With that said, we can use the core and cavity geometries discussed in Section 3.2.5.2 to design the appropriate cooling system. The cooling system has to meet the cooling

requirements of both parts A and B as well as not interfere with any other subsystems, such as the ejector system or any side actions. The actual design and optimization of the exact cooling channel layout is outside the scope of this thesis, and it will be assumed the approximate layout is known, either designed based on experience, or from algorithms such as Li's. Once the layouts are specified, it becomes trivial to calculate the length of the required drilled holes. The total length is simply the sum of the individual cooling channel lengths for each variant:

$$l_{\text{cool}} = n_{\text{cav}} \left[(1 - \phi) (l_{\text{cool}_1} + l_{\text{cool}_2} + l_{\text{cool}_3} + l_{\text{cool}_4}) + \phi (2l_{\text{cool}_1} + l_{\text{cool}_2} + l_{\text{cool}_4}) \right] + l_{\text{extra}} \quad (3.41)$$

Total length of drilled cooling channels	l_{cool}	[in]
Length of cooling channels for layout 1 (core A and core AB)	l_{cool_1}	[in]
Length of cooling channels for layout 2 (cavity A and cavity AB, shot A)	l_{cool_2}	[in]
Length of cooling channels for layout 3 (core B)	l_{cool_3}	[in]
Length of cooling channels for layout 4 (cavity B and cavity AB, shot B)	l_{cool_4}	[in]
Extra length of drilled channels (to connect adjacent core/cavity sets)	l_{extra}	[in]

The above equation assumes the cooling channel layout will be the same for each set of matching cores/cavities, and these identical and adjacent channel sets will be connected by additional drilled channels. The extra length required for drilling these connecting channels is expressed as l_{extra} . This term should be the same for both variants, and can be omitted without affecting the relative costs, if desired.

While the model requires that the length in the above equation be known inputs, there is one rough guideline one can use to roughly determine the amount of drilling required. That is, in a worst-case scenario, all holes will be drilled completely through the entire mold base. If this is the case, then the length of one hole is simply the dimension of

the mold base along which it is parallel (please refer to Fig. 3.6 to see mold base dimensions). If it the hole is drilled at an angle, rather than parallel to the walls of the mold base, then the maximum hole length will be no longer than the longest diagonal length of the mold base. With this worst-case scenario assumed, one simply needs to estimate the total number of holes that need to be drilled and multiply this number by the maximum hole length. This type of cooling channel layout is illustrated in Fig. 3.11 below. In this case, equation 3.41 will be neglected, and the simple formula shown in the figure will be used to calculate l_{cool} .

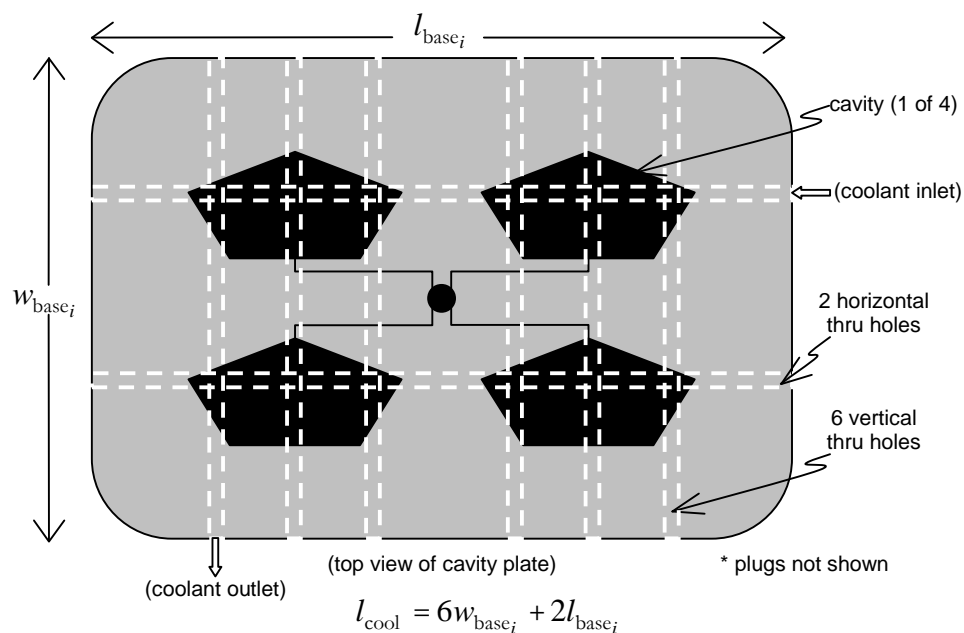


Figure 3.11 – Example of cooling channels drilled through entire mold base

▪ **Relative Accuracy of Estimated Cooling System Costs**

It must be emphasized here that since the cooling channel layouts are assumed to be nearly identical for both process variants, any errors made in determining the associated cooling channel machining costs will be present in cost estimates for both variants. These errors will have the tendency to cancel each other out, in a relative cost-comparison sense.

The cooling system cost estimation equations developed in this section were based on first principles and discussion with molding experts. Their validity will hold as long as the cooling channel layout is properly specified and the machining parameters are accurate.

3.2.5.7 – *Side Action Systems Costs*

If the part geometry absolutely requires undercuts with respect to the mold parting direction, side actions will have to be utilized on each side of the mold cavity that contains said undercuts. The cost of integrating side actions into a mold base depends directly on the type of side action mechanism used, which is in turn, depends of the number and nature of the undercuts. Unfortunately, the cost of implementing side actions is very case-specific and difficult to model. However, some general guidelines and simple reasoning can be used to generate estimates adequate in a relative cost comparison sense.

This model will use ideas from both Poli and Boothroyd's side action cost estimation methods, and slightly adapt them to incorporate MMM. In essence, the number of required side actions will be totaled based on the part features, and an associated cost for each side action will be applied. It should first be stated that if the geometry of parts A and B are nearly identical for both process variants, then they will have the same undercuts, and resultantly, use the same side action systems. However, this is not required for the model to function properly. As long as the number and location of all undercuts is identified, the model can estimate the associated cost. Of course if the side action systems are the same for both variants, then the total cost of these systems should also be the same or very close.

The first step is to count the number of features on each part that will cause internal or external undercuts. For review, internal undercuts can be molded via side actions inside the core half of the mold and external undercuts can be molded via side actions inside the cavity half of the mold. The number of undercuts is equal to the number of unique surfaces that have undercuts. In addition to simply counting each undercut surface, we must also calculate the total bounding cross-sectional area of each undercut's features. This will help us determine the required size of the corresponding side action, which will be used to

estimate its cost. The results of the undercut counting and area calculation may resemble an indexed list as shown in Table 3.3. Representative examples of undercut counting, and cross-sectional undercut area computation are described below.

Table 3.3 – Structure of an Indexed Undercut List		
internal undercut #	external undercut #	cross-sectional bounding area of undercuts' features
1	-	A_{int_1}
2	-	A_{int_2}
⋮	-	⋮
j	-	A_{int_j}
⋮	-	⋮
n_{int}	-	A_{int_n}
-	1	A_{ext_1}
-	2	A_{ext_2}
-	⋮	⋮
-	k	A_{ext_k}
-	⋮	⋮
-	n_{ext}	A_{ext_n}

The above table attempts to illustrate that each internal and external undercut must be separately classified along with the associated features' area. The list must be numbered so that each undercut has a unique index (here the subscripts i and j are used to label internal and external undercuts, respectively).

A simple example of counting undercuts is illustrated in Fig. 3.12. It shows two components with undercuts on several internal and external faces. The surfaces with one or more undercuts are shaded a darker color for clarity. The counting is performed as follows:

- 1) The rightmost exterior face of part A has three protrusions that would form undercuts (one cylindrical pin and two rectangular bosses) – these count as only one external undercut because they are all on the same face and can be formed by one side action.
- 2) The topmost interior face of part A has one semicircular indentation which does not penetrate through the entire wall. This counts as one internal undercut.

- 3) The leftmost interior face of part A has one hemispherical protrusion. This counts as one internal undercut.
- 4) The rightmost exterior face of part B has two rectangular bosses (to mate with the corresponding ones on part A) and one through hole (to allow the cylindrical pin of part A to pass through it). The two bosses form one external undercut. Because the circular hole goes through the entire wall, it can be formed via either an internal or external side action. However, because there is already one external side action associated with this face, the hole will be considered to be an external undercut. Hence, one side action can form all three features and therefore they count as one external undercut.
- 5) The leftmost interior face of part B has one triangular indentation. This counts as one internal undercut.

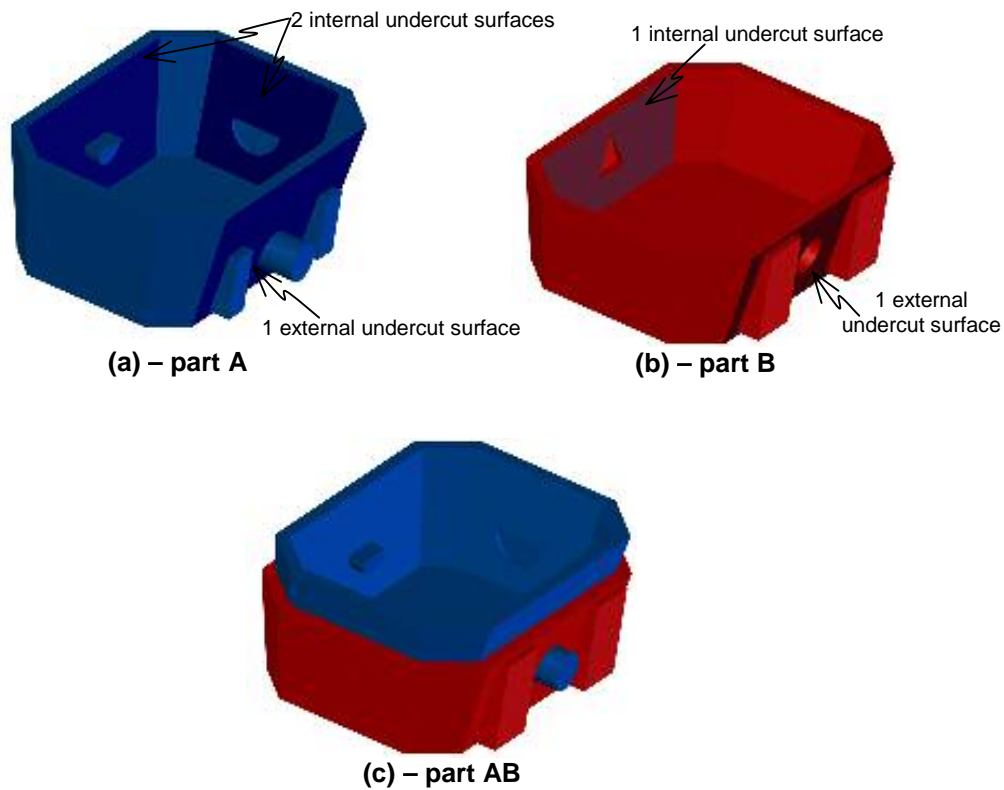
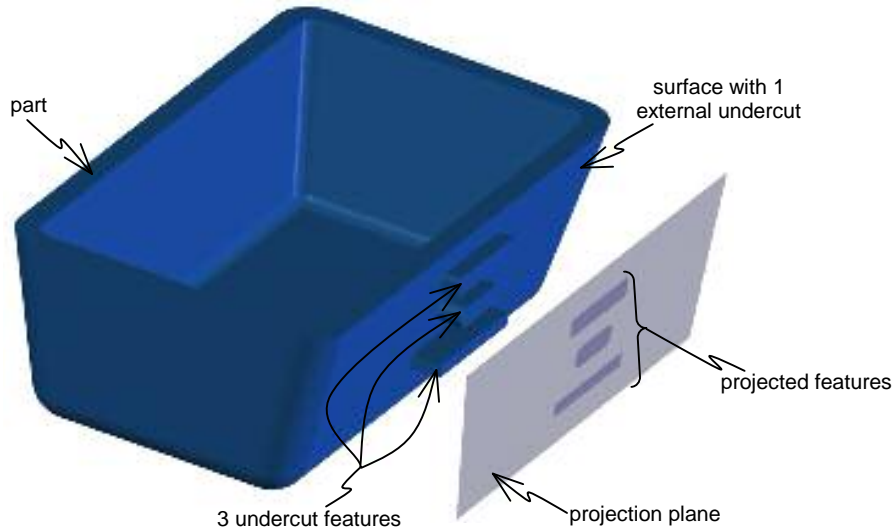


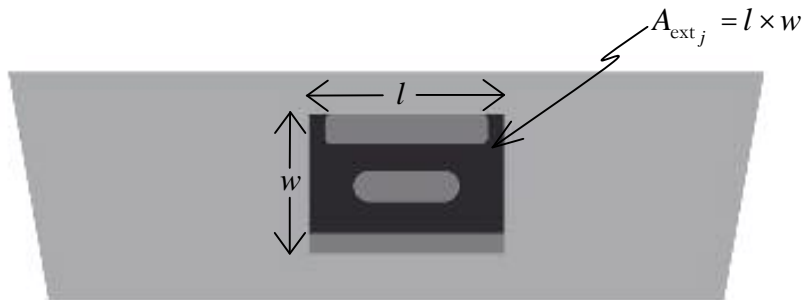
Figure 3.12 – Example of counting internal/external undercuts

A simple example of computing undercut cross-sectional area is shown below in Fig. 3.13. The idea is to project the undercut feature's area onto a plane whose normal vector is parallel to the direction of side action movement. Then the area of the bounding rectangle is used as the area of the undercut. In this example, the three protrusions on the rightmost external surface are counted as one undercut feature, as discussed above. The feature geometries are then projected onto a plane whose normal vector is along the direction of

side action movement (in this case, this direction is also parallel to the extrusion direction of the features forming the three protrusions). Then a rectangle is drawn around the features so that it completely bounds all three of them. The area of this rectangle is the associated area of the undercut, which will be used to determine the side action cost.



(a) – projecting undercut features



(b) – calculating associated area

Figure 3.13 – Example of calculating undercut areas

From the above considerations, the total number of external and internal undercuts for both parts A and B can be expressed as:

$$\begin{aligned}
 n_{\text{ext}} &= (1 - \phi) [n_{\text{ext}_A} + n_{\text{ext}_B}] + \phi [n_{\text{ext}_{AB-A}} + n_{\text{ext}_{AB-B}}] \\
 n_{\text{int}} &= (1 - \phi) [n_{\text{int}_A} + n_{\text{int}_B}] + \phi \cdot 2n_{\text{int}_{AB}}
 \end{aligned}
 \tag{3.42}$$

Total number of external undercuts for one core/cavity set	n_{ext}	[#]
Total number of internal undercuts for one core/cavity set	n_{int}	[#]

Number of external undercuts required in cavity side of mold i	n_{ext_i}	[#]
Number of external undercuts required in cavity side of mold AB, cavity i	$n_{\text{ext}_{\text{AB-}i}}$	[#]
Number of internal undercuts required in core side of mold i	n_{int_i}	[#]
Number of internal undercuts required in common core side of mold AB	$n_{\text{int}_{\text{AB}}}$	[#]

The above equation simply tallies up the two different kinds of undercuts for each mold core and cavity, and then adds them together. For the example of Fig. 3.12, the final results of the counting would yield: $n_{\text{ext}} = 2 + 0 = 2$, and $n_{\text{int}} = 2 + 1 = 3$. The above equation allows for the possibility that the two variants have different numbers of undercuts (that is, n_{ext_A} can be different from $n_{\text{ext}_{\text{AB-A}}}$). However, in most practical cases, the number, configuration, and geometry of undercuts will be the same for both variants. Additionally, the equation emphasizes the fact that since MMM uses common cores, the total number of undercuts in one core is doubled to account for this.

A list resembling Table 3.3 is helpful in keeping track of each undercut's type and associated area. Please note that every undercut, starting at indices " $j=1$ ", " $k=1$ " and ending at indices " $j=n_{\text{ext}}$ ", " $k=n_{\text{int}}$ " must have an associated area, even if some of the areas are the same. From this information, we will construct an estimate for the total cost of building all of the required side actions into the mold. The following notation will be used to label the areas of the undercuts:

$$A_{\text{int}_j} \quad \text{for } j = \{1, 2, \dots, n_{\text{int}}\}$$

$$A_{\text{ext}_k} \quad \text{for } k = \{1, 2, \dots, n_{\text{ext}}\}$$

Area of j^{th} internal undercut	A_{int_j}	[in ²]
Area of k^{th} external undercut	A_{ext_k}	[in ²]

We will estimate the cost of each side action by recognizing the fact that the cost of building a side action into the mold is a direct function of how much space it takes up in the mold (in addition the exact mechanism used to actuate the side action). With this in mind, we will relate the cost of a side action as a linear function of its associated cross sectional area:

$$\begin{aligned}
 C_{SA_j} &= \alpha_{\text{int}} A_{\text{int}_j} + \beta_{\text{int}} \quad \text{for } j = \{1, 2, \dots, n_{\text{int}}\} \\
 C_{SA_k} &= \alpha_{\text{ext}} A_{\text{ext}_k} + \beta_{\text{ext}} \quad \text{for } k = \{1, 2, \dots, n_{\text{ext}}\}
 \end{aligned}
 \tag{3.43}$$

Cost of j^{th} internal side action	C_{SA_j}	[\$]
Cost of k^{th} external side action	C_{SA_k}	[\$]
Linear internal side action cost constant 1, intercept	β_{int}	[\$]
Linear internal side action cost constant 2, slope	α_{int}	[\$/in ²]
Linear external side action cost constant 1, intercept	β_{ext}	[\$]
Linear external side action cost constant 2, slope	α_{ext}	[\$/in ²]

Eq. 3.43 estimates the cost of each external and internal side action by assuming the cost of a side action is linearly proportional to its size, which is specified by the area of the undercut features which it must produce. While the actual cost of a specific side action may be related to a more complex function than the linear one suggested above, this should be sufficient for relative cost comparison in the early design stages. Furthermore, this model takes side action cost estimation one step further than Boothroyd or Poli, because it relates cost to size rather than assuming one constant cost for all side actions. Because the cost of building similar external or internal side actions can be different, two sets of linear constants are used. The actual values of these linear cost constants are company-specific and must be input to the model based on historical cost data.

After the cost of each side actions is estimated as described above, the total cost is simply the sum of these individual costs:

$$C_{SA} = n_{cav} \left(\sum_{j=1}^{j=n_{int}} C_{SA_j} + \sum_{k=1}^{k=n_{ext}} C_{SA_k} \right) \quad (3.44)$$

It should be noted that Eq. 3.44 multiplies the cost of side actions by the number of cavities. This is based on the assumption that a single side action cannot be used to produce undercut geometries on more than one cavity. Sometimes however, it may be possible to arrange the cavity layout so that one side action can be used to produce undercuts in multiple cavities. This advantageous possibility depends entirely on the cavity layout and would be hard to predict in the early design stages of the product. However, if it is known that this will be the case for a particular mold, the total cost of building side actions can be adjusted by simply subtracting the appropriate number of side actions from n_{ext} and/or n_{int} .

- Relative Accuracy of Side Action System Costs

Any inaccuracies resulting from the above reasoning will tend to have no effect on the cost estimates in a relative sense. This is especially true if the required side actions are the same in both process variants.

The equations developed in this section were directly adapted from Boothroyd's work. Based on analysis of the literature and discussion with molding shops, the reasoning used to develop expressions for the side action system was shown to be valid.

3.2.5.8 – Hot Runner Systems Costs

Hot runner systems, as discussed in Section 1.2.1.1, are required in the MMM variant’s mold and optional in both or either of the SMM&A’s molds. The total cost of hot runner systems can then be expressed as:

$$C_{HR} = (1 - \phi)[C_{HR_A} + C_{HR_B}] + \phi[C_{HR_{AB}}] \quad (3.45)$$

Total cost of hot runner systems	C_{HR}	[\$]
Cost of hot runners in mold i	C_{HR_i}	[\$]
Cost of hot runners in mold AB	$C_{HR_{AB}}$	[\$]

Typically hot runner systems are custom-built by a specialized company to meet the molder’s needs. Resultantly, the associated hot runner system costs are controlled directly by their manufacturer. The cost is estimated from quotes provided by the hot runner system manufacturers, which are in turn, based on the engineering drawings of the molds. In general, the cost of a hot runner system is dictated by the number of cavities it must feed, and the temperature/flow characteristics of the specific resin being molded.

Because of this specificity, it is difficult to develop a universal model to estimate hot runner system costs. However, some general reasoning can be used to estimate representative costs for relative comparison purposes. More specifically, we can use linear size-based assumptions, similar to others used throughout this model. We will use the fact that the cost of a hot runner system is proportional to its size, which is itself a function of the mold base’s size and the number of cavities. We could write the cost as a linear function of both mold base size and number of cavities, but since the mold base’s size is also a function of n_{cav} , we will transform it into a linear function of only one independent variable. The function has the following form:

$$C_{HR_i} = \begin{cases} \alpha_{HR} A_{base_i} + \beta_{HR} & , \text{if hotrunners used in mold } i \\ 0 & , \text{if hotrunners not used in mold } i \end{cases} \quad (3.46)$$

$$C_{HR_{AB}} = \alpha_{HR} A_{base_{AB}} + \beta_{HR}$$

Cost of hot runners in mold i	C_{HR_i}	[\$]
Cost of hot runners in mold AB	$C_{HR_{AB}}$	[\$]
Linear hot runner system cost constant 1, slope	α_{HR}	[\$/in ²]
Linear hot runner system cost constant 2, intercept	β_{HR}	[\$]

The above equation assumes that the cost of a hot runner system for a single mold is linearly dependent on the mold base's area (which is itself a function and the number of cavities, Eq. 3.18 in Section 3.2.5.1). While the actual prices quoted by the manufacturer may be different, these equations should produce reasonable estimates for comparative purposes, provided both cost constants are correctly input. These values depend on the specific hot runner system manufacturer, and can be obtained by curve fitting historical hot runner system quotes from one or several manufacturers. Of course these values can be hard to obtain if the manufacturers aren't cooperative in sharing their price history.

- **Relative Accuracy of Estimated Hot Runner System Costs**

Even if the hot runner system estimates aren't fully accurate, the above equations should at least serve to differentiate the costs between MMM and SMM&A, especially if the designers opt to not utilize hot runners in the SMM&A variant. For relative cost comparison purposes, the equation emphasizes the fact that the hot runner system will cost more in the MMM variant due to it having a larger overall mold base size.

The linear cost estimation equations proposed in this section were based on first principles and confirmed valid through discussion with experts in the molding industry.

3.2.5.9 – Mold Setup Costs

The mold setup cost is a one-time cost associated with installing the mold into the molding press and preparing it for production. The cost is incurred simply because it takes time and manpower to hoist a mold onto the press and ensure that it works properly. This also includes the time required for setting the controller for proper operation as well as putting the machine through any necessary dry-runs and getting it up to steady-state production. The total setup cost can be expressed as the sum of the individual setup costs for either process variant:

$$C_{SU} = (1 - \phi)[C_{SU_A} + C_{SU_B}] + \phi[C_{SU_{AB}}] \quad (3.47)$$

Total cost to setup the mold/s	C_{SU}	[\$]
Cost to set up mold i	C_{SU_i}	[\$]
Cost to set up mold AB	$C_{SU_{AB}}$	[\$]

To estimate the individual setup costs above, we could predict how much time each mold setup requires and multiply it by an associated hourly rate, as we have done in previous sections of the model. But instead, we will just use the fact that mold setup time is proportional mainly to its size and complexity and suggest a linear function to model the associated cost of this time. Although in reality the mold setup time also depends greatly on the number and nature of its various subsystems and general complexity, we will keep our method simple by assuming setup time, and resultantly, cost, is a linear function of the mold's size. Because the mold's size can be related to the mold base area, a function of the following form is proposed:

$$\begin{aligned} C_{SU_i} &= \alpha_{SU} A_{base_i} + \beta_{SU_1} \\ C_{SU_{AB}} &= \alpha_{SU} A_{base_{AB}} + \beta_{SU_2} \end{aligned} \quad (3.48)$$

Cost to set up mold i	C_{SU_i}	[\$]
Cost to set up mold AB	$C_{SU_{AB}}$	[\$]
Linear mold setup cost constant 1, slope	α_{SU}	[\$/in ²]
Linear mold setup cost constant 2, intercept (SMM&A)	β_{SU_1}	[\$]
Linear mold setup cost constant 3, intercept (MMM)	β_{SU_2}	[\$]

The above equation allows for two different intercept constants ($\beta_{SU_1} < \beta_{SU_2}$)

because in general, it is more difficult to set up a MSM mold with a rotary platen and hot runners than a standard SM mold. This lets the user input two different mold setup base costs associated with both variants. The actual values of these linear cost constants must be directly input to the model, as they are company specific and depend on historical mold setup cost data.

If the cost constants cannot be accurately determined, the error in both predicted mold setup costs will be of the same magnitude. For cost comparison purposes, this will not affect the relative costs of the variants, and the key difference that SMM&A requires two mold setups will still be emphasized.

The linear cost estimation equations proposed in this section were based on first principles and confirmed valid through discussion with experts in the molding industry.

3.2.6 – Basic Overhead Costs

The term “basic overhead” will be used here to refer to the hourly cost of running the production line, including labor costs and machine rates. While there are many complicated and accurate means to calculate the total cost of overhead, a simple approach will be used here. Specifically, the direct labor and machine costs will be adjusted to account for indirect overhead costs, by applying appropriate overhead rates via the method discussed in Section 2.1.3.3.

Although methods like ABC or other kinds of technical modeling could be used to form an accurate estimate of overhead, they are quite involved and require a lot of information that would not normally be available during the conceptual design stage. Our approach for estimating overhead should be sufficient for relative process comparison purposes. The goal is to emphasize the main differences in overhead between the processes rather than compute the actual absolute value.

First we start with a generic overhead cost term modified from Ashby's equation:

$$C_{BO} = (1 - \phi) \sum_{m=1}^{m=5} \Theta_m \dot{C}_{BO_m} + \phi \cdot \sum_{m=6}^{m=8} \Theta_m \dot{C}_{BO_m} \quad (3.49)$$

Total basic overhead cost	C_{BO}	[\$]
Effective production time of station m	Θ_m	[hr]
Basic overhead rate for station m	\dot{C}_{BO_m}	[\$/hr]

The above relation simply states that the overhead can be expressed as a sum of hourly rates multiplied by the effective total production time. The key then, is to use appropriate values for the overhead rates that yield overhead cost estimates useful for relative comparison purposes. With this in mind, we can split the overhead rate into a sum of applicable rates representing the various activities relevant to MMM and SMMM&A:

$$\begin{aligned} \dot{C}_{BO_1} &= (1 + f_{OH_1}) (\dot{r}_{\text{mold}_A} + \dot{r}_{\text{oper}}) ; \quad \dot{C}_{BO_2} = (1 + f_{OH_2}) (\dot{r}_{\text{mold}_B} + \dot{r}_{\text{oper}}) \\ \dot{C}_{BO_3} &= (1 + f_{OH_3}) \dot{r}_{\text{insp}} = \dot{C}_{BO_7} ; \quad \dot{C}_{BO_4} = (1 + f_{OH_4}) \dot{r}_{\text{assm}} \\ \dot{C}_{BO_5} &= (1 + f_{OH_5}) \dot{r}_{\text{pack}} = \dot{C}_{BO_8} ; \quad \dot{C}_{BO_6} = (1 + f_{OH_6}) (\dot{r}_{\text{mold}_{AB}} + \dot{r}_{\text{oper}}) \end{aligned} \quad (3.50)$$

Basic overhead rate for station m	\dot{C}_{BO_m}	[\$/hr]
Factory overhead rate applied to station m	f_{OH_m}	[%]
Hourly rate for molding machine i	\dot{r}_{mold_i}	[\$/hr]
Hourly rate for multi-shot molding machine	$\dot{r}_{\text{mold}_{AB}}$	[\$/hr]
Labor rate for a machine operator	\dot{r}_{oper}	[\$/hr]

Labor rate for an assembler	\dot{r}_{assm}	\$/hr]
Labor rate for an inspector	\dot{r}_{insp}	\$/hr]
Labor rate for a packager	\dot{r}_{pack}	\$/hr]

Here, the basic overhead rate is split into a sum of 1) direct labor costs, and 2) molding machine/s operational costs, which are then adjusted by corresponding overhead rates. Eq. 3.49 might seem like a gross oversimplification because it only sums the various overhead costs without weighting them based on what percentage of total production time each activity takes. A more detailed approach that accounts for utilizations, cycle times, and other factors would potentially yield more accurate cost estimates, but this is not important in a relative sense. For cost comparison purposes, it should suffice to sum up all the total hourly production costs and divide by the production rate (or equivalently, multiply by the total cycle time) to estimate the overhead costs. The estimation of the labor, molding, and overhead rates are discussed below.

3.2.6.1 – Labor Rates

The labore rates (e.g. \dot{r}_{assm}) account for the different hourly wages paid to different laborers involved with production. The actual values for these rates depends on the individual company’s practices as well as the level of skill required for the product under consideration. These numbers can be calculated from historical and geographical data. A single labor rate can be used for simplicity. A few guidelines concerning determining the proper labor strategy are given below:

The number of laborers required for a particular manufacturing operation depends on the specific equipment and level of automation in the production line. For the two variants dealt with in this model, common labor activities would include: 1) molding machine operation, 2) assembly, 3) inspection, and 4) packaging. These individual tasks

could each be performed by separate personnel, or multiple tasks could be assigned to one individual. Furthermore, it is possible to have more than one worker performing the same task (e.g. two assemblers). The particular labor distribution strategy is up to the company, based on the production schedule's needs.

Regardless of the chosen strategy, the number of laborers assigned to each task actually will not affect the labor rate. Rather, the effect of the labor distribution has been accounted for in the computation of the production rates, as discussed in Section 3.2.3.2. For the purposes of computing the effective total labor rates, a simple approach involving the hourly labor rates will be used. Before the computation of this labor rate is detailed, a brief discussion of two possible labor scenarios is given below:

- **Minimal Labor**

If the assemblies being manufactured are non-complex, their production might not be labor-intensive; that is, a minimal number of workers would be required to keep the production line running. This would generally happen when all of the required post-molding operations are relatively quick, and not tending to cause a bottleneck in the production line. For example if the molding cycle time is 30 seconds while the combined assembly, inspection, and packaging times is 15 seconds, a minimal number of laborers would be required to man the production line. For both process variants, the absolute minimum number of laborers would be one.

For the SMM&A variant, the lone worker would be responsible for manning a station adjacent to the molding machines. Her job would include following tasks:

- 1) Oversee the operation of both molding machines. (This is to ensure they are running properly and have not jammed or otherwise stopped molding parts).
- 2) Collect and inspect parts A and B, discarding any defective pieces.
- 3) Assemble parts A and B (and any fasteners) to produce assembly AB.

- 4) Package the finished assemblies.

For the MMM variant, the lone worker would be responsible for a slightly less labor-intensive set of tasks, including:

- 1) Oversee the operation of the multi-shot molding machine.
- 2) Collect and inspect molded assembly AB's.
- 3) Package the finished assemblies.

- Maximal Labor

Complex products may require more labor throughout their production, potentially requiring more than one dedicated laborer. This would generally happen when one or more post-molding tasks takes significant time compared to the molding cycle time. In this case, one or more workers would be assigned to each of the four tasks described above. Depending on the variant, the lowest possible number of laborers required for maximal labor would start at three or four workers (one for each task).

As stated earlier, the exact labor requirements depend on the product complexity, and the production schedule (which is based on product demand and delivery requirements). The strategy will have to be chosen by the model user based on these considerations and using common sense and/or historical data. Once the labor strategy has been chosen, the production rate can be calculated using equations from Section 3.2.3.2, and the computation of the total cost of labor follows using Eq. 3.50.

3.2.6.2 – Machine Rates

The machine rates refers to the hourly cost of running the injection molding machines. This accounts for the power consumption and other utilities used during their operation. The total per-part cost of overhead associated with running molding machines is directly dependent on the amount of time each machine is operated for each part

The molding machines' hourly rates are based on their overall size as well as the number and complexity of subsystems they control. This includes cooling systems, side actions, hot runners, and rotary platens. The rates can be expressed as generic functions of size and number of subsystems:

$$\dot{r}_{\text{mold}_i} = \Psi_1(\{\text{size}\}_i, \{\text{cooling}\}_i, n_{\text{SA}})$$

$$\dot{r}_{\text{mold}_{AB}} = \Psi_2(\{\text{size}\}_{AB}, \{\text{cooling}\}_{AB}, \{\text{hot runners}\}, \{\text{rotary platen}\}, n_{\text{SA}})$$

$$\text{where } n_{\text{SA}} = n_{\text{ext}} + n_{\text{int}}$$

Hourly rate for molding machine i	\dot{r}_{mold_i}	[\$/hr]
Generic function relating SMM machine rate with size and subsystems	$\Psi_1(\dots)$	N/A
Size of molding machine i	$\{\text{size}\}_i$	N/A
Cooling system layout for mold i	$\{\text{cooling}\}_i$	N/A
Number of side actions in mold	n_{SA}	[#]
Hourly rate for multi-shot molding machine	$\dot{r}_{\text{mold}_{AB}}$	[\$/hr]
Generic function relating MSM machine rate with size and subsystems	$\Psi_2(\dots)$	N/A
Size of multi-shot molding machine	$\{\text{size}\}_{AB}$	N/A
Cooling system layout for mold AB	$\{\text{cooling}\}_{AB}$	N/A
Hot runner system layout for mold AB	$\{\text{hot runners}\}$	N/A
Rotary platen size for mold AB	$\{\text{rotary platen}\}$	N/A
Number of side actions in mold AB	$n_{\text{SA}_{AB}}$	[#]

Unfortunately, the above equation cannot be explicitly evaluated. Furthermore, with the exception of machine size and the number of side actions, the rest of the terms in the equation (denoted with curly braces, “{...}”) cannot be expressed as simple numeric values. The equation is only given to show the relation between molding machine hourly rates and machine size/subsystem parameters. This is because each subsystem will have its own hourly costs associated with it due to power consumption and other run costs. Additionally, the equation emphasizes the fact that the hourly rate for a MS machine is dependent upon

more parameters than a single-material machine. In general, it will cost more to run a MS machine due its larger size and the operation of more complex subsystems.

Once the sizes and specifics of the machines and required subsystems are determined, the rates can be estimated from the machine manufacturer's data, or historical machine rate data. A simple way to estimate the value would be to run the machines for a period of time and find the average power consumption rate. The cost of electricity and other consumables can then be estimated.

The calculation of the required molding machine size is discussed in Section 3.2.7.1.

3.2.6.3 – Factory Overhead Rates

The eight overhead rates in Eq. 3.50 are used to provide a simple means of accounting for indirect costs by adjusting the direct costs. They can be calculated by the method discussed in Section 2.1.3.3. Specifically, historical data based on total annual indirect factory costs must be divided by annual direct costs to obtain these rates. For example, if total labor costs for the previous year equaled x million dollars, and the total indirect overhead costs associated with station m equaled y_m million dollars, the factory overhead rate applied to labor would be calculated as: $f_{OH_m} = y_m/x$

In some scenarios it may not be possible to calculate these overhead rates due to a lack of historical data. If this is the case, the overhead rates can be omitted for the purposes of relative cost comparison. This is justifiable because while they do have an important effect on total cost, they have no effect in a relative sense because the same rates are applied to the hourly costs for both process variants, thus canceling each other out. This omission is along the same lines as Groover's omission of corporate overhead rates from production cost estimation. His reasoning is that "these corporate overhead expenses are present whether or not either or none of the [process variants] alternatives is selected" [25].

The equations proposed in this section were taken directly from Groover's work and have been shown to hold valid in industrial settings.

3.2.7 – Capital Investment Costs

The total capital investment cost is simply the cost of all the required production line equipment amortized over a period of time. It is amortized over a time rather than a production quantity because the equipment is typically used throughout several product lines, rather than dedicated to a single product. For instance, the same molding machine will be used to manufacture many different parts. Starting with a modified version of Ashby's generic capital cost term, the following expression is used to represent the total cost of capital:

$$C_{CI} = \frac{f_I}{f_L t_{WO}} \left[(1 - \phi) \sum_{m=1}^{m=5} \Theta_m C_{C_m} + \phi \cdot \sum_{m=6}^{m=8} \Theta_m C_{C_m} \right] \quad (3.51)$$

Total capital investment cost	C_{CI}	[\$]
Capital cost of equipment for station m	C_{C_m}	[\$]
Interest factor	f_I	[%]
Load factor	f_L	[%]
Write off time of investment	t_{WO}	[hr]

3.2.7.1 – Equipment Cost

The equipment simply refers to all of the machinery required to manufacture and assemble the product. This includes the molding machines, assembly equipment, and other miscellaneous items (e.g. packaging equipment). This also includes the rotary platen required for the MMM variant. Equipment cost can be expressed as:

$$\begin{aligned} C_{C_1} &= C_{mach_A} \quad ; \quad C_{C_2} = C_{mach_B} \quad ; \quad C_{C_3} = C_{insp} = C_{C_7} \quad ; \quad C_{C_4} = C_{assm} \\ C_{C_5} &= C_{pack} = C_{C_8} \quad ; \quad C_{C_6} = C_{mach_{AB}} + C_{platen} \end{aligned} \quad (3.52)$$

Capital cost of equipment for station m	C_{C_m}	[\$]
Cost of molding machine for shot i	C_{mach_i}	[\$]
Cost of assembly station	C_{assm}	[\$]
Cost of inspection station	C_{insp}	[\$]
Cost of multi-shot molding machine	$C_{mach_{AB}}$	[\$]
Cost of rotary platen	C_{platen}	[\$]
Cost of packaging station	C_{pack}	[\$]

Here the capital equipment cost is broken down into a sum of individual equipment costs, and adjusted to account for interest. The interest factor is discussed in Section 3.2.7.2. The model requires all of the costs of capital equipment to be known. Fortunately, this data is readily available from specific manufacturer's price lists.

Table 3.4 lists some common capital equipment that must be priced, including both required and optional equipment:

	SMM&A	MMM
required equipment	molding machine A molding machine B assembly station	molding machine AB rotary platen
optional equipment	robotics packaging equipment inspection equipment resin dehumidifiers resin regrinders assembly tools	robotics packaging equipment inspection equipment resin dehumidifiers

While Table 3.4 is by no means a comprehensive list, it shows all of the required equipment as well as some typical auxiliary equipment that should be considered for production of either product variant.

- Molding machine costs

The cost of each molding machine includes the cost of the press and the necessary injection unit/s:

$$C_{mach_i} = C_{press_i} + C_{inj_i}$$

$$C_{mach_{AB}} = C_{press_{AB}} + C_{inj_A} + C_{inj_B}$$
(3.53)

Cost of molding machine for shot i	C_{mach_i}	[\$]
Cost of molding press for shot i	C_{press_i}	[\$]
Cost of injection unit for shot i	C_{inj_i}	[\$]
Cost of multi-shot molding machine	$C_{mach_{AB}}$	[\$]
Cost of multi-shot molding press	$C_{press_{AB}}$	[\$]

- Molding Press Costs

The molding press refers to the part of the molding machine which holds the clamp mechanism that controls the opening/closing of the mold. The price of the press is a function of the press size, which is a function of the required clamping force. The exact nature of this cost function is dependent on the press manufacturer, but a generic equation can be written as:

$$C_{press_i} = \Phi_1(F_{clamp_i})$$

$$C_{press_{AB}} = \Phi_1(F_{clamp_{AB}})$$

Cost of molding press for shot i	C_{press_i}	[\$]
(generic function relating clamp force to press cost)	$\Phi_1(\dots)$	N/A
Clamp force required of press i	F_{clamp_i}	[lb]
Cost of multi-shot molding press	$C_{press_{AB}}$	[\$]
Clamp force required of multi-shot press	$F_{clamp_{AB}}$	[lb]

Although Φ_1 cannot be explicitly defined, and hence evaluated, it is still easy to find the press cost once the clamp force has been determined. One simply finds the required clamp force, and looks up the price of the smallest press that can accommodate it in a manufacturer's price list.

The clamp force required to hold the mold together during injection depends on the injection pressure and the total surface area it acts upon. In order to account for MMM, Eq. 2.13 was adapted to yield:

$$F_{\text{clamp}_i} = f_{\text{safe}} P_{\text{inj}_i} A_{\text{proj}_i}$$

$$F_{\text{clamp}_{AB}} = f_{\text{safe}} \left[P_{\text{inj}_A} A_{\text{proj}_A} + P_{\text{inj}_B} A_{\text{proj}_B} \right] \quad (3.54)$$

Clamp force required of press <i>i</i>	F_{clamp_i}	[lb]
Clamp force safety factor	f_{safe}	[%]
Maximum pressure during shot <i>i</i>	P_{inj_i}	[psi]
Projected mold cavity area for shot <i>i</i>	A_{proj_i}	[in ²]
Clamp force required of multi-shot press	$F_{\text{clamp}_{AB}}$	[lb]

It is obvious from the above equation that the clamp force will be higher in the MMM variant. This is because both sets of cavities are being filled simultaneously, exerting more pressure forces on the mold. This emphasizes the fact that MMM requires bulkier (and costlier) molding presses.

The required injection pressure is dependent on the viscosity of the resin, with thicker materials needing a higher pressure in order to fill the cavity. The recommend pressure can be obtained from the resin manufacturer. The safety factor is included to ensure that the mold stays closed. This prevents unwanted material flash and potential mold/machine damage. A conservative value should be chosen for this number. The projected area includes all of the surface area (projected normal to the clamp direction) that the injection pressure acts on. Specifically, this includes the cavities as well as the gating system:

$$A_{\text{proj}_i} = n_{\text{cav}} A_{\text{part}_i} + A_{\text{gating}_i} \quad (3.55)$$

Projected mold cavity area for shot i	A_{proj_i}	[in ²]
Projected area of part (normal to clamp direction)	A_{part_i}	[in ²]
Projected area of gating system (normal to clamp direction)	A_{gating_i}	[in ²]

The required projected areas are easily obtained from the CAD model of the part and the chosen gating strategy. A_{gating_i} can be computed as the runner diameter times the total length of the runners.

- Injection Unit Costs

Like the molding press, the cost of the injection unit is a function of its size. The required size is in turn, a function of the total shot volume. The injection unit's size is characterized by the volume of the plasticizing barrel. According to Bryce, the ideal barrel size is twice the volume of one shot [11]. With this in mind, we can write another generic cost function (similar molding press cost equation):

$$C_{inj_i} = \Phi_2(V_{barrel_i})$$

$$\text{where : } V_{barrel_i} \geq 2V_{shot_i}$$

Cost of injection unit for shot i	C_{inj_i}	[\$]
(generic function relating barrel size to injection unit cost)	$\Phi_2(\dots)$	N/A
Required volume of barrel of injection unit i	V_{barrel_i}	[in ³]

After the required barrel size is computed, the price of the injection unit can be obtained from a manufacturer's price table, in the same manner as pricing the molding press.

- Assembly Station Cost

The cost of the assembly station for the SMM&A variant includes the cost of any tools, fixtures, and workbenches required at the assembly station. The total cost is entirely dependent on the station's configuration and must be input to the model by the user. The station could consist of a simple table and chair, or an elaborate assembly cell with drop-

down tools and conveyors, etc... Once the assembly requirements are determined, the cost of the associated equipment should be simple to compute.

- Rotary Platen Cost

The rotary platen adds a significant cost to the MMM process variant. A typical platen can be in the ballpark of \$50K-\$60K (for instance, the platen in the Case Study II in Section 2.4.1 cost \$57K [26]). The cost of the platen is a direct function of its size, which is in turn, a function of the size of the mold base that it rotates. The mold core side of the mold base essentially bolts directly to the rotary platen, so the platen should be large enough to accommodate the base. As a general rule, the platen's diameter should be slightly larger than the length of the diagonal of the mold base. Fig. 3.14 illustrates this concept (see Figs. 1.30 & 1.31 for examples of rotary platens). With this, we can write yet another generic cost function:

$$C_{\text{platen}} = \Phi_3(D_{\text{platen}})$$

where : $D_{\text{platen}} > l_{\text{base}}$

Cost of rotary platen	C_{platen}	[\$]
(generic function platen size to cost)	$\Phi_3(\dots)$	N/A
Required diameter of platen	D_{platen}	[in]
Diagonal length of mold base	l_{base}	[in]

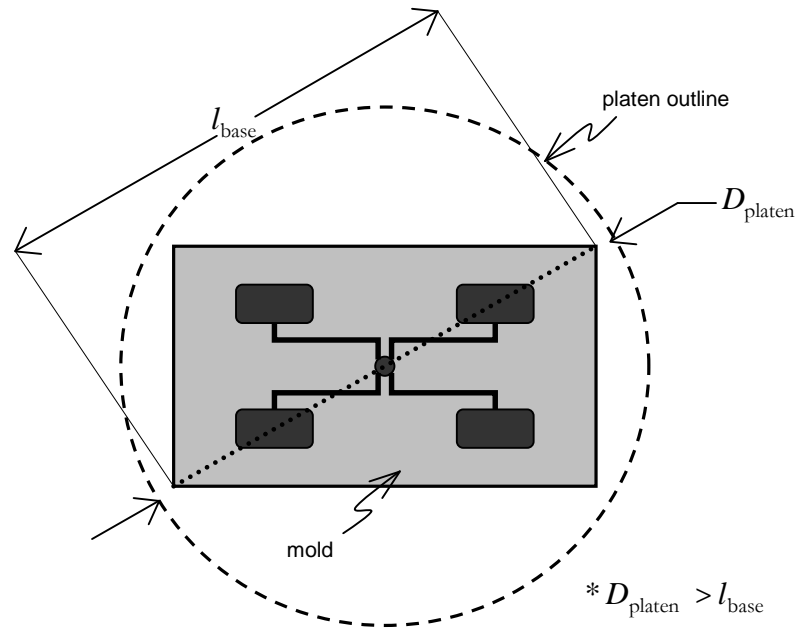


Figure 3.14 – Sizing the Rotary Platen

The diagonal length of the mold base can easily be obtained from its size, the calculation of which was discussed in Section 3.2.5.1. As with the previous two generic cost functions, the cost of the rotary platen can be from a manufacturer's price table, based on its size.

- **Auxiliary Equipment Costs**

The auxiliary equipment term is intended to include all the other optional equipment outside of the direct molding/assembly items. This could include things such as resin dehumidifiers, packaging equipment, etc... The presence of such extra equipment is case-specific and the costs must be supplied by the user. In fact, this term is only included in the model for completeness. If desired, it can be dropped because it won't tend to have an effect on cost in a relative sense. For instance, the costs associated with a packaging station will exist in both variants, and hence tend to cancel each other out.

3.2.7.2 – Capital Investment Parameters

The capital investment parameters, namely the load factor and write off time, are highly dependent on the investment strategy of each individual company and their

accounting practices. These values have to be determined based on the company's specific needs in order to be input to the model.

- Interest Factor

The “interest factor” used in Eq. 3.51 is a term added to include the cost of capital; that is, the interest incurred throughout the repayment of the loan. It is computed by the standard simple-interest capital recovery equation:

$$f_I = \frac{I(1 + I)^{n_{\text{pay}}}}{(1 + I)^{n_{\text{pay}}} - 1} \quad (3.56)$$

Interest factor	f_I	[%]
Interest rate	I	[%]
Number of payments	n_{pay}	[#]

Here the interest rate and the number of payments must be appropriately determined based on the current rates and the desired length of the loan. The interest factor term serves to adjust the capital cost by a constant factor, and is only included for completeness and more accurate estimates. In terms of comparing the two process variants, it is not important in a relative cost estimation sense, and can be omitted if desired.

- Write-Off Time

The write-off time is simply a time period over which the capital cost of the equipment is to be recovered. This would typically be the length of the loan taken out to pay for the equipment. As with the interest factor, the write-off time is rather unimportant, as it only serves to scale the total cost and yield the correct units [\$] in Eq. 3.51. It should have no relative effect between MMM and SMM&A cost estimates, and can be chosen arbitrarily if desired. It should be noted that the number of payments and the write-off time from Eq. 3.51 are directly coupled. Specifically, n_{pay} is the number of equal payment periods

in two. For example, if the write-off time is five years and the total number of payments is ten, then the capital loan payments are being made twice a year.

- **Load Factor**

The load factor is used to represent how effectively the equipment is used. It can account for things such as breakdowns, scheduled downtimes (for maintenance, etc...), and the possibility that the equipment is used on several product lines rather than dedicated to the production run being estimated. This actual number can be difficult to estimate, especially in the early product design stages, as there are many uncertainties associated with running a production line. This number can be conservatively estimated based on historical data, or using more sophisticated means such as discrete event simulation. Furthermore, the single value for load factor must be able to account for the various equipment used in production, each of which may have their own load factors and run conditions. The accurate computation of the load factor is beyond the scope of the model.

Fortunately, this term is also unimportant in a relative sense because it simply serves to scale the capital cost, similar to the investment factor and write-off time. If desired, the load factor can be set to an ideal value of unity for relative process comparison purposes.

The equations presented in this section were based off of simple reasoning and common accounting practices. These accounting methods have been shown to be valid ways of representing the cost of capital in industrial settings.

3.2.8 – Plant Floor Space Costs

Since the entire production line will be taking up space in some manufacturing plant, a rather significant cost is incurred as a result. This is because it simply costs money to rent and maintain facilities. Bulky molding machines take up precious floor space that could otherwise be used on other production lines or as storage room. While this cost could be

absorbed into the basic overhead as with several other factors, it will be independently considered here for greater emphasis and ease of calculation.

Based on the facilities' rent cost as well as other factors such as maintenance fees, the cost of space is determined by multiplying the total area used by an appropriate space rental rate. From an adapted version of Ashby's generic cost equation, the cost of space can be written as:

$$C_S = \tilde{C}_S \left[(1 - \phi) \sum_{m=1}^{m=5} \Theta_m A_m + \phi \cdot \sum_{m=6}^{m=8} \Theta_m A_m \right] \quad (3.57)$$

Total cost of plant floor space	C_S	[\$]
Total floor space used by station m	A_m	[ft ²]
Hourly cost of space	\tilde{C}_S	[\$/(ft ² •hr)]

3.2.8.1 – Floor Space Used by Production Line

The total floor space is the sum of all the space used by every station in the production line, including molding machines (and their associated auxiliary equipment), assembly stations, and packaging stations. The individual areas of each station can be written as:

$$\begin{aligned} A_1 &= A_{injA} & ; & & A_2 &= A_{injB} & ; & & A_3 &= A_{insp} = A_7 & ; & & A_4 &= A_{assm} \\ A_5 &= A_{pack} = A_8 & ; & & A_6 &= A_{injAB} \end{aligned} \quad (3.58)$$

Total floor space used by production line	A	[ft ²]
Floor space used by injection machine i	A_{inj_i}	[ft ²]
Floor space used by injection machine AB	$A_{inj_{AB}}$	[ft ²]
Floor space used by assembly station	A_{assm}	[ft ²]
Floor space used by inspection station	A_{insp}	[ft ²]
Floor space used by packaging station	A_{pack}	[ft ²]

All of the various areas in Eq. 3.59 are dependent on the specific molding machines, assembly station layouts, and packaging/inspection station sizes, and hence must be input by the user. These values should be simple enough to determine based on manufacturer's data and the assembly strategy. The molding machines' areas ("footprints") are based on their size, the computation of which was discussed in Section 3.2.7.1. The equation emphasizes the significant difference in floor space usage between the two process variants; that is, the fact that SMM&A requires two machines and an assembly station, whereas MMM requires only one (although usually larger) machine. This difference could significantly affect the relative costs between the two processes. It should be noted that the footprint of the MMM machine is highly dependent on the layout of the injection units. Some of the common layouts were schematically illustrated in Fig. 1.19, and 3D views of these same layouts are shown below in Fig. 3.15 for quick reference:

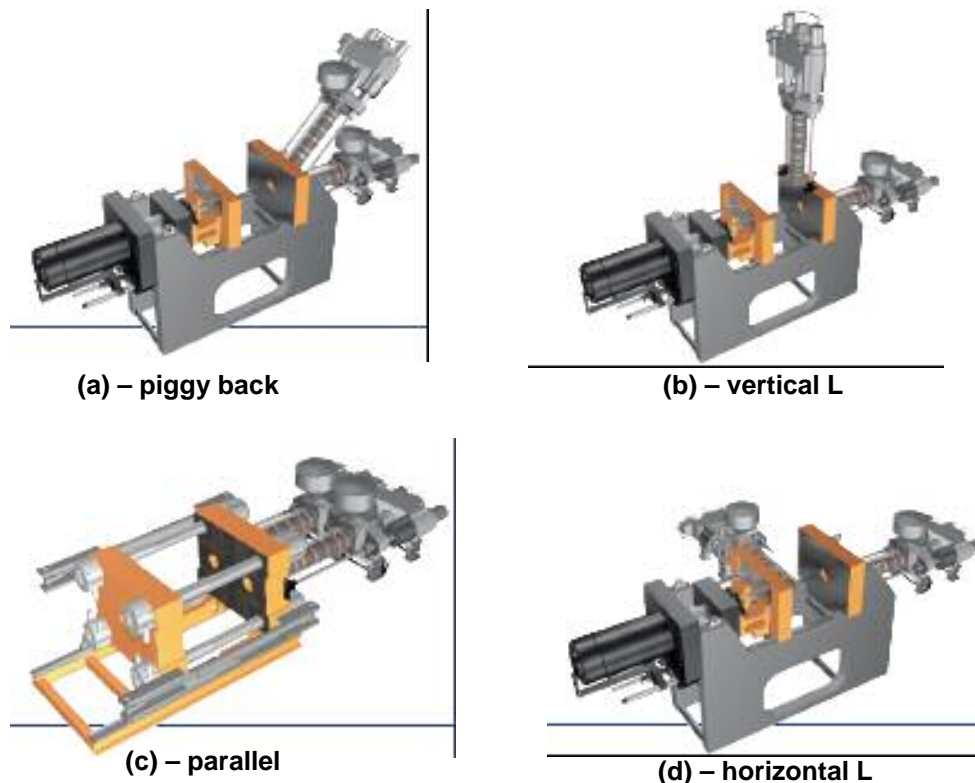


Figure 3.15 – Common dual injection unit molding machine configurations

Source: <http://www.eurotecsls.com/>

3.2.8.2 – Hourly Cost of Space

The hourly cost of space must be determined based on the cost of renting the entire manufacturing facility as well as other factors such as upkeep. These values are company-specific and should be readily calculated based on historical data. Although this cost might be represented as a monthly rate, it must be converted to hourly for unit consistency.

The equations presented in this section were borrowed directly from Ashby's work, who has shown them to be valid in industrial settings.

3.3 – Summary

In summary, a novel cost estimation model was presented for comparing the relative costs of SMM&A and MMM process variants. The model was built from modified versions of theories discussed in Chapter 2, making extensive use of Boothroyd's equations. The model is comprehensive in the fact that it included all of the costs considered important in a variety of different commonly-used models, including industrial and academic work.

The model attempts to emphasize the key difference between the two variants rather than provide absolute accuracy in the cost estimates. Many of the equations required customization based on the specific company in order to be explicitly evaluated.

The model made use of extensive assumptions regarding the relationships between cost drivers such as part geometries and process capabilities and the resultant costs using semi-empirical formulas. Many of these assumptions involved fitting linear equations to historical or averaged cost data.

CHAPTER 4 – PERFORMANCE EVALUATION

This chapter presents the basis for a performance evaluation model that relatively compare the performances of functionally-similar products produced via MMM and SMM&A. The model is based completely on original work, using simple reasoning to define and evaluate several performance characteristics. First the purpose of the model is stated, and then the assumptions are listed before the performance characteristics are defined.

4.1 – Introduction

This section lays the groundwork needed for understanding and utilizing the performance evaluation model. The purpose, scope, and assumptions underlying the model are explained.

It should first be stated that the majority of this thesis concentrates on the cost-based comparison of the two process variants. However, it is felt that cost is only half of the picture, and that a process comparison model is incomplete without some sort of relative performance evaluation. Hence for the sake of completeness, a simple methodology for such is proposed. However, this model will be kept significantly less detailed than the first for the sake of brevity.

Based on collaboration with several SM and MM molders, including Space Limited, Multishot, and Black & Decker, several important performance issues were identified. Based on this information, corresponding performance aspect definitions and measurement techniques were developed as detailed below.

4.1.1 – Model Purpose

The purpose of this model is similar to that of the cost estimation model of Chapter 3. The only difference is that performance measurement metrics will be used in stead of a cost-based metric. Specifically, the model is designed to help decision makers choose between two process variants based on several measurable performance characteristics. The CAD model of the products would be input to the model, and with minimal other user inputs, the performance aspects would be evaluated and output side-by-side so a decision could be made. Based on the numerical results obtained through evaluation of the model, the exact decision process is left up to the product designers. Specific decision-making methods (such as decision-based-design or multi-objective optimization) are outside the scope of this thesis.

4.1.2 – Model Embodiment

The model is designed to evaluate several performance aspects of a product through geometric analysis of the CAD model. Although full automation is the eventual goal of this model, much of the CAD analysis will be manually performed for the time being (i.e. certain things must be input, like the mold parting direction, etc...).

Unlike the cost estimation model, this model would not have a graphical output like quantity-cost curves. This model's output is simple numerical values that can be displayed as a table for relative comparison purposes. Each row of the table would correspond to an independent measurable physical characteristic, and the columns would represent the measured values for both SMM&A and MMM variants. A generic example of such an output table is shown below in Table 4.1:

Table 4.1 – Generic Example of Performance Evaluation Output			
	SMM&A	MMM	Advantage
PA#1	.123 lbs.	.234 lbs.	SMM&A
PA#2	12 in.	9 in.	MMM

⋮	⋮	⋮	⋮
PA#<i>n</i>	<numeric value>	<numeric value>	<better variant>

Unlike the cost estimation model, this model would require very few equation evaluations - much of the needed information should be extracted directly from the CAD files.

The model will not use a weighting system to rank the various performance aspects. This is because the relative performance of the performance aspects is both subjective and application-specific. For instance, for a certain product, weight may be a very important consideration, while assembly clearances are not. We will leave this weighting to the model user.

In stead of providing a concrete decision-making model, this model is simply intended to help evaluate certain relevant physical characteristics of the molded products. The output of this model can be input to a suitable decision-making model, such as a multi-objective optimization routine. It is recommended that a strategy, such as plotting Pareto-optimal frontiers be used to help the decision makers choose the better variant based on their specific needs.

4.1.3 – Model Scope and Assumptions

The scope of the model is the same as the cost estimation model of Chapter 3. All of the assumptions listed in Section 3.1.3 still hold, but are less important for this model, as they are not used to evaluate most of the performance characteristics.

4.1.4 – Model Application Example

This model could be used in the same application example of Section 3.1.4 (the hinge box, Fig. 3.3). Here, instead of evaluating the manufacturing costs of each variant, their relative performance in several separate categories will be evaluated. This model is intended to supplement the cost estimation model of Chapter 3 by providing several

separate performance metrics that can be used in conjunction with cost to choose the better variant.

4.2 – Model Formulation

This section defines and describes measurement techniques for several performance characteristics deemed appropriate for plastic products. While there are many subjective ways of classifying and quantifying a product’s performance and quality, we will stick to only a few of the more well-defined aspects that can be physically measured. Certain characteristics that are important in plastic product design will be quantified and measured as performance aspects. For example, parameters such as weight and strength are both relevant and quantifiable, so they will be considered in this model.

For clarity, we will henceforth define a “performance aspect” (PA) as a measurable physical quality of a plastic product assembly that non-subjectively and non-arbitrarily quantifies its desirability. Therefore, each PA will have actual physical units (e.g. grams, millimeters, etc...) used to describe it. The following subsections will define the relevant PA’s and describe how to measure and/or compute them.

4.2.1 – Performance Aspect 1: Weight

In most applications, weight reduction is an important goal. By minimizing the total weight of a product, significant performance increases (as well as cost reduction) can be achieved. In general, minimizing weight without sacrificing other performance aspects (e.g. strength) is a common goal for most products.

The computation of a product’s total weight is simple. Although the actual weight of each shot can vary because the molded resin density varies throughout the part due to processing conditions, the nominal part weight can easily be calculated from its volume and

the resin's average density. Hence, the nominal part weight will be used as PA 1. This value can be instantaneously and accurately be automatically calculated from the CAD file of the assembly. For MMM and SMM&A, the total product weight is the sum of both parts A and B, and any fasteners/adhesives. Most popular CAD systems will output the total weight of an assembly given the materials and/or densities of the components. We will use ounces as our measurement units for weight.

Weight is a valid PA because weight minimization is a common goal across all product classes. It is a proven performance measurement, and one that is calculated with relative ease.

4.2.2 – Performance Aspect 2: Interface Strength

The term “strength” can refer to a wide range of physical characteristics defining how well an object can sustain loads and moments. There are many material properties and corresponding physical tests that can be used to form some measure of the strength of a component or assembly.

4.2.2.1 – Definition of Interface Strength

Here we will use the strength of the interface as our PA; that is, how hard it is to separate components A and B at their mutual interface. It should be noted that here, the definition of an interface will be loosened to include any section on the assembly where the separate materials meet, whether there is microscopic bonding or not. This way, articulated parts such as hinges or joints can have a strength PA associated with them.

Interface separation strength was chosen as a PA to represent strength since it is relatively straightforward and universal for the type of assemblies under analysis. This is because all two-material assemblies possess an interface, and separation is a defining and possible failure mode for two-material assemblies. While fracture of either or both materials

is also a possible failure mode, interface separation is probably more likely (unless the interface is optimally designed) and is a defining characteristic of assemblies. Regardless, the strength test should allow for all possible failure modes. Furthermore, this PA was chosen to coincide with the physical tests commonly used in industry to characterize the strength of various material interfaces. Hence, interface strength will be defined as the force or moment required to produce one of the following three failure modes:

- 1) Complete separation of the components A and B along their common interface (“mode AB”)
- 2) Fracture of component A (“mode A”)
- 3) Fracture of component B (“mode B”)

Although there are actually five possible types of failure mechanisms, only two mechanisms (embodied in the three failure modes listed above) are sufficient to characterize strength for the purposes of this model. This is based off observance of typical failed multi-material assembly specimens.

4.2.2.2 – Types of Interface Strength Tests

Like all other measures of strength, interface strength could be characterized by a number of different attributes that define how well the interface performs under a particular loading scenario. Typically, the interface could be pulled apart (tension), or twisted apart (torsion). These two types of tests, among others, are valid strength attributes, but we will focus on only tensile and torsional forces here for the sake of brevity. This is because in industry tests, shear and normal strength are the most commonly-tested attributes. The model could quite easily be adapted to include other strength tests.

In addition to specifying the types of strength tests to use, the appropriate method of conducting such tests must also be defined. That is, the nature and directions of loadings and the type and location of restraints must be specified for each type of test.

Unfortunately, it can be quite difficult to define a set of appropriate physical tests that can be universally applied to all types of assemblies, regardless of geometry or intended functionality. As with most physical tests or finite element simulations, the appropriate set of testing conditions should be chosen based on the product's structure as well as the expected conditions it will experience under normal use.

These conditions are typically chosen based on common sense and experience. For example, although a steel bolt could theoretically be loaded in an infinite number of arbitrary directions, tensile testing is usually conducted parallel to the bolt's axis, because this is the type of loading it would normally experience. Similar reasoning should be used to determine the appropriate loading conditions for plastic assemblies. For example, when tensile testing the hinge box of Fig. 3.3, it seems reasonable to assume that the assembly would first break somewhere along the hinge. Therefore, a valid tensile test would attempt to pull the lid apart from the base by loading the lid parallel to its surface (and resultantly intersecting the hinge's center), as shown below in Fig. 4.1.

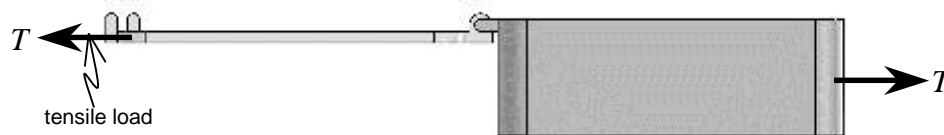


Figure 4.1 – One appropriate tensile loading scenario for the hinge box

It is highly recommended that each assembly be carefully analyzed and assigned an appropriate set of physical tests which are specifically catered to the form and function of the product. However, a set of universal physical tests will next be prescribed for the sake of consistency as well as the relative comparison purposes of this model.

4.2.2.3 – Prescribed Loadings and Constraints

The model will take advantage of the way the products are assembled to establish the proper loading directions and restraints. In essence, the loads will be applied in a direction

coinciding with assembly direction. In SMM&A, one component is usually inserted into another fixed component along a single direction. This insertion vector will be used as the primary loading direction for the SMM&A variant. For MMM, although there is no actual assembly, the nature of rotary platen MSM generally causes one material to be stacked directly on top of the other during the injection process. This direction, the mold's opening direction, will be used as the primary loading direction for the MMM variant. It should be noted that while the directions chosen for each variant could be different, in general, they will be identical, due to the geometric similarity between variants. For example, both hinge box variants have the same basic geometry, so they could be tested using the same loading directions. Furthermore, the same direction will be used to represent both the resultant tensile and torsional loads. Torsional loads are caused by moments which are uniquely defined by a vector perpendicular to the plane of rotation using the right hand rule. The moment vector will hence be collinear with the tension force vector.

Instead of assigning restraints (e.g. fixed surfaces or edges), the assemblies will be considered unrestrained with equal and opposite loadings. That is, the same forces will be applied in opposing directions on parts A and B to keep the entire assembly fixed in space.

Fig. 4.2 shows two examples of choosing the proper loading direction based on the mold opening direction and insertion direction. It can be seen that the chosen loading directions are the most natural ones for the separation of the two parts. This is simply a result of the fact that they are put together along these same directions. While the figure only shows resultant tensile load pairs (equal and opposite), it should be noted that the loading would actually be manifested as a distributed loading over the entire exposed surfaces of the parts. These surface stresses are omitted from the figure for clarity.

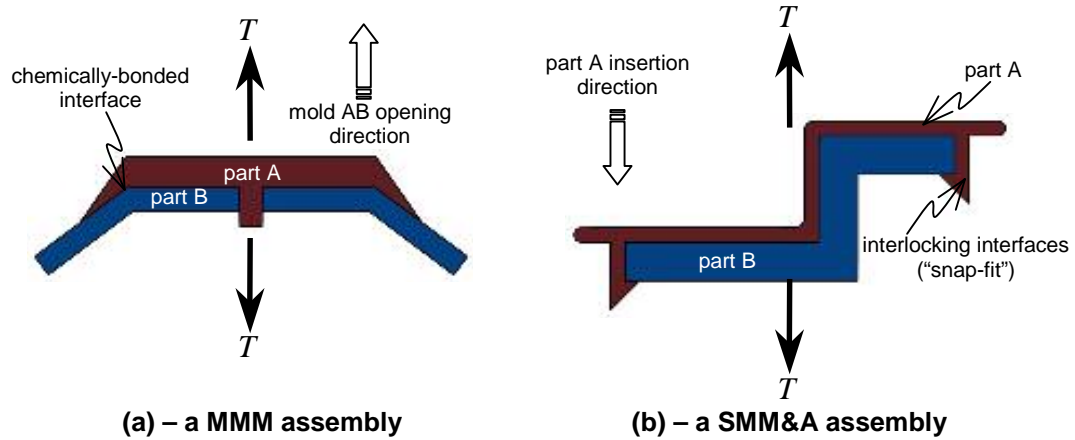


Figure 4.2 – Examples of determining loading directions

The resultant load vector for a torsional force would look the same as that for the tensile loading. For the examples of Fig. 4.2, the resultant moment vectors would also be vertical, and the resulting shear stress would tend to distort the part surfaces tangentially (in a horizontal circular path perpendicular to the page).

4.2.2.4 – Conducting the Strength Tests

Actually conducting tensile and torsional tests on manufactured or prototyped assemblies would be physically difficult, cost prohibitive, and most importantly, it would negate the purpose of the model, which is to provide designers with performance estimates early on in the product development stages. Fortunately, computational mechanics allows designers to test their ideas before they are ever produced. Most CAD packages offer comprehensive finite element analysis (FEA) plug-ins that allow a range of physical testing on single parts or entire assemblies.

This model requires the use “virtual testing” through the use of such FEA packages to determine the tensile and torsional strength of the assemblies under comparison. It is actually a trivial matter to run the physical simulations on CAD files once the loads and restraints have been appropriately prescribed as discussed above. Unfortunately, most software has trouble accurately modeling either chemical bonds or adhesive bonding, the

former of which is essential in most assemblies produced via MMM. This shortcoming makes it difficult to obtain accurate strength estimates for MM assemblies, which typically possess combination locking and chemical interfaces. Furthermore, it is possible to have purely chemical interfaces, which would result in meaningless strength values of zero from standard FEA simulations which only recognize mechanical locking.

In order to get around this difficulty, interface strength will be broken up into several independent subsidiary PA's rather than attempting to estimate the absolute interface strength. In stead of one load value representing total strength, we will split it into the following six independent PA's:

PA 2a: Tensile strength of the assembly's purely mechanically-locked interface (virtual testing of the actual un-bonded assembly)

PA 2b: Torsional strength of the assembly's purely mechanically-locked interface (virtual testing of the actual un-bonded assembly)

PA 2c: Relative shear strength of a test specimen with a purely chemically-bonded flat interface (physical testing on a representative specimen, value valid for MMM variant only)






PA 2d: Relative peeling strength of a test specimen with a purely chemically-bonded flat interface (physical testing on a representative specimen, value valid for MMM variant only)

PA 2e (optional): Relative tensile separation strength of a test specimen with a purely chemically-bonded flat interface (physical testing on a representative specimen, value valid for MMM variant only)

PA 2f (optional): Relative torsional separation strength of a test specimen with a purely chemically-bonded flat interface (physical testing on a representative specimen, value valid for MMM variant only)

Of the above six PA's, the first two are determined through FEA simulations, while the second two (and if necessary, the optional remaining two) are determined through actual physical testing on standardized specimens. Although physical testing on the actual assemblies is cost and time prohibitive, testing of standard specimens is straightforward as their molds should be readily available. All that is required is a quick molding run using the desired resin combinations on the existing MS molds for making the test specimens.

The first two PA's measure the specific mechanical strength of the interface, which depends solely on its geometry. The remaining four PA's measure the generic adhesion strength between the two materials. This strength is based solely on the polymers' chemical compatibility as well as the resin processing conditions used to mold both shots. While the actual chemical bond strength depends on many parameters such as the exact resin grade, the presence of fillers/colorants, and the specific processing conditions, several resin manufacturers have published independent results of material compatibility tests, such as the one shown in Fig. 4.3.

Good Bonding  Poor Bonding  No Bonding  Not Evaluated  

Raw Material	ABS	ASA	CA	EVA	PA 6	PA 6.6	PC	PE-HD	PE-LD	PMMA	POM	PP	PPO	PS-GP	PS-HI	PTMT	TPU	PVC-W	SAN	PSU
ABS	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
ASA	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
CA	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
EVA	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PA 6	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PA 6.6	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PC	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PE-HD	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PE-LD	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PMMA	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
POM	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PP	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PPO	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PS-GP	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PS-HI	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PTMT	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
TPU	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PVC-W	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
SAN	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
PSU	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good

Figure 4.3 – A compatibility matrix for various polymers

(Source: www.multishot.com)

While charts such as the one above are useful as rough guides for determining the applicability of various resin combinations, it is strongly recommended that independent physical testing be conducted on potential resin combinations for the products under analysis. Simple test specimens should be molded under identical processing conditions as the intended product and physically tested to accurately determine the relative interface bonding strengths. Testing methods for PA's 2a through 2f are detailed below.

- PA's 2a and 2b: Tensile/Torsional Mechanical Locking Interface Strengths

These two PA's represent the maximum tensional/torsional load the assembly could sustain before failure, assuming there is no chemical bonding along the interface. These force values are calculated using any 3D FEA package (e.g. Pro/Mechanica, ANSYS, COSMOSWorks, etc...). The tensional and torsional strengths must be determined through separate simulations. The process is typically conducted as follows:

- 1) All of the materials are defined, including those of parts A and B and any fasteners.
- 2) No constraints should be set so that the assembly remains unfixed as described above.
- 3) The loading directions are prescribed as discussed above. The loads can be applied as distributed loadings (surface pressures) over all of the exposed surfaces of the assemblies, so that the resultant load is parallel to either the mold opening direction or the insertion direction (depending on the variant). An example of this type of loading is shown below in Figure 4.4.
- 4) Finally, the simulation is run to obtain either the tensional or torsional locking strength of the assembly [lbs] (PA's 2a and 2b, respectively).

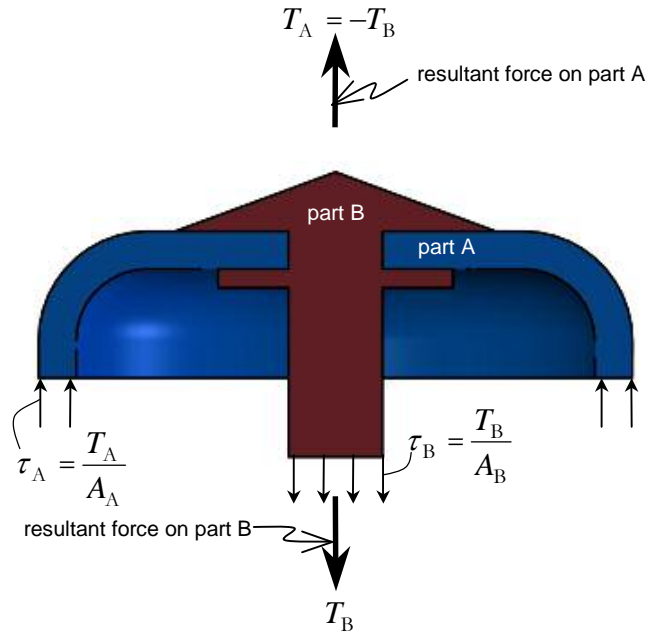


Figure 4.4 – Application of tensile loads as surface forces

It should be noted that currently, standard FEA packages are unable to accurately model bonded assemblies such as the MMM variants under consideration. Therefore, it must be emphasized that the simulations suggested here are only used to indicate the relative locking strength of the assemblies. The actual bonded assemblies may perform quite differently in reality due to complex physical mechanisms such as bonded ligament failure [22].

- PA's 2c and 2d: Shear/Peeling Chemical Interface Strengths

These two strength tests measure how well the chemical interfaces resist shear stresses and peeling, respectively. These are the most commonly-used PA's by the MSM industry. The physical tests are conducted on simple two-shot specimens, which are shown below in Fig. 4.5:

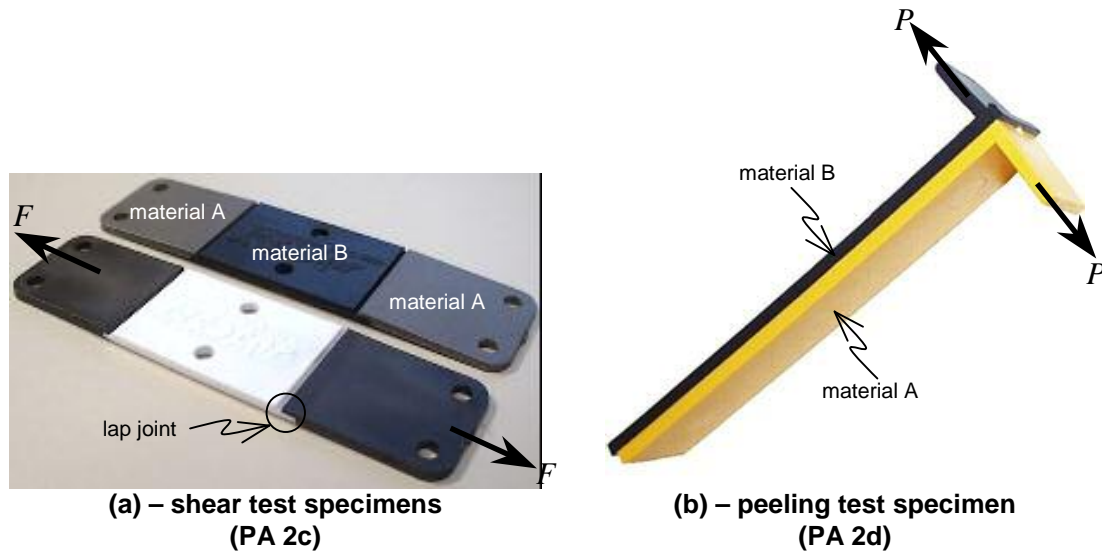


Figure 4.5 – Two types of physical testing specimens

(Source: [Multishot™](#))

The shear (lap-joint) test specimen (Fig. 4.5a) is loaded with an increasing tensile force until a critical failure load, $F = F_c$, at which the two materials separate along the flat interface. The peeling test specimen (Fig. 4.5b) is loaded with a tensile force perpendicular to the flat interface until a critical failure load, $P = P_c$, at which the materials begins to peel apart. This load is then increased until total separation of the interface. Both PA 2c and 2d can be uniquely defined by their corresponding failure loads, F_c and P_c [lbs], respectively. The actual dimensions of the test specimens is unimportant, as long as they are consistent throughout all tests and feasibly made using the same MS equipment that would produce the actual assemblies.

- PA's 2e and 2f: Tensile/Torsional Chemical Interface Strengths

While some may argue that the two physical tests specimens discussed above are adequate to completely determine two materials' compatibility, an optional third type of test specimen is proposed in order to determine the purely tensional or torsional chemical interface strength. These optional tests are recommended in order to more closely match

the loading conditions prescribed in the FEA simulations. The specimen geometry, as illustrated in Fig. 4.6, consists of simple circular interfaces which will be pulled apart or twisted apart from pure tensional or torsional loads.

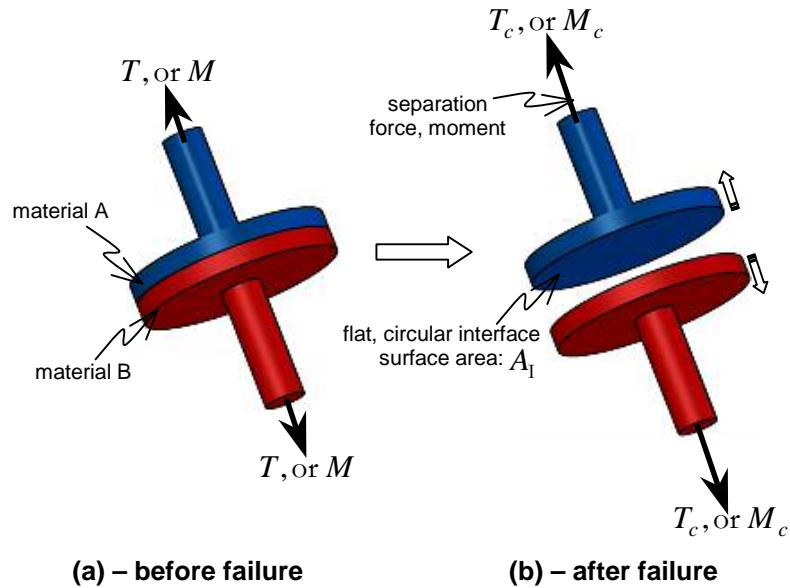


Figure 4.6 – optional testing specimen geometry (PA's 2e and 2f)

As with the previous two test specimens, the third test specimen can be used to determine measures for PA's 2e and 2f. These PA's are uniquely defined by the failure loads T_c and M_c , respectively.

4.2.2.5 – Validity of Performance Aspect 2

The tests recommended above should yield valid measures of relative strength between assemblies as they are just expanded forms of tests proven in the MS industry. Both the FEA simulations and standardized tests are common methods of evaluating strength of plastic components used today.

The methodology for testing interface strength as well suggested optional tests comes directly from experimental results of interfacial strength testing [22]. MMO's were molded with various interface geometries and bonding characteristics and then destroyed via

tensile testing and analyzed using digital image correlation (DIC) in order to understand the fundamental physics behind MMO interface separation and/or component fracture.

4.2.3 – Performance Aspect 3: Assembly Clearance Tolerances

In any assembly designed to have some form of relative movement between components, the precision and ease of this movement becomes an important performance issue. Here, PA 3 will refer to the combined relative accuracy between moving components in an assembly. If a product’s design requires no relative component movement, then PA 3 is irrelevant and does not need to be measured. An example of such a product is any one that has a fixed soft-touch grip (e.g. toothbrush or power tool housings). On the other hand, for assemblies with features such as hinges or sliding tracks, PA 3 becomes a very important quantity. For this model, it is assumed that if relative movement is desired, then no bonding will occur between separate shots in the MMM variant. If bonding did occur, relative movement would not be possible. The definition and measurement of PA 3 will be detailed below.

4.2.3.1 – Definition of Assembly Clearance Tolerances

Assembly accuracy could be measured in many relevant ways. Here, a straightforward approach involving clearances will be used. PA 3 is defined as the sum of the variations in clearances for all of the critical dimensions of an assembly. That is, each assembly dimension requiring a specified clearance will have an associated range of actual clearances when manufactured. These ranges, or “clearance bands” will be computed for each applicable dimension and summed to arrive at a value for PA 3.

In its simplest definition, a clearance is a gap that allows relative movement between two components in an assembly. For this model, only linear dimensions will be considered, so clearances (and the resulting PA 3) can be measured in units of length. Depending on the

exact interface geometry, at least one or more dimensions would be considered as critical clearances for the assembly to function as intended. Fig. 4.7 below illustrates identifying critical clearance dimensions between components.

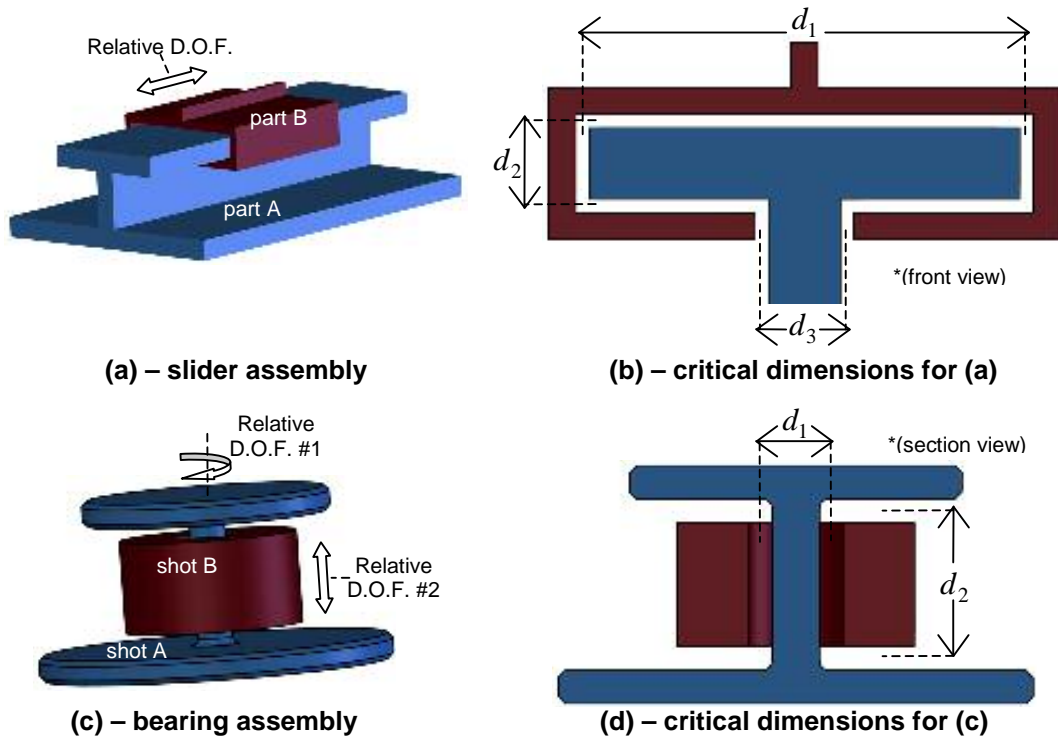


Figure 4.7 – Examples of determining critical clearance dimensions

The first example (Fig. 4.7a) involves an assembly with a sliding mechanism. Although there is only one specified degree of freedom between parts A and B, there are actually three critical dimensions (d_1, d_2, d_3 ; Fig. 4.7b) because of the geometry. Each one of these dimensions has an associated clearance value that must be within a specified allowable range for the assembly to function as desired (i.e. slide smoothly). The second example (Fig. 4.7c) involves an assembly with a bearing joint. There are two degrees of freedom (rotation, and up-down translation) and two associated critical dimensions. Each assembly has its own specific critical dimensions, and these should readily be identified from the CAD files.

Now that the topic of critical dimensions has been discussed, clearance variances (PA 3) can be defined. Each critical dimensions, d_i , has an associated clearance value, c_i , that measures the gap size between components at the location under consideration. This clearance value must be within an acceptable specified clearance band for the assembly to function properly ($c_{i_{\min}} \leq c_i \leq c_{i_{\max}}$). Because the desired (or “nominal”) value for each clearance is specified, the clearance variation can be defined as the deviation between the specified clearance and the actual clearance achieved by the manufacturing process:

$$(\Delta_c)_i \equiv c_i - c_i^* \quad (4.1)$$

Eq. 4.1 states that the associated clearance variation, $(\Delta_c)_i$, of the i^{th} critical dimension (d_i) is the difference between the actual clearance, c_i , and the designers’ specified clearance, c_i^* . It is a measure of how difficult it is to keep the dimension within the specified clearance band. PA 3, measured in inches, is simply the sum of these individual clearance variations:

$$\text{PA 3: } \Delta_c = \sum_{i=1}^{i=n_{\text{crit}}} (\Delta_c)_i \quad (4.2)$$

Where n_{crit} is the number of critical dimensions in the assembly. The mechanisms by which these clearance variations are formed are discussed below.

4.2.3.2 – Causes for Clearance Variations

As with all manufacturing processes, injection molding produces parts with dimensional variations. These variations are caused by fluctuations in the process parameters, and more importantly, part shrinkage. It is important for the designer to understand shrinkage, and the tolerances realistically achievable for both process variants.

Shrinkage is the tendency of plastic parts to become smaller during cooling. As the resin solidifies and become denser, the part's dimensions will start to decrease by a certain percentage. This occurs for all dimensions and along all directions, except where prevented by the mold. A simple example of part shrinkage is illustrated below in Fig. 4.8:

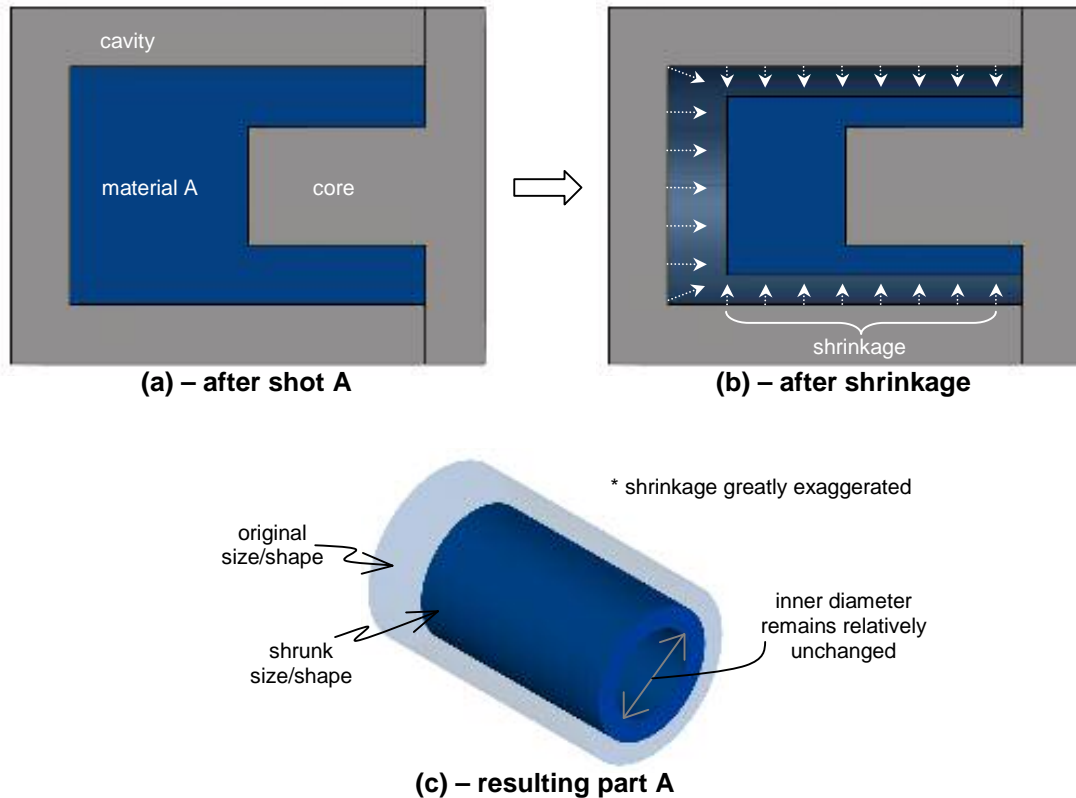


Figure 4.8 – Example of part shrinkage

The example part in Fig. 4.8 is a simple cylindrical pin with an internal blind hole produced via a protrusion in the mold's core. Right after injection of material A, the resin fills the cavity completely and takes on its shape. During the cooling phase, the resin tends to shrink away from the cavity and onto the core. Depending on how soon the part is ejected, the hole may or may not shrink as well. However, compared to the cavity-side shrinkage (which cannot really be prevented) the hole shrinkage should be small.

The effect of shrinkage is that the part dimensions will deviate from the mold's dimensions. A further complication is that the actual shrinkage percentage can vary from

shot to shot. Part shrinkages can have unexpected results when attempting to assemble molded parts or perform subsequent shots (in MMM only). This is what leads to clearance variations. The actual values of these variations depend highly on the process variant and are discussed below.

4.2.3.3 – Measurement of Clearance Variations

Through Eq. 4.1, clearance variations are specified by two values: 1) the desired or nominal clearance, and 2) the clearance variation achieved. Because the desired values are determined by the designers, measurement of the clearance variation only involves the prediction of the actual clearances produced by the process variant under consideration. This requires a thorough understanding of both process variants, and the associated shrinkage characteristics to consider. Specifically, each process variant has its own set of dimensional values which can or cannot be specified and or/controlled as a result of shrinkage.

An example of an assembly with one critical clearance dimension is illustrated below in Fig. 4.9. It emphasizes the differences between SMM&A and MMM and derives the method for computing the associated clearance variations. The SMM&A variant involves molding both components separately and then attempting to insert the pin B into hole A. The MMM variant involves molding the hole A and then molding pin B directly into the cavity in material A. Pin B would then shrink away from the cavity and form a clearance between components.

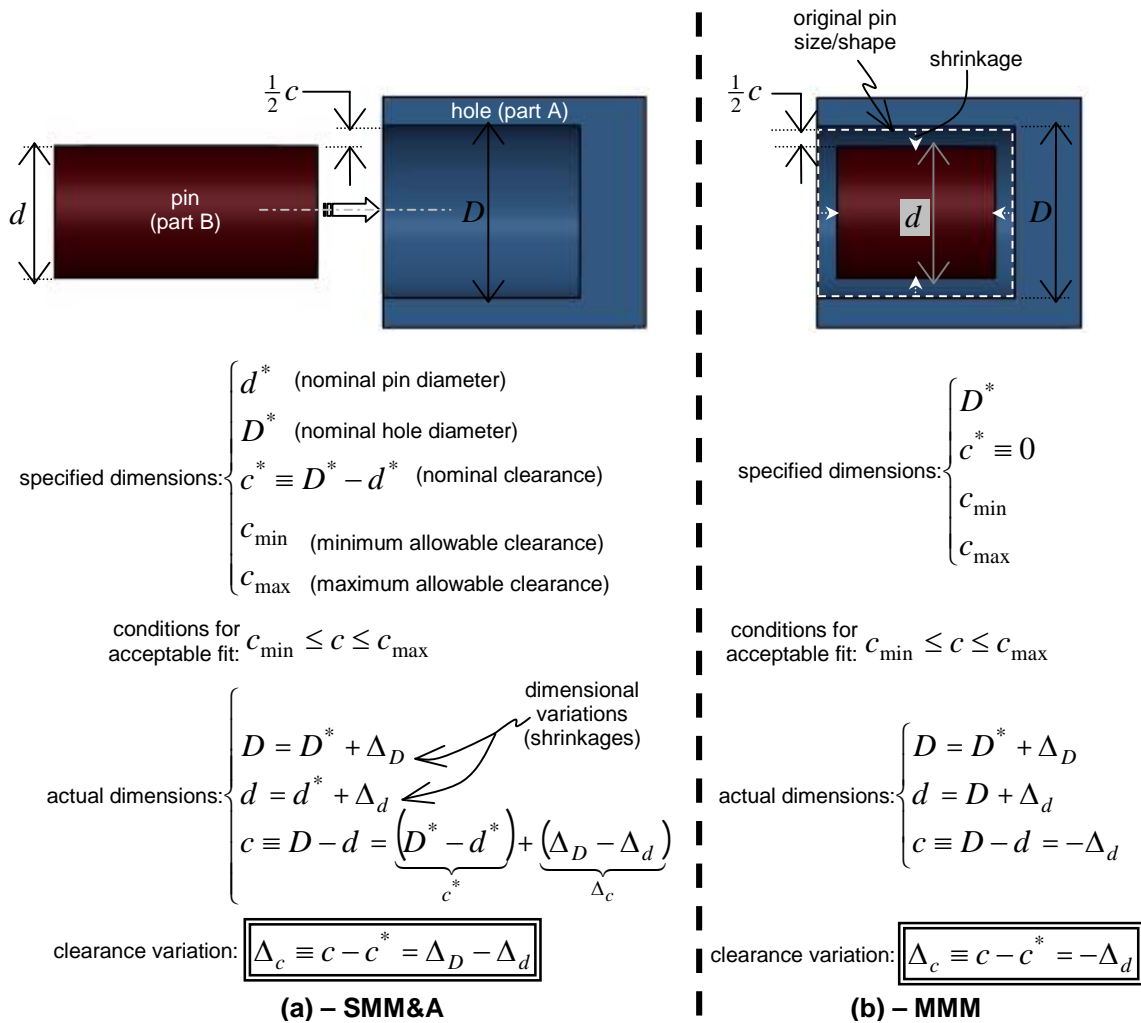


Figure 4.9 – Notations for determining assembly accuracy

Although the above example involves a simple cylindrical assembly with only one critical dimension, the same reasoning could be used for any geometry, and the result would be the same. The key difference to note is:

- 1) The SMM&A variant involves two dimensions to specify (D^* and d^*) along with associated actual dimensions (D and d) which must be sufficiently controlled
- 2) The MMM variant involves only one specified dimension (D^*). Resultantly, only the corresponding actual dimension (D) needs controlling, as the second dimension (d) is entirely dependent on the first and will always shrink to form a clearance.

In essence, the SMM&A variant involves assembly of two unrelated components with independent dimensional uncertainties, whereas the MMM variant involves two directly-related components and only one real dimensional uncertainty.

The end result of this difference is that for SMM&A, the clearance variation is controlled by two independent and uncertain variables (Δ_D and Δ_d) where the clearance variation for MMM is only controlled by one variable (Δ_d). These dimensional variations are directly caused by the shrinkages of their respective material. This difference usually results in the MMM variant having easier-to-meet clearance requirements. If values for Δ_D and Δ_d are known, PA 3 can be calculated explicitly.

Unfortunately, it may not be possible to predict the exact dimensional variations because shrinkage can vary from shot to shot. However, it is customary to predict a certain percentage of shrinkage based on the material and nominal processing conditions. These numbers can then be used as representative shrinkage values and then PA 3 can be estimated for relative comparison purposes.

As long as the “hole” is molded before the “pin”, this same reasoning can be used for most assembly geometries to determine PA 3. While each specific assembly must be analyzed on a case-by-case basis, the general analysis will be similar. The end result is usually that the MMM variant will provide a smaller clearance variation, and hence be more desirable in this respect.

4.2.3.4 – Validity of Performance Aspect 3

The validity of PA was confirmed through preliminary shrinkage tests conducted at the University of Maryland’s Manufacturing Automation Lab (MAL). Assembly clearance tests were conducted on MMO’s molded in various shot sequences. In general, it was found that if a pin is molded inside of a hole using incompatible materials, the pin will shrink away

from the hole and provide a clearance fit. These types of fits proved to exhibit equal or better clearances and freedom of movement when compared to assemblies composed of separately-molded components.

4.2.4 – Performance Aspect 4: Aesthetics and Ergonomics

While both aesthetics and ergonomics are subjective concepts that cannot be universally measured, we can define several quantifiable performance aspects that give us some relative measure of these qualities. For this model, aesthetics is defined as a measure of how attractive a product appears, and ergonomics is how well a product feels when used/held.

Although there are potentially many arbitrary ways to define PA's for quantifying aesthetics and ergonomics, this model uses two simple and measurable characteristics unique to injection molding processes. Specifically, SMM quality evaluation models were extended to MMM to correctly predict defects encountered in the MS industry.

Two important types of defects, part flash and crush, will be used to define ergonomic and aesthetic PA's, respectively. These phenomena will be defined and their measurement procedures will be detailed below.

4.2.4.1 – PA 4a: Flash

The phenomenon of part flash will be used as the PA for measuring the relative ergonomic quality of molded assemblies.

- **Definition of Flash**

Flash is defined as the undesirable formation of superfluous strips of material on a molded part's surfaces and/or edges. This is a relevant measure of ergonomics because flash is generally thin and sharp, causing discomfort or even scratches/cuts when held or otherwise interfaced with by a human. In general, the possibility of flash occurrence should

be minimized by the product's design, or it will have to be manually removed after molding (i.e. through grinding or filing). Fig. 4.10 shows a photograph of a MS part where the second material shot has flashed over top of the first:

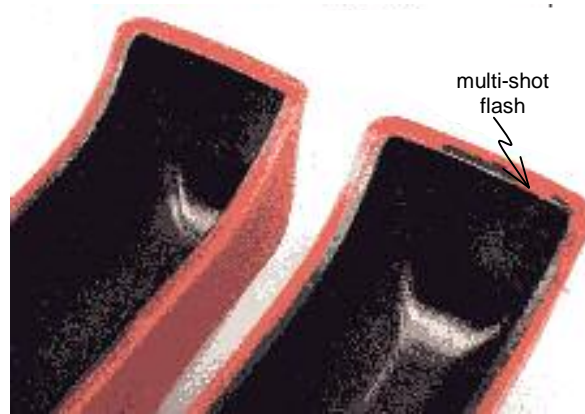


Figure 4.10 – Photo of multi-shot flash
(Source: [42])

- Formation of Flash

Flash occurs when some of the molten resin escapes the intended mold cavity through thin gaps in the mold, usually where the core and cavity halves meet. The resin then solidifies in the shape of the gap, and the part is ejected with these unwanted thin plastic strips attached. An example of where flash can form in a single-material mold is illustrated in Fig. 4.11 below:

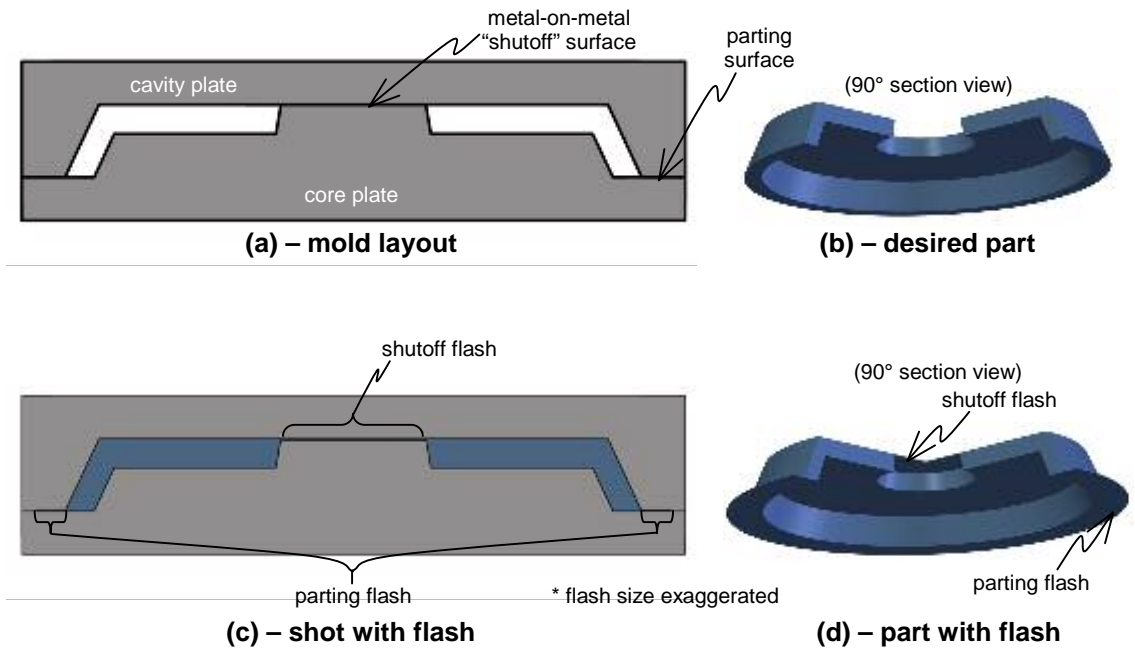


Figure 4.11 – Example of flash forming in a single-material mold

Fig. 4.11 shows how flash can form on surfaces where the mold halves meet, including the parting surface and any core-cavity shutoff surfaces. In this specific example, the flash occurs at the bottom outside edge of the part (“parting flash”) and at the top of the through hole on the top surface of the part (“shutoff flash”).

In addition to flash formed at metal-on-metal contact surfaces, MSM allows for the unique occurrence of flash at metal-on-plastic contact surfaces. As with metal shutoff flash, plastic shutoff (or “MS”) flash can occur anywhere the mold metal meets (“shuts off”) on plastic, as illustrated in Fig. 4.12 below:

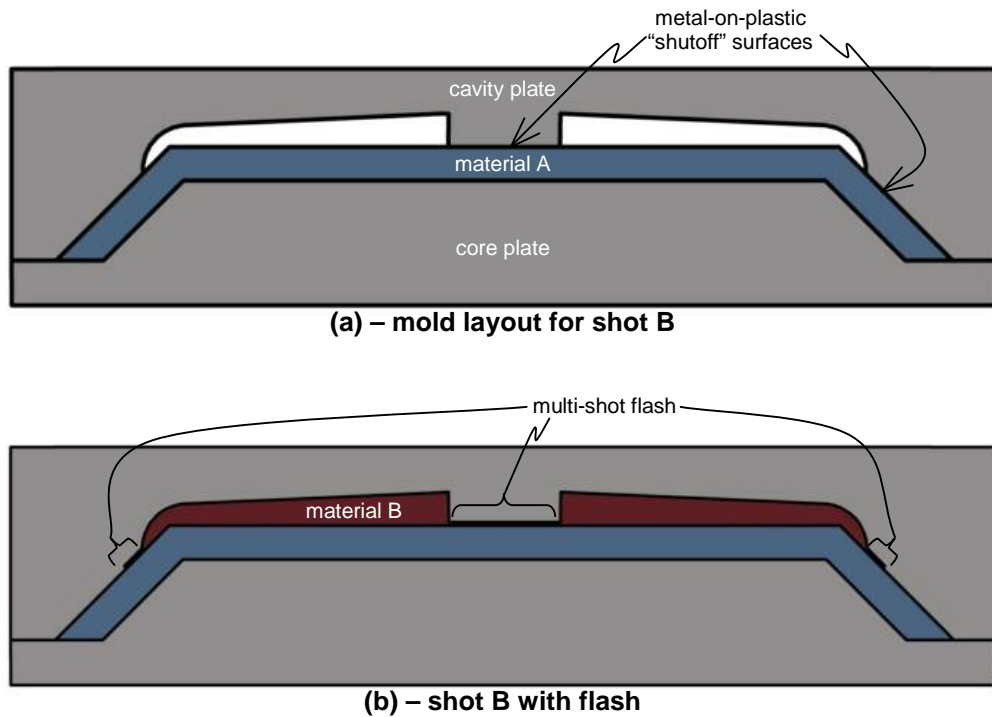


Figure 4.12 – Example of flash forming in a multi-shot mold

In the specific example above, the flash could form along the flat, slanted outer surfaces of shot A and at the bottom of the shutoff hole on the top of the assembly. Depending on the type of surface on which the flash forms, three distinct types of flash can be identified: 1) parting surface flash, 2) shutoff flash, and 3) MS flash.

Note that although both single-material flashes and MS flash form via very similar mechanisms, the end results are slightly different. That is, single-material flash usually forms on outside edges of the part whereas MS flash typically forms along the surface of previous materials. For example, the parting flash in Fig. 4.11 forms on the outside edge of the part directed away from the surface, whereas the MS flash (material B) of Fig. 4.12 forms along the surface of material A. This distinction between single-material and MS flash can cause significant differences in the appearance and/or quality of the final assembly. For example, it would be much easier to remove exterior parting line flash rather than MS flash adhered to

a surface. The former might require only simple cutting or grinding whereas the latter might require careful peeling.

For this model, it is assumed that MS flash only forms when there is an actual gap between the mold metal and the previous plastic shot. In other words, if the mold metal penetrates the plastic surface during shutoff, it is assumed there will be no flash between the mold and the plastic due to a tight seal being formed. This simplification allows the two phenomenon of MS flash and crush (discussed in Section 4.2.4.1) to be clearly distinguished and measured as separate PA's.

The occurrence of flash depends on a variety of factors such as mold accuracy/tolerances, resin properties, and processing parameters. It is difficult to predict when and to what extent flash will happen. Furthermore, for a particular molding run, flash can form on some parts and not on others (due to variations in the processing variables). Although it is nearly impossible to predict when/where flash will happen on individual parts in a batch, locations of probable flashing can at least be identified. Therefore, all locations where the formation of flash is *possible* will be used to measure PA 4a as discussed below.

- Measurement of Flash

As described above, flash can form at three different types of locations (e.g. at parting surfaces). All three types of flash are undesirable to some degree, depending on their exact location on the parts. Therefore, it becomes important to form a PA that measures the effect of flash, weighted based on the relative importance of its location. The most obvious way to measure flash is based on its size. Because flash is a geometric phenomenon, it can be uniquely defined by its dimensions, which include its thickness, width, and length. More specifically, only the total perimetric length of flash will be measured. This is because while width and height of flash may also be considered important, it is impossible to predict their

values as they can vary from shot to shot. Therefore, only the flash length will be considered for PA 4a. Specifically, PA 4a (measured in inches) is defined as the total length of flash on both parts A and B.

The length of a particular piece of flash can be defined as the perimeter of the mold gap in which it could potentially form. A simple example of a MS assembly with two types of flash is illustrated in Fig. 4.13 below. The length of the parting flash, l_1 , is the arc length of the semi-circular gap that forms the parting line between mold halves. The length of the MS flash, l_2 , is the straight length of the edge formed where cavity B contacts the surface of material A.

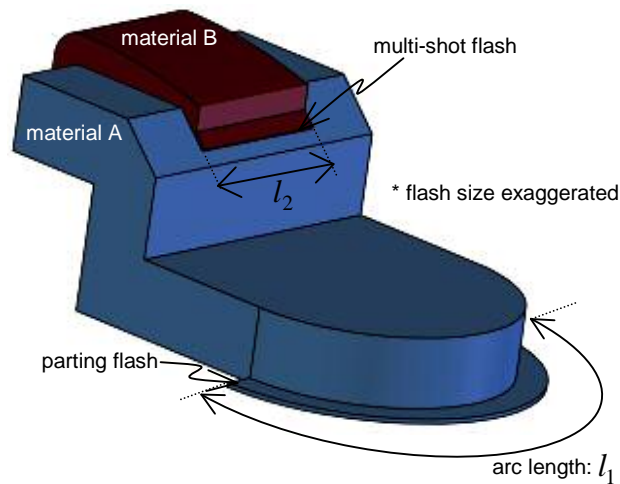


Figure 4.13 – Determining flash lengths

Using reasoning similar to that of the specific example above, the lengths of the various flash pieces can be calculated for any generic SMM&A or MMM product. A simple analysis of the part and mold CAD models will yield the perimetric length of each mold gap (parting line or shutoff edge) which equals the flash length. Once the individual lengths of each flash piece for both parts are calculated, PA 4a can be formed as a weighted sum of these lengths.

It is recommended that some sort of appropriate weighting scheme be used to assign relative importance to each pieces of flash based on their location. For example, if a certain piece of flash is somewhere on the part where it won't be seen or come into contact with, it wouldn't have much effect on the ergonomics, and could be weighted as unimportant by multiplying it by a small number (or even zero). On the other hand, flash occurring at a crucial location such as a handle would seriously affect the ergonomics, so it should be weighted by some appropriate factor (at least greater than unity). The exact weighting scheme would depend on how important the designer deems the effect of each flash piece.

4.2.4.2 – PA 4b: Crush

The phenomenon of part crush will be used as the PA for measuring the relative aesthetic quality of molded assemblies.

- Definition of Crush

Crush is a phenomenon unique to MMM caused by mold metal impinging upon (“crushing”) a plastic surface formed in a previous shot. The mechanism is very similar to MS flash except that there is no gap between the metal and plastic. Rather, the mold partially penetrates the plastic during shutoff, causing a visible mark on the part surface. A photo of a MS product with crush is shown in Fig. 4.14 below:



Figure 4.14 – An example of multi-shot crush
(Source: [42])

Fig. 4.14 shows a 2-material product (power tool housing) where the mold for the second shot has formed an indentation on the surface of the first shot. This discontinuity is

visually unappealing and can cause discomfort when gripped at the handle. Fig. 4.15 below schematically illustrates MS crush:

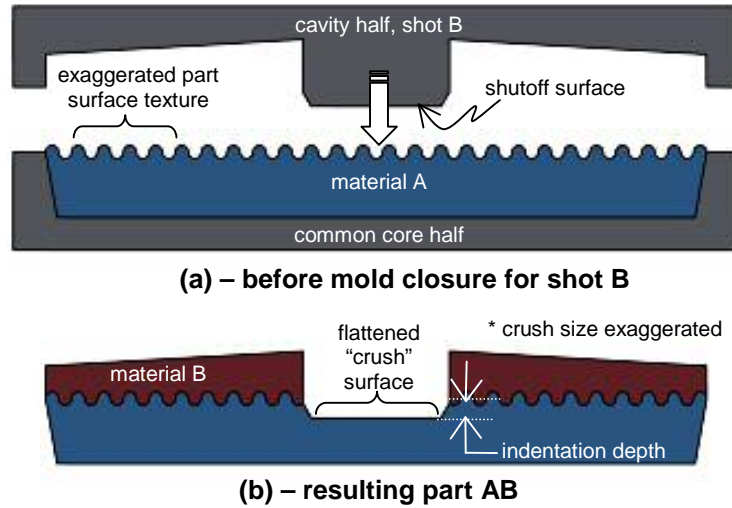


Figure 4.15 – Schematic of multi-shot crush

From Fig. 4.15 two potentially undesirable effects of crush are identifiable on the surface of part A: 1) a flattening of the texture or altering/marring the finish, and 2) an indentation or recess. In many cases such discontinuities caused by crush are considered visual defects that decrease the aesthetic quality of the product. Therefore, quantifying crush is one applicable PA related to aesthetics.

- **Formation of Crush**

Crush is formed any time the metal-on-plastic shutoff is designed such that the mold metal partially penetrates the plastic surface. This is opposite the situation of MS flash, where there is a slight gap between the mold and plastic. Obviously the extent of the crush depends on how deep the shutoff penetrates the plastic.

Wherever possible, crush should be minimized. There are several unique DFM rules that can be used to reduce or hide the occurrence of crush, but they will not be discussed here (see [42] for some crush design tips). Regardless, the mold-plastic shutoff interface specified in the product’s design completely determines the location and extent of crush.

Like flash, crush is another phenomenon that can be easily measured based on the mold geometry. Crush is characterized by the depth and surface area over which it occurs. The depth of crush can vary from shot to shot based on process variations. Because of this, and the fact that the exact depth is relatively unimportant in terms of visual appearance, only the surface area of the crush will be used in the measurement of the aesthetic PA. Therefore, PA 4b is defined as the total surface area over which crush occurs (measured in square inches).

- Measurement of Crush

Crush only needs to be measured for the MMM variant because, by definition, the crush on SMM&A variants is zero. The total surface area where crush will occur is simple to compute from the CAD models of the parts and cores/cavities. All metal-on-plastic shutoff features must be identified, and their associated surface area is equal to the crush area. The sum of these crushed surface areas is then the value for PA 4b.

4.2.4.2 – Validity of Performance Aspect 4

The two aesthetic/ergonomic measurement models described above represent valid ways to quantify relative performance as they address two of the most common and important types of defects associated with producing plastic parts. These issues have been identified by experts in the field to be two of the major problems in manufacturing quality plastic parts. The measurement techniques described are objective methods for classifying these performance aspects.

4.3 – Summary

In summary, a performance evaluation model was presented for comparing the relative performance of similar assemblies produced using both SMM&A and MMM. Based on consultation with plastic part designers at several SM and MM molders, the following

four PA's were identified as key factors affecting product performance: 1) weight, 2) interface strength, 3) assembly accuracy, and 4) aesthetics and ergonomics. Individual methods for evaluating each of these four quantities were developed. The model was built from simple reasoning and DFM rules for plastic part design.

The model attempts to emphasize the key differences between variants rather than provide absolute accuracy. It is still left up to the designers to choose the better variant based on the results of the four independent PA measurements.

The model is highly simplified and makes use of several assumptions in order to facilitate quick and easy comparisons. Despite these assumptions and simplifications, it should provide a significant basis for process selection purposes.

CHAPTER 5 – CASE STUDIES

This chapter presents the results of two case studies performed on real-world products. The cost estimation and performance evaluation models were applied to two dissimilar examples to illustrate their applicability and scope. Both case studies are summarized below.

5.1 – Case Study I: Knob

5.1.1 – Knob Product Description

The first case study was conducted for a relatively simple and inexpensive product. The chosen assembly was a two-material knob, similar to the trio knobs used in Goodship & Love's Case Study (Section 2.4.2) [24]. The relevant characteristics of the knob are discussed below.

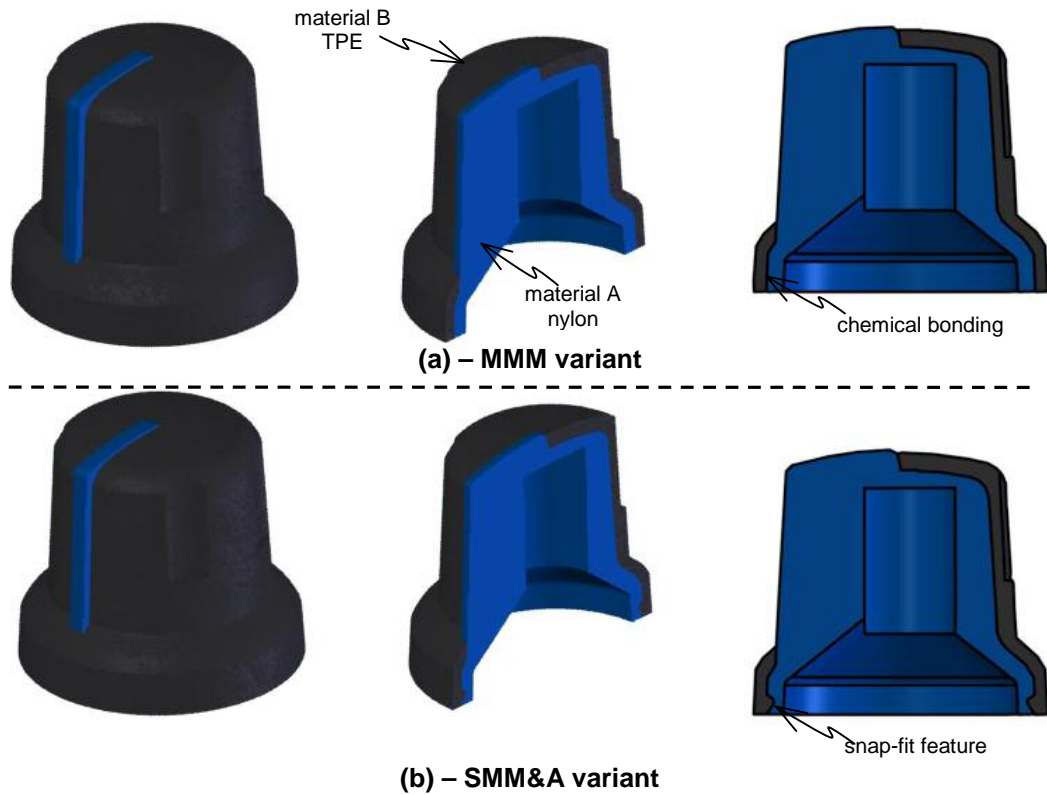


Figure 5.1 - Three rendered views of the knob variants

5.1.1.1 – Functionality

The knob, as illustrated in Figs. 5.1 & 5.2, is a small 2-component assembly used to control various types of electrical devices, including musical equipment such as mixers and recorders. It is designed to be easily manipulated with the fingers, comfortable, and easy to read (in terms of indicating its own angular position).

The knob consists of an inner firm base and an outer compliant sleeve. The colored base provides rigid support and possesses a fin that protrudes through sleeve to indicate the knob's position. The sleeve provides a soft, rubbery surface for interface with the user and is intended to provide both attractive aesthetic and ergonomic qualities.

The base and sleeve are rigidly connected and are not intended to have relative movement between each other. Once the product is assembled, both components are intended to remain attached. Please see Appendix C for more detailed dimensioned drawings of the knobs.

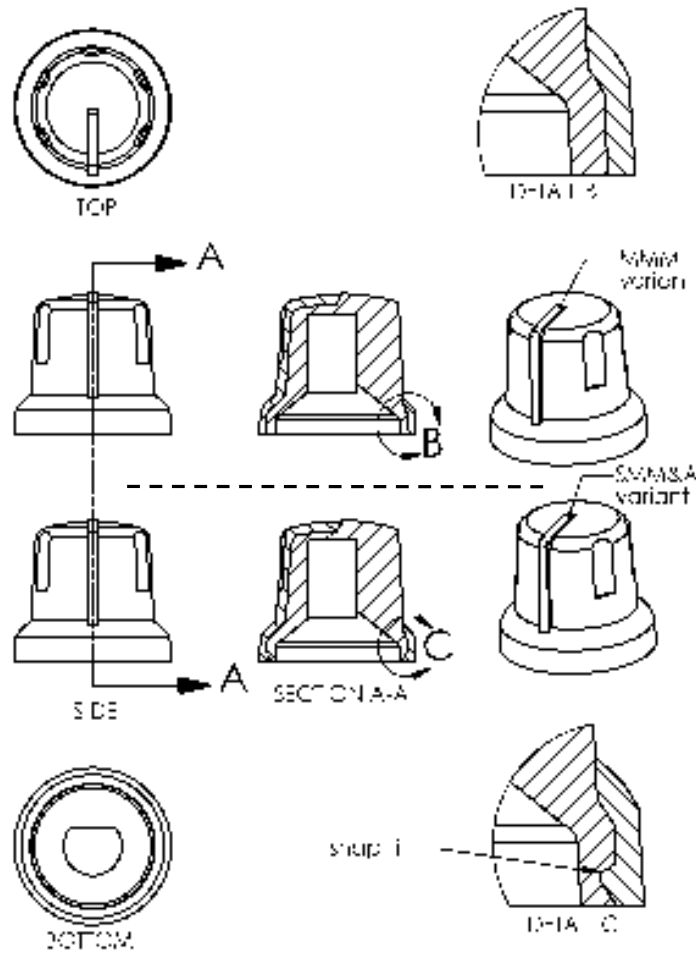


Figure 5.2 - Drawings of the knob variants

5.1.1.2 – Materials

The base (“part A”) is molded out of a generic blue-dyed nylon-6 thermoplastic. This material was chosen because it is quite rigid, and commonly used in knobs. The sleeve (“part B”) is molded out of a generic black thermoplastic elastomer (TPE) to provide a soft, rubbery grip texture. These materials were also chosen because they exhibit strong adhesive bonding when used for MSM, allowing the components in the MMM variant to remain attached.

5.1.1.3 – Comparison of Variants

The only difference between the two variants is in the way the materials are attached. The MMM variant utilizes the strong adhesive tendency of the two materials to form a

chemical bond along the entire contact interface. Because the SMM&A variant cannot take advantage of adhesion (due to assembly after the resins have completely solidified), it utilizes mechanical interlocking to secure the two components together. This is accomplished by a snap-fit feature near the bottom of the knob (see “DETAIL C” of Fig. 5.2). This simple bump allows the pieces to be snapped together during assembly.

5.1.1.4 – Molding Considerations

All four components (parts A and B for both variants) are relatively simple, and hence the required molds and molding operations are simple as well. Because the cavities are small (<.7" diameter), even a 10-cavity mold is relatively small. Since the product design requires no extra tolerancing, polishing, texturing, or side-actions, the molds are relatively inexpensive, requiring small mold bases and minimal machining and cooling channel drilling. It should be noted that although this snap-fit feature results in an undercut in both molds A and B, side actions will not be necessary. This is because both parts can still be ejected from their molds as long as they are still soft enough to slightly deform away from the undercut as they are pushed out by the ejector pins.

Molding such small and simple parts is relatively rapid and straightforward. In terms of labor, only minimal time and effort would need to go into inspection, assembly, and packaging. Furthermore, the required molding equipment would be relatively small and wouldn't require many sophisticated and costly features.

It should be stated (as per the assumption in Section 3.1.3.6) that it is assumed the same mold material will be used, no matter the production quantity. The mold base and tooling cost equations are set to only accommodate one type of mold base (i.e. steel). However, in real industry practice, the chosen mold metal depends on the intended

production quantity, with more expensive and longer-lasting metals used for higher production runs, and cheaper/weaker metals (e.g. aluminum) used for low-volume runs.

5.1.2 – Knob Cost Estimation

All of the various input parameters were collected, where applicable and/or possible, and the cost estimation model was run for the knob. For a list of the input values used, and the MATLAB code, please refer to Appendices A and B, respectively. The plots output from MATLAB are reproduced below in Figs. 5.3 and 5.4:

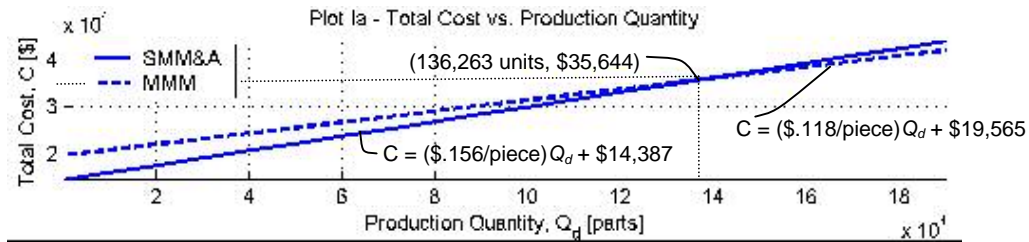


Figure 5.3 - Plot Ia: Total Cost vs. Production Quantity

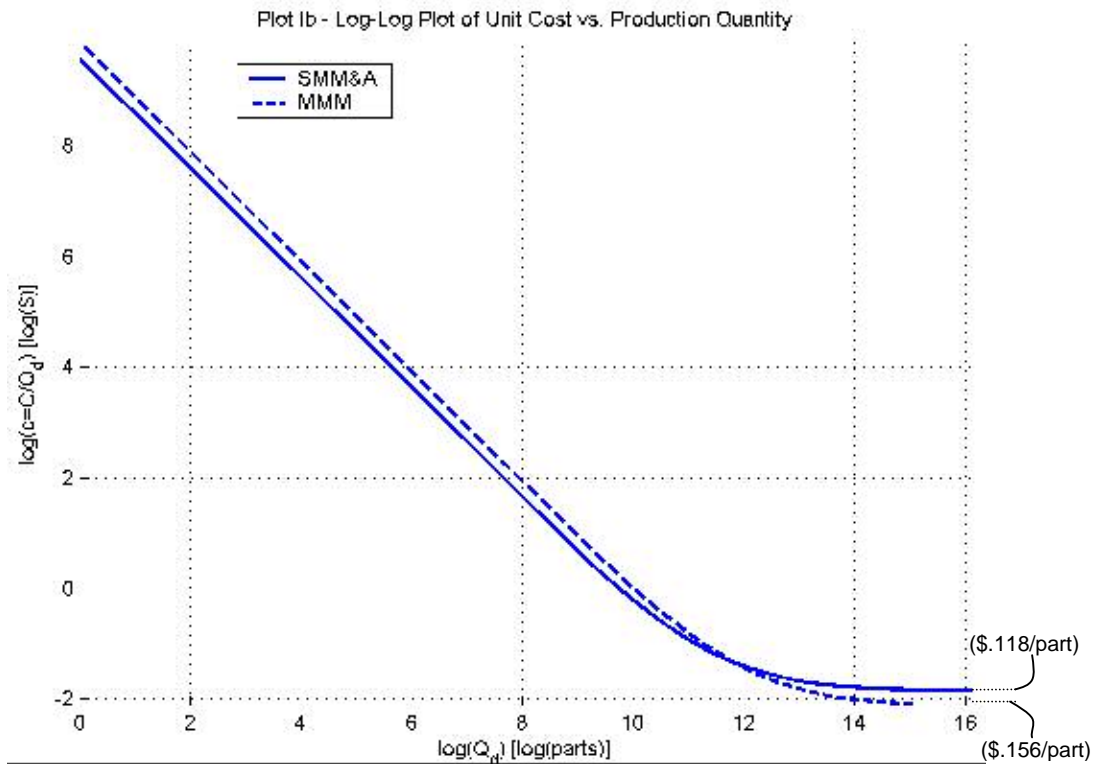


Figure 5.4 - Plot Ib: log-log plot of Unit Cost vs. Production Quantity

Plot Ia shows the total manufacturing cost as a function of desired production quantity for a small domain of Q_d values (1 to 185K parts). The linear C - Q_d equations are displayed next to their respective curves, and the breakeven point (at 136,263 units, and \$35,644) is labeled. As expected, the MMM costs start out higher than SMM&A due to the higher fixed costs due to more expensive tooling. This is manifested as the higher y-intercept value for MMM (\$19,565 compared to \$14,387). However, eventually the SMM&A curve overtakes the MMM curve due to higher per-piece manufacturing costs. This is manifested in the higher slope value for SMM&A (\$.156/piece compared to \$.118/piece). Although there isn't a vast difference in costs between the variants, SMM&A has the cost advantage up until the breakeven point at 136,236 units, where MMM takes over as the cheaper alternative.

Although total cost is an important measure, it is perhaps more instructive to look at the per-piece costs in stead. Plot Ib graphs the unit cost of the knobs, logarithmically-scaled for compactness. It can be seen that both curves follow similar paths until they start to level off near the right side of the graph. This is because at first the unit cost is relatively high, being dominated by the fixed costs of tooling and other capital equipment. As the production quantity increases, these costs are amortized over larger volumes and the unit costs become lower, now being dominated by variable costs such as material and processing costs. Depending on the underlying cost function, the per-piece cost curves start to level off after certain production quantities. To the right of each curve is the final per-piece cost at 10M units. As Q_d approaches infinity, the per-piece cost curves start to level out at the slope of the total cost curves. The SMM&A and MMM variants per-piece costs approach \$.156/piece and \$.118/piece, respectively.

5.1.3 – Knob Performance Evaluation

The model files for the knob and its core and cavity inserts were analyzed to yield values for the performance measures discussed in Chapter 4. The results of these analyses are summarized below.

5.1.3.1 – PA1: Weight

The nominal weight of the knob was computed as the sum of the weights of parts A and B. The individual weights were calculated automatically via SolidWorks' mass properties tool. The results of the analysis are listed below in Table 5.1:

	SMM&A	MMM
Part A weight	.00171 lbs	.00174 lbs
Part B weight	.00081 lbs	.00079 lbs
Total weight	.00252 lbs	.00253 lbs

As evident in Table 5.1, the difference in weight between the variants is negligible, only becoming evident in the hundred-thousandths decimal place. This is because the part volumes are extremely close due to almost identical geometry. The effect of the snap-fit feature in the SMM&A variant is negligible. For all intents and purposes both knobs are both equal in terms of PA1. Furthermore, in the particular intended application for the knobs, weight reduction is unimportant.

5.1.3.2 – PA2: Interface Strength

The knob is not designed to be a load-bearing device, and would rarely experience service loads that would tend to separate the components at the interface. If anything, the knob would be subject to compressive loadings rather than tensile. For this reason, PA2 is deemed unimportant for this product and extensive FEA or experimental tests were not conducted.

However, it should be said that because nylon and the chosen TPE experience strong bonding, the MMM variant would be more difficult to separate than the SMM&A variant, which utilizes weaker mechanical locking. In the same way it is assembled, it would

be possible to pop the sleeve off the base with some effort. If this possible separation is deemed important, than the inseparable MMM variant would have the advantage.

5.1.3.3 – PA3: Assembly Clearances

Because the knob is not designed to have relative motion between the components, this PA is unimportant. However, some qualitative comparisons can be made between the variants regarding the quality of the final assembly. The major difference would be that because there is no bonding along the entire interface in the SMM&A variant, the knob would tend to feel slightly looser than its MMM counterpart. That is, there could be a slight wiggle between the sleeve and base of the SMM&A variant when it is manipulated, whereas in the MMM variant, both components of the knob would feel firmly attached at all times. In this respect, the MMM variant again has an advantage.

5.1.3.4 – PA4a: Flash

The amount of potential flash was measured for both variants through analysis of the part and mold model files. The results for each part are summarized below:

- **SMM&A Variant, Part A**

For part A, the only possible place for flash to form is at the parting line of the mold, where the core and cavity halves meet. The parting line forms the outside bottom circular edge of the part. This is where flash could form, so the edge length defines the total flash for the part. The results of this analysis are shown below in Fig. 5.5:

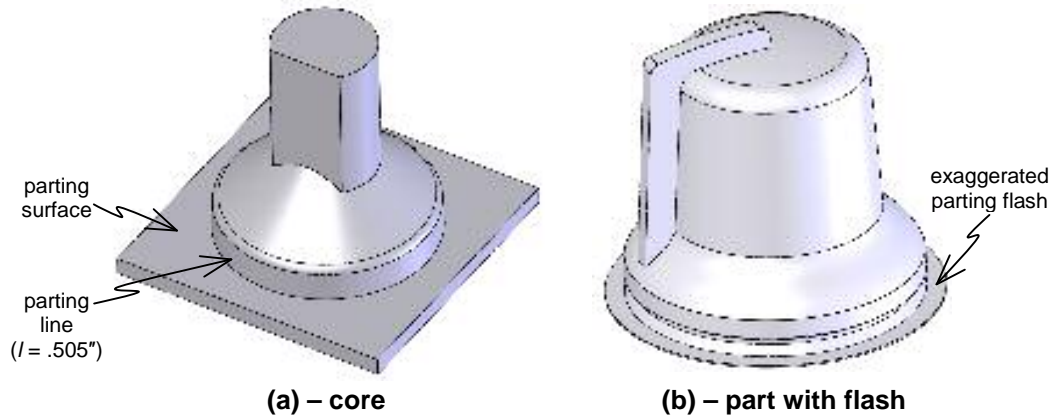


Figure 5.5 - Flash measurement for SMM&A knob, part A

As shown in Fig. 5.5, the total flash length for the SMM&A knob, Part A is .505 inches.

- SMM&A Variant, Part B
 Part B would tend to form flash in the same location as Part A, that is along the outer bottom circular edge of the part. Using similar reasoning as above, the total flash length for the SMM&A knob, Part B is .634 inches.
- MMM Variant, Part A
 The MMM variant of Part A is formed in the exact same manner as the SMM&A variant, so the resulting flash would be the same. Because the parting line is the same length, the total flash length for the MMM knob, Part A is .505 inches.
- MMM Variant, Part B
 The flash formed on Part B of the MMM variant is a little more complex because there would be potential gaps between cavity B and shot A. Therefore, there would be both parting line flash as with the previous three cases, and MS flash along the parting line between cavity B and shot A. This is difficult to demonstrate in a 2D figure, but the measurement of flash for the MMM variant of Part B is shown below in Fig. 5.6:

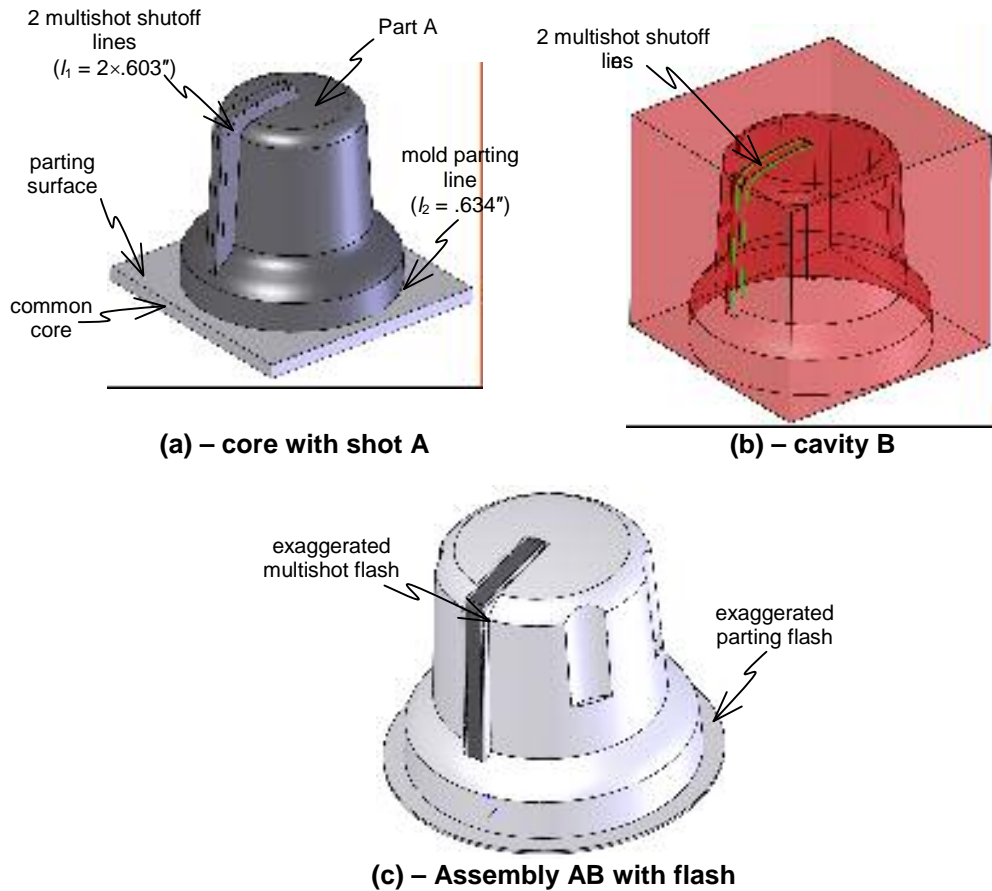


Figure 5.6 - Flash measurement for MMM knob, part B

For the purposes of this analysis, it is assumed that the seal between cavity B and the top surface of Shot A is tight enough so that flash does not occur over top of all of the exposed sections of material A. This would result in the blue fin being completely obscured by the sleeve material. So assuming that the top surface does not experience flash, it will be used in the calculation of crush, as discussed in Section 5.1.3.5. Noting this, it is assumed that flash would occur on the sides of the fin, due to a small gap existing there between cavity B and shot A. The MS parting line length was used to measure the MS flash. Accounting for both MS and parting flash, the total flash length for the MMM knob, part B is 1.84 inches.

- **Summary**

The results of the analysis for PA4a are summarized in Table 5.2 below:

Table 5.2 – Results of Flash Analysis for Knob		
	SMM&A	MMM
Part A flash length	.505 in.	.505 in.
Part B flash length	.634 in.	1.84 in.
Total flash length	1.139 in.	2.345 in.

It is clear from Table 5.2 that the SMM&A variant has less flash, and hence the advantage over MMM in terms of PA4a. For this analysis, no weighting scheme will be used to emphasize (or de-emphasize) the relative importance of flash at different locations. That is, all flash is measurement was weighted by a factor of unity.

5.1.3.5 – PA4b: Crush

The total surface area of crushed surfaces for both variants was measured through analysis of the part and mold model files. The results are summarized below:

- SMM&A Variant

By definition, the total amount of crushed surface area in the SMM&A variant is zero. This is because at no point does mold B contact part A to crush it.

- MMM Variant

As discussed in Section 5.1.3.4, it was assumed that the seal on the topmost surface of the fin on Part A was sealed tightly against cavity B. The surfaces experiencing crush over all or part of their area are illustrated in Fig. 5.7 below:

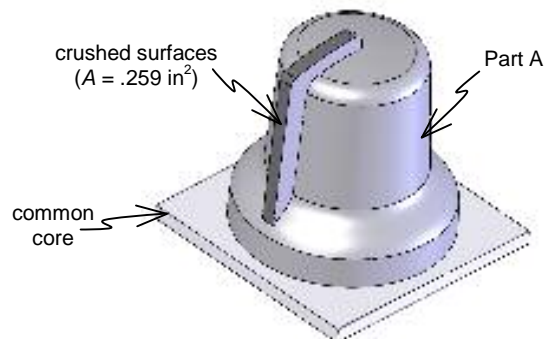


Figure 5.7 - Crush measurement for MMM knob

The total amount of crushed area for the MMM variant of the knob was measured to be .259 square inches.

5.1.3.6 – Summary and Conclusions

The results of the cost estimation and performance evaluation analyses conducted on the knob are summarized in Table 5.3 below:

Table 5.3 – Results of Cost & Performance Analyses for the Knob			
	SMM&A	MMM	Advantage
Cost curve	.156Q _d + 14,387 [\$]	.118Q _d + 19,565 [\$]	-
Under 136,236 units produced	-	-	SMM&A
Over 136,236 units produced	-	-	MMM
Total weight	.00252 [lbs.]	.00253 [lbs.]	N/A
Total interface strength	N/A [lbs.]	N/A [lbs.]	MMM*
Total assembly clearances	N/A [in.]	N/A [in.]	MMM*
Total flash length	1.139 [in.]	2.345 [in.]	SMM&A
Total crush area	0 [in ²]	.259 [in ²]	SMM&A
* - Deemed advantageous through qualitative considerations only			

From Table 5.3, it is apparent that neither variant is better in terms of all the cost or performance categories. Each variant has its advantages and disadvantages. Based on these results, the designers could choose the better variant based on the cost and their perceived notions of the better quality product.

Despite the seemingly neutral results of Table 5.3, most molders might agree that the MMM is the better overall variant. First, although the SMM&A variant is actually cheaper under 136K units produced, this is a rather small quantity for injection molding, so in most situations, the MMM variant will be more cost effective. Furthermore, in terms of the intended application of the knob, the MMM variant is better overall in a qualitative sense. The tighter locking fit between components and higher level of automation combined with lower cost makes the MMM variant more attractive overall.

5.2 – Case Study II: Vent

5.2.1 – Vent Product Description

The second case study was performed on an assembly with considerably more complexity than the knob of Case Study I. The product, as illustrated in Figs. 5.8 through

5.10, is a two-material vent device. The relevant characteristics of the vent are discussed below.

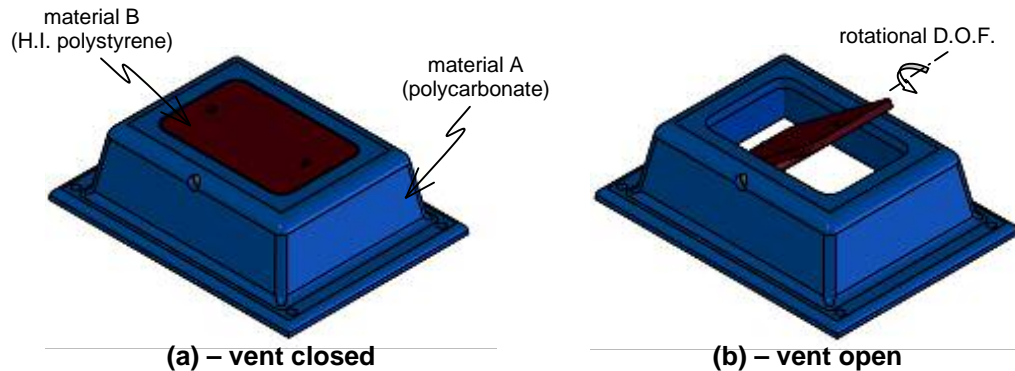


Figure 5.8 - Rendered view of the vent (SMM&A variant only)

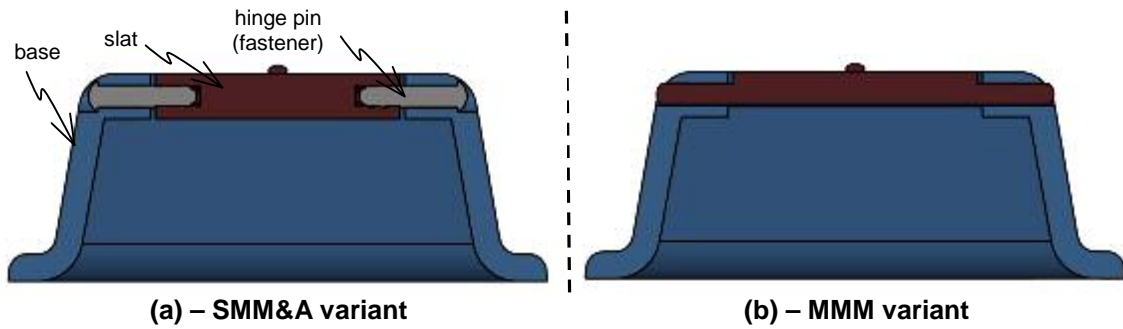


Figure 5.9 - Sectioned views of both vent variants

5.2.1.1 – Functionality

The vent is a two-material assembly designed to control the amount of airflow through an orifice. This device is a simplified version of those found commonly in automotive applications (e.g. dashboard vents). The vent allows minimal airflow when closed (Fig. 5.8a) and maximum airflow when opened by ninety degrees (Fig. 5.8b).

The vent consists of a prismatic base and a flat, hinged slat. The base provides support and would be attached to the outlet or opening through which air escapes. The slat controls the amount of airflow out of the base by rotating to cover/uncover the outlet hole in the base.

The slat has one rotational degree of freedom relative to the base. Once the product is assembled, the slat should be free to rotate along its hinge axis with minimal human effort.

This means the hinge action should be free enough to allow the vent to be easily opened/closed, but not so loose as to allow free spinning of the slat due to small disturbances like vibrations. Please see Appendix C for more detailed drawings of the vent.

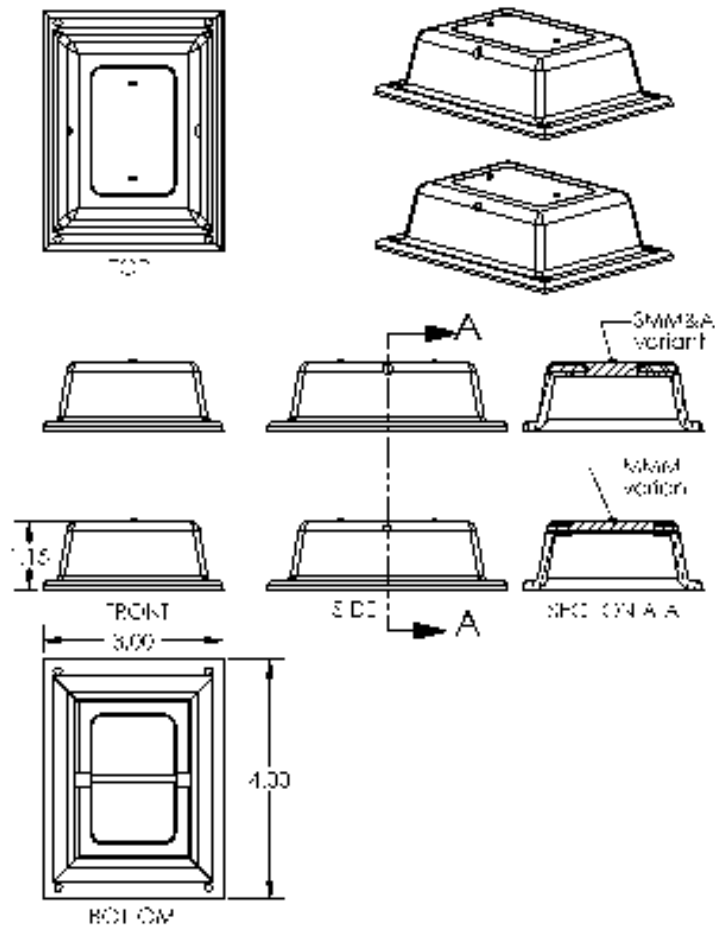


Figure 5.10 - Drawings of the vent variants

5.2.1.2 – Materials

The base (“part A”) is molded out of a generic white polycarbonate. This material was chosen because it is quite rigid. The sleeve (“part B”) is molded out of a generic white high-impact polystyrene, which is also rigid enough for this application. These materials were chosen because they exhibit no adhesive bonding when used for MSM, allowing relative movement between components in the MMM variant.

5.2.1.3 – Comparison of Variants

The major difference between the variants is how the slat is attached to the base. In the SMM&A variant, both the slat and the base have holes through which are aligned with hinge pins. On either side of the assembly, a cylindrical metal fastener is inserted, forming clearance fits with the base, and press fits with the slat. This allows the slat to freely rotate, while the pins stay joined with the rest of the assembly. The MMM variant incorporates a built-in hinge on the slat, which is formed during molding by shot B filling in the holes in the base. As shot B cools, it shrinks away from shot B, forming enough clearance between the formed pins and their corresponding holes. This difference, similar to the hinge box discussed previously, is most readily noticed in Fig. 5.9 above.

5.2.1.4 – Molding Considerations

The molds required for the vent are considerably larger and more complex than those for the knob. Furthermore, the core/cavity geometry required for shot B differs greatly for both variants. This needs to be taken into account when performing machining time estimations. Compared to the smaller knob, the vent's relatively large mold size and extensive machining required will drive up the tooling costs. Furthermore, mold cavity A for both variants will require two external side action mechanisms to produce the undercuts formed by the hinge. Other than the mold base, core/cavity machining, cooling channel drilling, and side actions, the mold will not require and other costly operations such as finishing or polishing.

As with Case Study I, this case study assumes the same mold material will be used regardless of the production volume.

5.2.2 – Vent Cost Estimation

In a similar manner as Case Study I, the MATLAB code was run to estimate the total manufacturing costs for both variants of the vent. The only difference was that the values

for the input variables were changed, and some new override variables were defined to directly input certain quantities, such as tooling time. The plots output from MATLAB are reproduced below in Figs. 5.11 and 5.12:

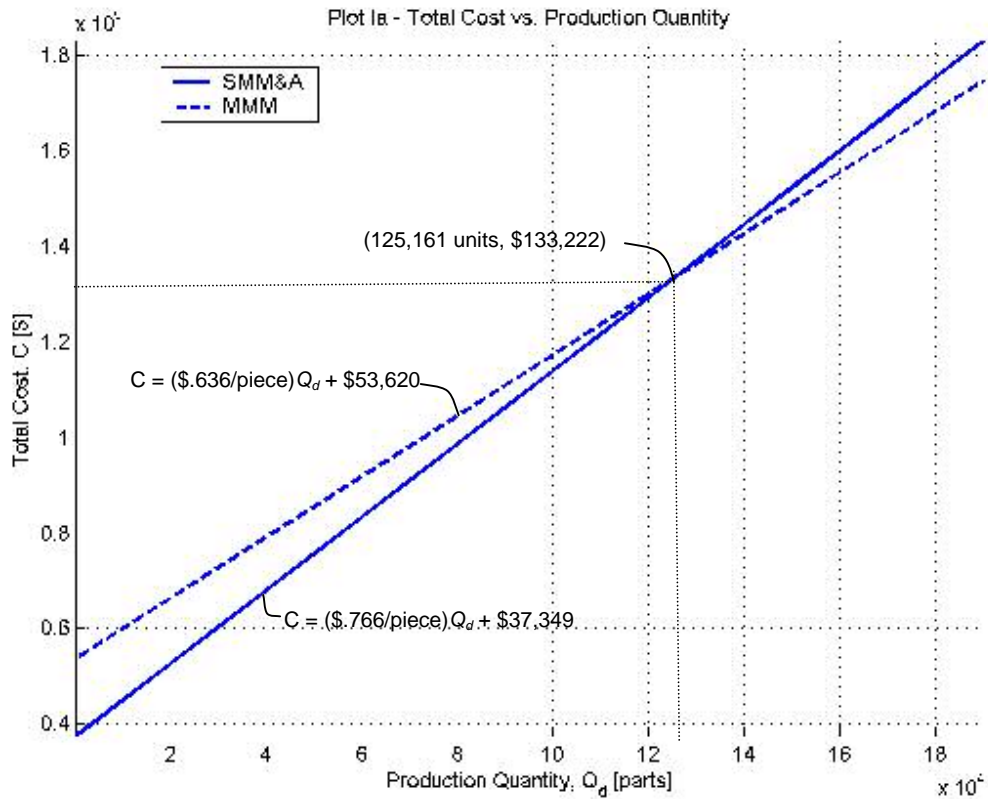


Figure 5.11 - Plot Ia: Total Cost vs. Production Quantity

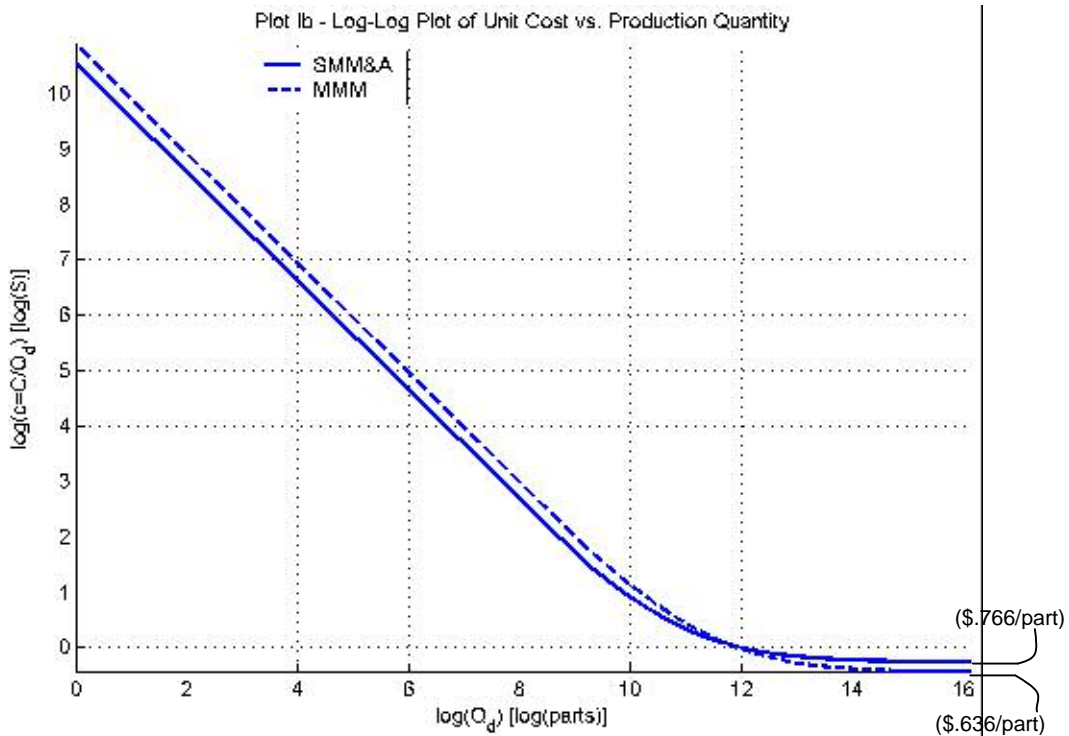


Figure 5.12 - Plot IIc: log-log plot of Unit Cost vs. Production Quantity

The results of the cost estimation section of Case Study II were similar to those of Case Study I. Although the total magnitudes of costs were greater, as expected due to higher part complexity and size, the shapes and locations of the cost curves were the same. Plots IIa and IIb are analogous to plots Ia through Ib, so the explanations for the curves follow similar logic.

As seen from Plot IIa, the SMM&A variant is initially less costly due to the lower capital investment and tooling costs, but is caught by the MMM variant (at 125,161 units and \$133,222), which has a lower per-piece costs (slope) due to reduced processing and material costs. These results were expected.

Plot IIb is a log-log plot of per piece cost verse production quantity. It shows how $c = C/Q_d$ eventually flattens as Q_d increases and settles at the slope of the cost curves displayed in Plot IIb. Both curves start to flatten out at around 120,000 units. This is where the fixed

costs such as tooling and capital equipment start to become amortized over a large enough volume of production to become economically feasible.

5.2.3 – Vent Performance Evaluation

The relevant performance aspects of the vent were analyzed according to Chapter 4’s guidelines, in a similar manner as for the knob. The results are summarized below.

5.2.3.1 – PA1: Weight

The weights for both assemblies were calculated and summed as with Section 5.1.3.1.

The results are summarized in Table 5.4 below:

	SMM&A	MMM
Part A weight	.12780 lbs.	.12790 lbs.
Part B weight	.01220 lbs.	.01160 lbs.
Fastener 1 weight	.00191 lbs.	-
Fastener 2 weight	.00191 lbs.	-
Total weight	.14382 lbs.	.13950 lbs.

From Table 5.4, it can be seen that the MMM variant is lighter than the SMM&A variant by only just over .004 lbs (less than 2 grams). Although this isn’t much of a difference, it gives the MMM variant a slight advantage in terms of weight. Of course it is not enough to be much of a deciding factor in selecting the better variant.

5.2.3.2 – PA2: Interface Strength

Although the vent is not intended to be a high load-bearing structure, interface strength is still an important issue and valid basis for comparison of variants. Here, “interface strength” will refer to the load required to break the assembly at the hinge so that the slat becomes detached from the base. From analysis of the vent assembly, the most likely interface failure mode appears to be from shear fracture of the hinge pins undergoing simple beam bending. This type of failure would occur when a large enough resultant load is applied in any direction perpendicular to the axis of the hinge.

Because there is no bonding in either variant, interface strength is only achieved through mechanical locking. The most accurate way to estimate the interface strengths of both variants would be to conduct a detailed FEA analysis on the entire assemblies. This would result in the final failure loads and fracture locations for both variants. Unfortunately, due to time limitations, and inability to access SolidWorks' full-featured FEA package, COSMOSWorks, only simplified FEA analysis was conducted on the individual components using the limited package, COSMOSExpress. This limited the analysis to specifying simple loads and restraints on single components in order to estimate the resulting stress distributions. However, this analysis, combined with simple reasoning and intuition was enough to identify the stronger variant, in a qualitative sense.

From simple stress considerations, it was initially hypothesized that the SMM&A variant was stronger due to the hinge pins being composed of steel rather than the polystyrene used in the MMM variant. Furthermore, it was assumed that both assemblies would separate through fracture of the slat somewhere near or at the hinge pins. This reasoning was used to set up the FEA analysis with simple loads and restraints and yielded the stress distributions shown below in Fig. 5.13. Please see Appendix D for information regarding the restraints and imposed loads for both variants.

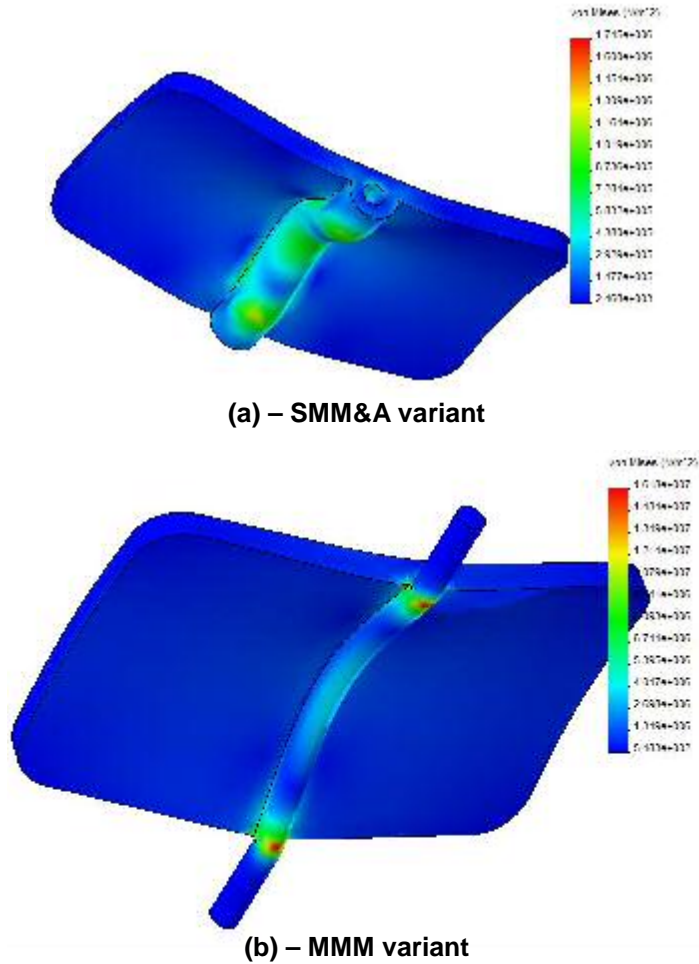


Figure 5.13 - Stress distribution results from FEA analysis

The results of Fig. 5.13 coincide with the initial hypotheses regarding the fracture locations and the higher interface strength of the SMM&A variant. The maximum Von-Mises stresses computed were $1.745E6 \text{ N/m}^2$ and $1.618E7 \text{ N/m}^2$ for the SMM&A and MMM variants, respectively. This implies that under identical loading situations, the stresses experienced by the MMM variant are almost an order of magnitude greater than those experienced by the SMM&A variant. Although exact force values for interface strength were unable to be found through this simplified analysis, the results seem to agree with the initial hypothesis that the SMM&A variant is better in terms of interface strength.

5.2.3.3 – PA3: Assembly Clearances

Because the slat is designed to have a rotational degree of freedom with respect to the base, assembly clearances become an important performance aspect for comparative purposes. An accurate quantitative assembly clearance analysis would require a detailed mold flow and cooling simulation in order to predict the shrinkage of all four shots (two for each variant). Due to a lack of material information and molding/cooling simulation software, a detailed quantitative analysis of this performance aspect is outside the scope of this thesis. However, careful analysis of the fitting requirements can yield results suitable enough for qualitative comparison of the variants. Fig. 5.14 below will be used to explain the qualitative analysis used to compare the vent variants:

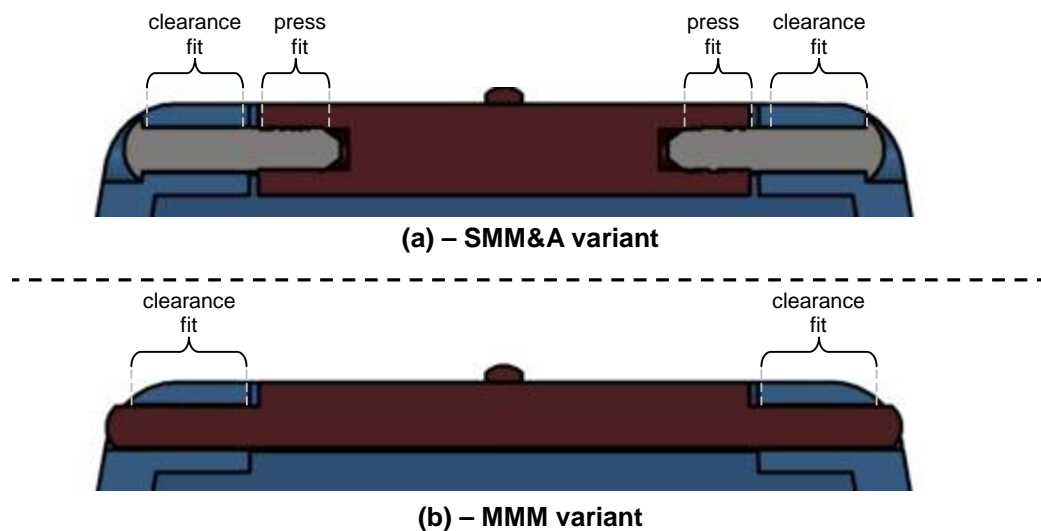


Figure 5.14 – Close-up view of vents' hinges and fit requirements

- SMM&A Variant Clearance Analysis

As shown in Fig. 5.14, the SMM&A variant requires four separate fits between the components: two clearance fits between the slat's hinge pins and the holes in the base, and two press fits between the same pins and the holes in the slat. The clearance fits allow the pins and the connected slat to freely rotate, while the press fits keep the pins secure inside the slat. This causes the pins to rotate with the slat and prevents them from separating axially from the entire assembly. Assuming the dimensions of the hinge pins are within tight

enough tolerances to assume constant, these four fitting requirements mean that four separate dimensions must be adequately controlled so that the assembly functions as desired. This involves controlling the amount of shrinkage that the holes diameters can experience. Because all four holes are formed by protrusions in the mold (i.e. the side action pins), their tendency to shrink will be limited, and their variance minimal. However, it is still possible for the holes to become smaller if the side actions are disengaged while the part is still cooling.

- MMM Variant Clearance Analysis

As shown in Fig. 5.14, the SMM&A variant requires only two separate fits between the components: clearance fits between the slat's hinge pins and the holes in the base. Even though it is important for enough clearance to exist between the pins and the holes, an adequate amount is almost always assured by the way the assembly is molded. This is because no matter what the diameters of the base's holes are, the pins will always be smaller and form a clearance. This is because the pins are molded inside the holes, so they will tend to shrink away from the cavities formed by the holes.

- Conclusions

From a qualitative standpoint, the MMM variant is better in terms of assembly clearances because it only poses two clearance dimensions which are *automatically* controlled, whereas the SMM&A variant possesses four clearance dimensions that need to be controlled through maintaining proper processing conditions.

5.2.3.4 – PA4a: Flash

The amount of potential flash was measured for both variants through analysis of the part and mold model files. The results for each part are summarized below:

- SMM&A Variant, Part A

For part A, there are two parting surfaces at which flash could form. This is illustrated in Fig. 5.15 below:

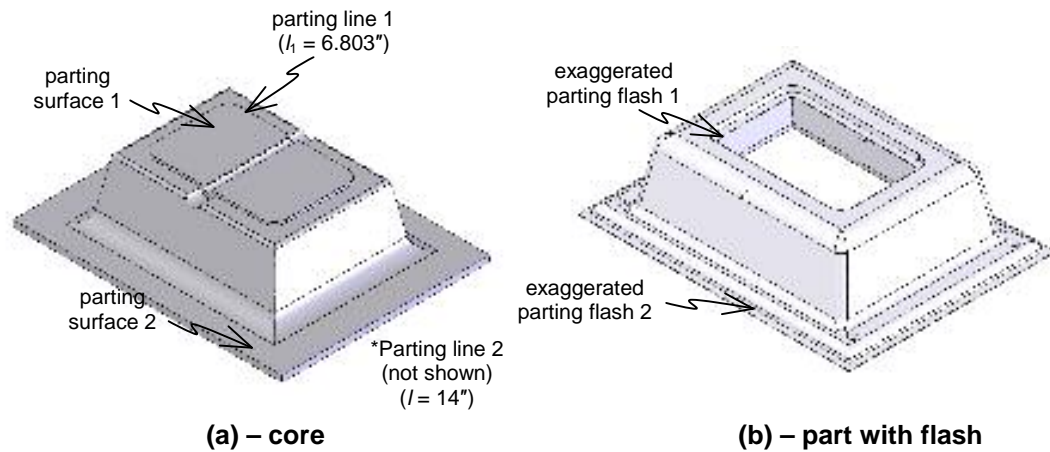


Figure 5.15 - Flash measurement for SMM&A vent, part A

From measuring and summing the length of the two flash locations in Fig. 5.15, we get a total flash length for the SMM&A vent, Part A is 20.803 inches.

- SMM&A Variant, Part B
Part B of the SMM&A variant only has one parting surface and corresponding parting line, located on the top outer edge of the part. This is the only possible location for flash, as shown in Fig. 5.16 below:

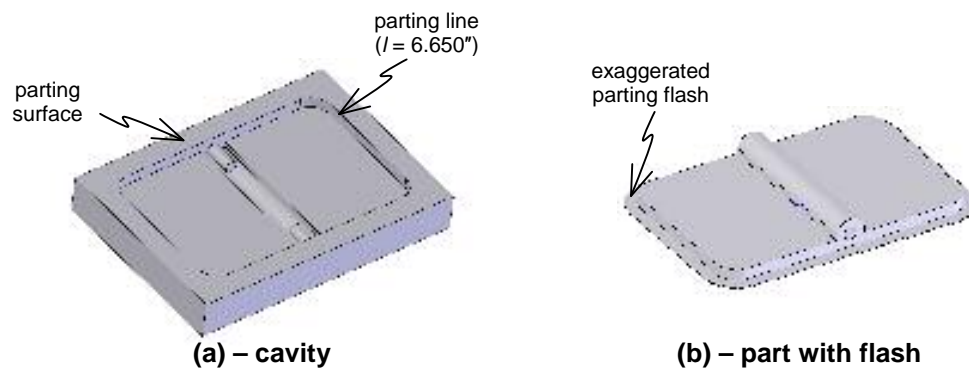


Figure 5.16 - Flash measurement for SMM&A vent, part B

As shown in Fig. 5.16, the total flash length for the SMM&A vent, Part B is 6.650 inches.

- **MMM Variant, Part A**
The MMM variant of part A is molded in the same manner as the SMM&A variant, and hence has the same flash length of 20.803 inches.

- **MMM Variant, Part B**
Assuming that cavity B comes down on top of Shot A resting on the common core, there is no parting surface through which flash can occur. Hence, the total flash length for the MMM vent, Part B is 0 inches. Because cavity B presses against Shot A, the issue of crush will be addressed Section 5.2.3.5.

- **Summary**
The results of the analysis for PA4a are summarized in Table 5.2 below:

Table 5.5 – Results of Flash Analysis for Vent		
	SMM&A	MMM
Part A flash length	20.803 in.	20.803 in.
Part B flash length	6.650 in.	0 in.
Total flash length	27.453 in.	20.803 in.

It is clear from Table 5.5 that the MMM variant has less flash, and hence the advantage over SMM&A in terms of PA4a. For this analysis, no weighting scheme will be used to emphasize (or de-emphasize) the relative importance of flash at different locations. That is, all flash is measurement was weighted by a factor of unity.

5.2.3.5 – PA4b: Crush

The total surface area of crushed surfaces for both variants was measured through analysis of the part and mold model files. The results are summarized below:

- **SMM&A Variant**
By definition, the total amount of crushed surface area in the SMM&A variant is zero. This is because at no point does mold B contact part A to crush it.

- **MMM Variant**
Because it is assumed that cavity B forms a tight seal on Part A, it will tend to crush the top horizontal surface of Part A. Although cavity B actually comes in contact with all

other external surfaces on Part A, they are drafted or tapered enough to not be affected by this crushing action. Furthermore, because a tight seal between these surfaces is not required, proper mold design will ensure they are not crushed by cavity B. The affected surface, and its measured area is illustrated in Fig. 5.17 below:

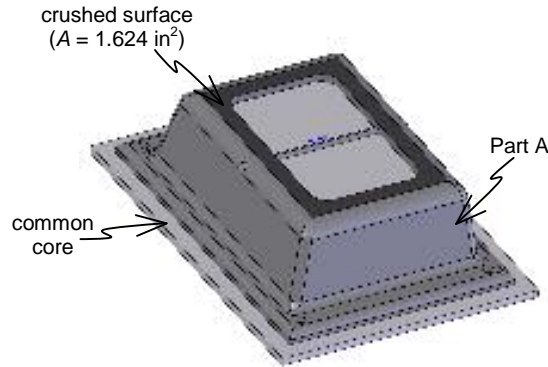


Figure 5.17 - Crush measurement for MMM vent

As seen from Fig. 5.17, the total crushed surface area for the MMM vent variant is 1.624 square inches.

5.2.3.6 – Summary and Conclusions

The results of the cost estimation and performance evaluation analyses conducted on the vent are summarized in Table 5.6 below:

Table 5.6 – Results of Cost & Performance Analyses for the Vent			
	SMM&A	MMM	Advantage
Cost curve	.706Q _d + 37,349 [\$]	.636Q _d + 53,620 [\$]	-
Under 125,161 units produced	-	-	SMM&A
Over 125,161 units produced	-	-	MMM
Total weight	. 14382 [lbs.]	. 13950 [lbs.]	MMM
Total interface strength	N/A [lbs.]	N/A [lbs.]	SMM&A*
Total assembly clearances	N/A [in.]	N/A [in.]	MMM*
Total flash length	27.453 [in.]	20.803 [in.]	MMM
Total crush area	0 [in ²]	1.624 [in ²]	SMM&A
* - Deemed advantageous through qualitative considerations only			

As with the first case study, from Table 5.3, it is apparent that neither variant is better in terms of all the cost or performance categories. However, the MMM variant becomes less expensive to produce after 125,161 units, which is a relatively small production quantity for injection molding. Furthermore, the MMM variant has an advantage over the

SMM&A variant in three out of five PA's. Based on these results it is likely that many designers would choose the MMM variant.

5.2 – Summary

In summary, two case studies involving very different real-world products were presented. Both products were described and analyzed, and then the cost estimation and performance evaluation models were conducted. Based on the results from the models, the variants for each product were compared and the better manufacturing process was chosen. Based on the models' results, MMM was chosen as the better variant for both case studies, based on the quantitative model results as well as some qualitative reasoning.

The results seemed to agree with the initial assumption that MMM is usually an less expensive manufacturing process than SMM&A after the breakeven point has been passed. However, the MMM variant is not always the best in terms of all the important PA's regarding molded components. This means the product designer's must still make personal choices based on both cost and quality.

CHAPTER 6 – CONCLUSIONS

This chapter concludes and summarizes this work. It lists the new research contributions, the potential industrial benefits, and recommends future work to supplement this preliminary research.

6.1 – Summary

This thesis presents two independent yet complementary models for comparing traditional injection molding and assembly operations with bi-material rotary platen MS injection molding. The first model uses a cost-based metric for evaluation and comparison where the second model uses a set of relevant performance aspects as a basis for comparison.

The cost estimation model uses an ordered set of semi-empirical formulas to evaluate the various important cost drivers associated with either process. It takes a large number of low-level input parameters and outputs the total estimated manufacturing cost as a function of production quantity. This allows designers and/or other decision makers to select the best process based on the production needs.

The performance evaluation model offers guidelines for measuring discrete quantities related to performance. The designers can then compare the values of these performance aspects side-by-side and select the preferred process based on their own subjective ranking schemes.

Unfortunately for a number of reasons, it is very difficult to completely validate both models in an industrial setting at this time. The major cause of this inability stems directly

from the lack of published information on MMM as well as a general reluctance from MS-capable businesses to provide the large amount of necessary information. Direct cost quotes from MS manufacturers would provide little insight as they would be latent with unknown profit markups as well as subject to wide variation based on the shops' current capacities. Furthermore, assuming full cooperation from injection molders, a long period of time would be required to collect adequate cost and performance data for a range of different product lines.

However, despite a lack of industrial data, the models are still valid in a completeness sense. Despite a lack of supportive numerical data, the model still holds significance from its thorough consideration of all the important factors controlling plastic products' cost and performance. All of the reasoning was based on expansion/adaptation of existing models as well as using first principles. The methods were then discussed with three experts in the field who agreed that all important details were considered. Furthermore, the methods were checked against all of the widely regarded methods published in the literature, and found to account for every single factor.

The models have also been shown to account for every structural aspect of SM and MM injection molding from a thorough analysis of several real-world products and their associated molds. Through generous information and collaboration from companies like Space Limited, Black & Decker and Multishot, the models have shown to be structurally correct. For example, the Dewalt (Black & Decker) saw housing shown below in Fig. 6.1 was carefully analyzed along with its production equipment in order to make sure the models accounted for every important aspect.



Figure 6.1 – Example of a multi-shot product studied for this research

6.2 – Research Contributions

The main contributions of this thesis come directly from the developed models and their method of application. The major contribution is the fact that the models presented are the first published work addressing cost estimation and performance evaluation for multi-material injection molding. While much has been published in the domains of single material molding and cost estimation, there is no significant or available literature on the important topic of multi-material molding cost and performance estimation. This work is a first attempt to bridge the gap between traditional molding and the newer MSM technologies. In essence, the models: 1) identified and compiled all the relevant models and equations for SMM&A, and 2) modified these models to accommodate MMM. Several new equations were developed, both through adaptation of prior work and reasoning from first principles. The correct use of these equations avoids the uncertainty involved with table lookups or guesstimates, and promotes consistency between separate applications of the model.

A second contribution of the cost estimation model is that it provides a comprehensive framework for cost comparison. The model is built from adapted pieces of

several other methods along with original work to provide a more complete picture of total cost. It incorporates all of the important cost drivers listed in the literature. Furthermore, the cost estimation model attempts to break all costs down into their lowest-possible components (usually physical parameters directly dependent on the part material or geometry). All of the reasoning and equations used in the model were based on first principles and all the terms are traceable to well-recognized expenses involved with injection molding.

A final contribution of the cost estimation model is that a MATLAB framework was written to evaluate all of the equations once the input parameters are specified. This allows fast and error-free computations. It also allows simple graphical output of the cost vs. quantity curves. Furthermore, the nature of the program allows parameters to be quickly changed in order to conduct sensitivity analysis and “what-if?” analyses.

The main contribution of the performance evaluation model is that it is the first published framework for SMM&A and MMM product comparison. It identifies important performance attributes for molded products and presents straightforward approaches for their measurement/evaluation. It accounts for the standard DFM rules and material properties such as flash/crush and shrinkage. Finally, the results of the model can be used as a basis for multi-objective quantitative comparisons using such techniques as optimizations routines.

6.3 – Industrial Benefits

The proposed models have the potential to benefit the injection molding industry in several ways. First, they provide relatively fast and comprehensive methods to evaluate

product designs. Designers would have rapid feedback on the effects of their decisions on cost and performance and could make changes accordingly.

The models' successful implementation may help save time, money, and design iterations. The designers could focus on design rather than be bogged down by complex and time-consuming cost modeling exercises. Furthermore, these models may increase the accuracy and consistency of cost and performance estimations by providing a systematic means of measuring cost and performance drivers.

Use of these models might also promote a better understanding of injection molding processes and their cost and performance drivers, especially for the relatively underdeveloped MMM processes. This could fuel a growth in the MS industry and significantly expand the design space for many industries.

6.4 – Directions for Future Work

While the proposed models are the first of their kind for SMM and MSM comparison, they are not without their limitations. Many of these limitations can be addressed in future works as potential research issues.

Many of these limitations are direct results of many of the simplifying assumptions used in the development of the cost estimation equations and performance measurement techniques. Most of these assumptions could conceivably be loosened or removed completely by appropriately increasing the complexity of the models. Some of the important possible directions for expansion are discussed below.

6.4.1 – Expanding to n -Material Objects

All of the proposed work assumes the product assemblies will consist of only *two* materials. This simplifies the reasoning used to develop the resultant equations. However,

MS products made of three or more materials are gaining increasing popularity so the models should be expanded to address this. Most of the equations could be simply adapted to incorporate more materials using similar reasoning to that for developing the bi-material equations. However, some parts of the model would require more extensive reworking, especially including the mold construction costs and the definitions/measurement of the performance aspects.

6.4.2 – Including Other Multi-Shot Molding Processes

The proposed work only considers rotary platen MSM as the MMM process. However, there are several other popular MMM processes, including other MS variants such as index plate molding and core-toggle molding. The model should be expanded to include other MMM processes to increase its versatility. The model could then be used to compare several process variants rather than only two. This would give designers greater flexibility and further expand the design space. Because of the large differences between the various MMM processes, significant work would be required to expand the model to accommodate these processes.

6.4.3 – Increasing Level of Automation

While the proposed models are the first step at automating the cost estimation and performance evaluation processes, they still require a great deal of manual user input and high-level decision making. The models assume that several complicated design decisions have been made early on in the design cycle such as the cooling channel layout and the ejector system design. It would be preferable to minimize the human effort required to accurately utilize the models. This would involve better automatic parameter extraction (from the CAD models) as well as automated mold design algorithms. The eventual goal would be to incorporate the cost and performance evaluation model into a suite of fully

automated software that can generate optimal mold designs based simply on the part geometry and material properties. The development and integration of such models is a rich area for future work.

6.4.4 – Validation in Industry

Finally, much work must be done in order to validate the use of the proposed models in an industrial setting. This would require intensive collaboration with MS-capable companies and data collection on a large number of product lines. One possible way to accomplish this would be to work closely with a design team that is trying to choose between SMM&A and MMM for making a particular product. The models could be presented and compared along side with the company's traditional cost/performance evaluation methods to relatively determine the applicability of the cost equations and PA measurement techniques. The company's feedback could be used to adapt and adjust the model accordingly, until the cost estimates provided were consistent with the company's actual manufacturing expenses.

This type of research could help find the appropriate numerical values for many of the equations used in the cost estimation model. Through extensive case studies and curve fitting, many of the empirical constants could be determined. Overall, industrial validation is the most important step in building from these models and implementing them to the benefit of the molding industry.

APPENDICES

Appendix A – Input Variables

The following table lists all of the input values used to perform the cost estimation for both case studies of Chapter 5. The sixth and seventh columns (“value 1” and “value 2”) list the numeric values used for Case Study I and Case Study II, respectively.

Many of the values were obtained from the CAD model files of the parts and/or mold inserts. Other values were material properties obtained from online services such as www.matweb.com. Some values were obtained directly from molding equipment manufacturers, molding shops, and/or machine shops. Some values were taken directly from the literature or slightly adapted from published values. In some cases, the data was simply not available, so the variables were either not used, or values were chosen on best estimates and common sense.

Input variables whose value is listed as “N/A” were not directly used in the evaluation of the cost estimation equations. This is because they were either not needed (e.g. no surfaces needed tolerancing, so the corresponding variables were not necessary), or they were bypassed by directly inputting a value of a parent variable. For example, in stead of using the rotary platen diameter to compute the rotary platen cost, the rotary platen price was directly input to the model based on a manufacturer’s price quote. This eliminated the need for values of D_{platen} and the platen cost function, Φ_3 .

#	Description	Symbol	Units	eqn. #	value 1	value 2	MATLAB name	category	source/notes
1	Expected defect rate of part A	r_{dA}		(3.4)	2.3%	3.0%	r_d_A	processing variable	historically estimated
2	Expected defect rate of part B	r_{dB}	[%]		2.0%	1.7%	r_d_B		
3	Number of cavities per mold	n_{cav}	[#]	(3.5)	10	2	n_cav	design decision	specified in design
4	Inspection time for part A	t_{inspA}		(3.5)	1.5	2	t_insp_A	processing variable	historically estimated based on
5	Inspection time for part B	t_{inspB}	[s/part]		1.5	1.5	t_insp_B		
6	Inspection time for part AB	t_{inspAB}			2	3	t_insp_AB		
7	Packaging time	t_{pack}	[s/part]	(3.5)	0.25	0.75	t_pack	processing variable	hist. est. based on part complexity
8	Mold resetting time for mold A	t_{resetA}		(3.6)	9	12	t_reset_A	processing variable	estimated via Boothroyd's Eqn.
9	Mold resetting time for mold B	t_{resetB}	[s/shot]		11	6	t_reset_B		
10	Mold resetting time for mold AB	$t_{resetAB}$			13	15	t_reset_AB		
11	Injection pressure for shot A	P_{injA}	[lb/in ²]	(3.7)	15997	16998	P_inj_A	processing variable based on mat. prop.	www.matweb.com
12	Injection pressure for shot B	P_{injB}			17000	13996	P_inj_B		
13	Injection power for shot A	Π_{injA}	[lb*in/s]	(3.7)	66000	70000	Pi_inj_A	injection unit property	obtained from injection unit manufacturer
14	Injection power for shot B	Π_{injB}			66000	65000	Pi_inj_B		
15	Maximum wall thickness for shot A	τ_{maxA}	[in]	(3.8)	0.126	0.166	tau_max_A	part geometry	CAD model file of part
16	Maximum wall thickness for shot B	τ_{maxB}			0.1	0.122	tau_max_B		
17	Thermal diffusivity coeff. for resin A	α_A	[in ² /s]	(3.8)	#####	#####	alpha_A	material property	www.matweb.com or resin manufacturer
18	Thermal diffusivity coef. for resin B	α_B			#####	#####	alpha_B		
19	Required injection temperature for	T_{injA}	[F]	(3.8)	540	576	T_inj_A	material property	www.matweb.com or resin manufacturer
20	Required injection temperature for	T_{injB}			470	424	T_inj_B		
21	Required mold wall temperature for shot A	T_{moldA}	[F]	(3.8)	153	196	T_mold_A	material property	www.matweb.com or resin manufacturer
22	Required mold wall temperature for shot B	T_{moldB}			80	81	T_mold_B		
23	Safe part ejection temperature for	T_{ejectA}	[F]	(3.8)	165	261	T_eject_A	material property	www.matweb.com or resin manufacturer

24	Safe part ejection temperature for	T_{ejectB}	[F]		90	171	$T_{\text{eject_B}}$	material property	www.matweb.com or resin manufacturer
25	Additional time (safety factor) for shot A	$t_{\text{extra_A}}$	[s/part]	(3.8)	0	0	$t_{\text{extra_A}}$	design decision	historically estimated
26	Additional time (safety factor) for shot B	$t_{\text{extra_B}}$	[s/part]		0	0	$t_{\text{extra_B}}$		
27	Handling time for part A	$t_{\text{handle_A}}$	[s/part]	(3.9)	1.6	2.2	$t_{\text{handle_A}}$	processing variable	estimated based on Poli's table
28	Handling time for part B	$t_{\text{handle_B}}$	[s/part]		1.6	1.6	$t_{\text{handle_B}}$		
29	Insertion time for part B	$t_{\text{insert_B}}$	[s/part]	(3.9)	2.7	4	$t_{\text{insert_B}}$	processing variable	estimated based on Poli's table
30	Handling time for jth fastener	$t_{\text{handle_j}}$	[s/part]	(3.9)	N/A	-	-	processing variable	estimated based on Poli's tab
-	Handling time for 1st fastener				N/A	1	-		
-	Handling time for 2nd fastener				N/A	1	-		
31	Insertion time for jth fastener	$t_{\text{insert_j}}$	[s/part]	(3.9)	N/A	-	-	processing variable	estimated based on Poli's tab
-	Insertion time for 1st fastener				N/A	2	-		
-	Insertion time for 2nd fastener				N/A	2	-		
32	Total number of fasteners	n_{fast}	[#]	(3.9)	0	2	n_{fast}	design decision	CAD model file of part
33	Cost of fasteners and/or adhesives	$c_{\text{fasteners}}$	[\$/part]	(3.10)	0	\$0.06	$c_{\text{fasteners}}$	supplier price	from supplier, e.g. McMaster-Carr
34	Miscellaneous material costs	c_{misc}	[\$/part]	(3.10)	0	0	c_{misc}	misc. price	estimated based on product specs.
35	Specific gravity of plasticized material A	γ_A	[lb/in ³]	(3.11)	0.039	0.052	γ_{A}	material property	www.matweb.com or resin manufacturer
36	Specific gravity of plasticized material B	γ_B			0.024	0.038	γ_{B}		
37	Supplier's price for resin A	$p_{\text{resin_A}}$	[\$/lb]	(3.11)	\$2.00	\$1.50	$p_{\text{resin_A}}$	supplier price	from resin supplier, e.g. Matweb
38	Supplier's price for resin B	$p_{\text{resin_B}}$			\$2.75	\$1.35	$p_{\text{resin_B}}$		
39	Volume of part A	$V_{\text{part_A}}$	[in ³]	(3.12)	0.044	2.459	$V_{\text{part_A}}$	part geometry	CAD model file of part
40	Volume of part B	$V_{\text{part_B}}$			0.033	0.305	$V_{\text{part_B}}$		
41	% of allowable regrind used in resin A	$f_{\text{rg_A}}$	[%]	(3.12)	0	0	$f_{\text{rg_A}}$	design decision	chosen based on desired resin quality
42	% of allowable regrind used in resin B	$f_{\text{rg_B}}$			0	0	$f_{\text{rg_B}}$		

43	Volume of sprue for mold A	V_{sprueA}	[in ³]	(3.13)	N/A	N/A	V_{sprue_A}	mold geometry	CAD model file of molds. Estimating f_{rg_i} in directly in stead.
44	Volume of sprue for mold B	V_{sprueB}			N/A	N/A	V_{sprue_B}		
45	Volume of runners for mold A	$V_{runnersA}$	[in ³]	(3.13)	N/A	N/A	$V_{runners_A}$	mold geometry	CAD model file of molds. Estimating f_{rg_i} in directly in stead.
46	Volume of runners for mold B	$V_{runnersB}$			N/A	N/A	$V_{runners_B}$		
47	Gating volume's percentage of total shot	f_{volA}	[%]	(3.14)	22%	10%	f_{vol_A}	mold geometry	estimated based on part size
48	Gating volume's percentage of total shot	f_{volB}			26%	21%	f_{vol_B}		
49	Mold base cost constant 1, intercept	β_{base}	[\$]	(3.17)	100		Beta_base	linear curve fit parameter	historically estimated, Boothroyd
50	Mold base cost constant 2, slope	α_{base}	[\$/in ^{1.45}]	(3.17)	0.45		alpha_base	linear curve fit parameter	historically estimated, Boothroyd
51	Length of bounding box for part A	l_A	[in]	(3.18)	0.579	4	l_A	part geometry	CAD model file of part
52	Length of bounding box for part B	l_B			0.634	2.111	l_B		
53	Width of bounding box for part A	w_A	[in]	(3.18)	0.579	3	w_A	part geometry	CAD model file of part
54	Width of bounding box for part B	w_B			0.634	2.206	w_B		
55	Mold wall clearance factor, area	f_A	[%]	(3.18)	165%	50%	f_A	design decision	est. based on safety and mold strength
56	Addtl. mold base area for SAs in mold A	A_{SA_A}	[in ²]	(3.18)	0	18	A_{SA_A}	mold subsystem parameter	historically estimated based on common side action mechanism size
57	Addtl. mold base area for SAs in mold B	A_{SA_B}			0	0	A_{SA_B}		
58	Addtl. mold base area for SAs in mold AB	A_{SA_AB}			0	18	A_{SA_AB}		
59	Height of bounding box for part A	h_A	[in]	(3.19)	0.573	1.15	h_A	part geometry	CAD model file of part
60	Height of bounding box for part B	h_B			0.567	0.228	h_B		
61	Height of bounding box for part AB	h_{AB}			0.567	1.15	h_{AB}		
62	Mold wall clearance factor, height	f_h	[%]	(3.19)	160%	50%	f_h	design decision	est. based on safety and mold strength
63	Addtl. mold base height for SAs, mold A	h_{SA_A}	[in]	(3.19)	0	3	h_{SA_A}	mold subsystem parameter	historically estimated based on common side action mechanism size
64	Addtl. mold base height for SAs, mold B	h_{SA_B}			0	0	h_{SA_B}		
65	Addtl. mold base height for SAs, mold AB	h_{SA_AB}			0	3	h_{SA_AB}		

66	Hourly machining rate	\dot{V}_{mach}	[\$/hr]	(3.21)	50		r _{dot} _mach	machining rate	quoted from machine shop
67	Average material removal rate	\dot{V}_{mill}	[in ³ /hr]	(3.23)	0.03		V _{dot} _mill	machining capability	historically estimated from machine shop
68	Convex portion's vol. for part A	$V_{convexA}$	[in ³]	(3.25)	0.082	8.537	V_convex_A	part geometry	CAD model file of part
69	Convex portion's vol. for part B	$V_{convexB}$			0.115	0.322	V_convex_B		
70	Concave portion's vol. for part A	$V_{concaveA}$	[in ³]	(3.25)	0.038	6.078	V_concave_A	part geometry	CAD model file of part
71	Concave portion's vol. for part B	$V_{concaveB}$			0.081	0.000	V_concave_B		
72	Shrinkage factor for material A	$f_{shrinkA}$	[%]	(3.26)	0	0	f_shrink_A	material property	www.matwsb.com or resin manufacturer (neglected here)
73	Shrinkage factor for material B	$f_{shrinkB}$			0	0	f_shrink_B		
74	Height of core for part A	h_{coreA}	[in]	(3.27)	0.491	1.05	h_core_A	mold geometry	CAD model file of part
75	Height of core for part B	h_{coreB}	[in]		0.567	0.025	h_core_B		
76	Hourly rate associated with tol. machining	\dot{V}_{tol}	[\$/hr]	(3.29)	50		r _{dot} _tol	machining rate	quoted from machine shop
77	# of surfs. reqng. tol., mold A core & cav.	n_{tolA}	[#]	(3.30)	0	0	n_tol_A	part property	CAD model file of part
78	# of surfs. reqng. tol., mold B core & cav.	n_{tolB}			0	0	n_tol_B		
79	# of surfs. reqng. tol., mold AB cav A	$n_{tolAB-cavA}$	[#]	(3.30)	0	0	n_tol_AB_cavA	part property	CAD model file of part
80	# of surfs. reqng. tol., mold AB cav B	$n_{tolAB-cavB}$			0	0	n_tol_AB_cavB		
81	# of surfs. reqng. tol., mold AB core	$n_{tolAB-core}$	[#]	(3.30)	0	0	n_tol_AB_core	part property	CAD model file of part
82	Surface area of surface j	A_j	[in ²]	(3.31)	N/A	N/A	-	part geometry	CAD model file of part
83	Dim. tol. provided by rough milling	d_{rough}	[in]	(3.31)	9.84E-04		d_rough	machining capability	obtained from machine shop
84	Dim. tol. required for surface j	d_j	[in]	(3.31)	N/A	N/A	-	part property	CAD model file of part
85	Average feed rate for surface milling	\dot{i}_{tol}	[in/hr]	(3.31)	30		l _{dot} _tol	machining capability	obtained from machine shop
86	Tol. time norm. constant 1, exponent	α_{tol}	[# = x]	(3.31)	N/A	N/A	alpha_tol	linear curve fit parameter	historically estimated
87	Tol. time norm. constant 2, denominator	β_{tol}	[in ^{1-x}]	(3.31)	N/A	N/A	Beta_tol	linear curve fit parameter	historically estimated
88	Hourly rate associated with hand polishing	\dot{V}_{polish}	[\$/hr]	(3.32)	50		r _{dot} _polish	machining capability	obtained from machine shop

89	Polishing time for surface j	t_{polish_j}	[hr]	(3.32)	N/A	N/A	-	part property	historically estimated
90	# of surfaces requiring polishing	n_{polish}	[#]	(3.32)	0	0	n_{polish}	part property	CAD model file of part
91	Hourly rate associated with texturing	$\dot{r}_{texture}$	[\$/hr]	(3.32)	50		$r_{dot_texture}$	machining rate	quoted from machine shop
92	Total mold text. ops. for one core/cavity set	$t_{texture}$	[hr]	(3.32)	0	0	$t_{texture}$	mold geometry	estimated based on surface reqments
93	# surfs. reqng polish. mold A core & cav.	n_{polish_A}	[#]	(3.33)	0	0	n_{polish_A}	part property	CAD model file of part
94	# surfs. reqng polish. mold B core & cav.	n_{polish_B}			0	0	n_{polish_B}		
95	# surfs. reqng polish. mold AB cav. A	$n_{polish_{AB-cavA}}$			0	0	n_{polish_ABcavA}		
96	# surfs. reqng polish. mold AB cav. B	$n_{polish_{AB-cavB}}$		(3.33)	0	0	n_{polish_ABcavB}	part property	CAD model file of part
97	# surfs. reqng polish. mold AB core	$n_{polish_{AB-core}}$		(3.33)	0	0	n_{polish_ABcore}	part property	CAD model file of part
98	Surface area of surface j	A_j	[in ²]	(3.34)	N/A	N/A	-	part property	CAD model file of part
99	Surface area code (from Table 3.2)	s_j	[#]	(3.34)	N/A	N/A	-	Surface category	Table 3.2
100	Average surface area polishing rate	\dot{A}_{polish}	[in ² /hr]	(3.34)	4.2		A_{dot_polish}	machining rate	quoted from machine shop
101	Polishing time norm. constant 1, exponent	α_{polish}	[#]	(3.34)	N/A		α_{polish}	linear curve fit parameter	historically estimated
102	Polishing time norm. constant 2, denominator	β_{polish}	[#]	(3.34)	N/A		β_{polish}	linear curve fit parameter	historically estimated
103	Texturing time factor related to machining time	$f_{texture}$	[%]	(3.35)	0	0	$f_{texture}$	simplifying factor	historically estimated
104	Ejector pin linear cost constant 1,	α_{pins}	[\$/pin]	(3.36)	125		α_{pins}	linear curve fit parameter	historically estimated, Boothroyd
105	Ejector pin linear cost constant 2,	β_{pins}	[\$]	(3.36)	0		β_{pins}	linear curve fit parameter	historically estimated, Boothroyd
106	Pin number cost constant 1, multiplier	α_{area}	[in ⁻²]	(3.38)	1		α_{area}	linear curve fit parameter	historically estimated, Boothroyd
107	Pin number cost constant 2, exponent	β_{area}	[# = x]	(3.38)	0.5		β_{area}	linear curve fit parameter	historically estimated, Boothroyd
108	Hourly machining rate (for drilling)	\dot{r}_{drill}	[\$/hr]	(3.39)	50		r_{dot_drill}	machining rate	quoted from machine shop
109	Drilling feed rate	i_{drill}	[in/hr]	(3.40)	10		i_{dot_drill}	machining capability	obtained from machine shop
110	Length of cooling channels for layout 1	l_{cool_1}	[in]	(3.41)	15	34	L_{cool_1}	mold geometry	CAD model file of mold
111	Length of cooling channels for layout 2	l_{cool_2}	[in]	(3.41)	17	34	L_{cool_2}	mold geometry	CAD model file of mold

112	Length of cooling channels for layout 3	l_{cool3}	[in]	(3.41)	15	12	L_{cool3}	mold geometry	CAD model file of mold
113	Length of cooling channels for layout 4	l_{cool4}	[in]	(3.41)	17	0	L_{cool4}	mold geometry	CAD model file of mold
114	Extra length of drilled channels	l_{extra}	[in]	(3.41)	11	15	L_{extra}	mold geometry	CAD model file of mold
115	# of external undercuts cav. A	n_{extA}	[#]	(3.42)	0	2	n_{extA}	mold geometry	CAD model file of part
116	# of external undercuts cav. B	n_{extB}			0	0	n_{extB}		
117	# of ext. UCs cav. A, mold AB	$n_{extAB-A}$	[#]	(3.42)	0	2	n_{extABA}	mold geometry	CAD model file of part
118	# of ext. UCs cav. B, mold AB	$n_{extAB-B}$			0	0	n_{extABB}		
119	# of int. UCs core A	n_{intA}	[#]	(3.42)	0	0	n_{intA}	mold geometry	CAD model file of part
120	# of int. UCs core B	n_{intB}			0	0	n_{intB}		
121	# of int. UCs core AB	n_{intAB}			0	0	n_{intAB}		
122	Area of jth internal undercut	A_{intj}	[in ²]	-	N/A	N/A	-	part geometry	CAD model file of part
123	Area of kth external undercut	A_{extk}	[in ²]	-	N/A	-	-	part geometry	CAD model file of part
-	Area of 1st undercut	-			N/A	0.024	-		
-	Area of 2nd undercut	-			N/A	0.024	-		
124	Linear int. SA cost constant 1, intercept	β_{int}	[\$]	(3.43)	N/A		Beta_int	linear curve fit parameter	historically estimated, Boothroyd
125	Linear int. SA cost constant 2, slope	α_{int}	[\$/in ²]	(3.43)	N/A		alpha_int	linear curve fit parameter	historically estimated, Boothroyd
126	Linear ext. SA cost constant 1, intercept	β_{ext}	[\$]	(3.43)	\$3,250		Beta_ext	linear curve fit parameter	historically estimated
127	Linear ext. SA cost constant 2, slope	α_{ext}	[\$/in ²]	(3.43)	0		alpha_ext	linear curve fit parameter	historically estimated, overridden
128	Linear HR cost constant 1, slope	α_{HR}	[\$/in ²]	(3.46)	N/A		alpha_HR	linear curve fit parameter	historically estimated, overridden
129	Linear HR cost constant 2, intercept	β_{HR}	[\$]	(3.46)	N/A		Beta_HR	linear curve fit parameter	historically estimated, overridden
130	Linear mold SU constant 1, slope	α_{SU}	[\$/in ²]	(3.48)	N/A		alpha_SU	linear curve fit parameter	historically estimated, overridden
131	Linear mold SU constant 2, intercept	β_{SU1}	[\$]	(3.48)	N/A		Beta_SU1	linear curve fit parameter	historically estimated, overridden
132	Linear mold SU constant 3, intercept	β_{SU2}	[\$]	(3.48)	N/A		Beta_SU2	linear curve fit parameter	historically estimated, overridden

133	Factory OH rate applied to station 1	f_{OH_1}	(%)	(3.50)		37%		f_{OH_1}	factory accounting variables	historically estimated
134	Factory OH rate applied to station 2	f_{OH_2}	(%)	(3.50)		37%		f_{OH_2}		
135	Factory OH rate applied to station 3	f_{OH_3}	(%)	(3.50)		10%		f_{OH_3}		
136	Factory OH rate applied to station 4	f_{OH_4}	(%)	(3.50)		10%		f_{OH_4}		
137	Factory OH rate applied to station 5	f_{OH_5}	(%)	(3.50)		10%		f_{OH_5}		
138	Factory OH rate applied to station 6	f_{OH_6}	(%)	(3.50)		25%		f_{OH_6}		
139	Factory OH rate applied to station 7	f_{OH_7}	(%)	(3.50)		10%		f_{OH_7}		
140	Factory OH rate applied to station 8	f_{OH_8}	(%)	(3.50)		10%		f_{OH_8}		
141	Labor rate for a machine operator	\dot{r}_{oper}	[\$/hr]	(3.50)		11		r_{dot_oper}	labor rate	based on business practices
142	Labor rate for an assembler	\dot{r}_{assm}	[\$/hr]	(3.50)		11		r_{dot_assm}	labor rate	based on business practices
143	Labor rate for an inspector	\dot{r}_{insp}	[\$/hr]	(3.50)		11		r_{dot_insp}	labor rate	based on business practices
144	Labor rate for a packager	\dot{r}_{pack}	[\$/hr]	(3.50)		11		r_{dot_pack}	labor rate	based on business practices
145	Hourly rate for molding machine A	\dot{r}_{moldA}				30	35	$r_{dot_mold_A}$	machine hourly rate	estimated from historical machine operation data (values from Space Limited)
146	Hourly rate for molding machine B	\dot{r}_{moldB}	[\$/hr]	-		30	30	$r_{dot_mold_B}$		
147	Hourly rate for MSM machine	\dot{r}_{moldMS}				36	38	$r_{dot_mold_AB}$		
148	Load factor	f_L	(%)	(3.51)		100%	100%	f_L	investment parameter	specified/estimated (set for simplicity)
149	Write off time of investment	t_{WO}	[hr]	(3.51)		43800	43800	t_{WO}	investment parameter	set based on investment practices
150	Cost of assembly station	C_{assm}	[\$]	(3.52)		250	250	C_{assm}	equipment cost	obtained from manufacturer
151	Cost of inspection station	C_{insp}	[\$]	(3.52)		250	250	C_{insp}	equipment cost	obtained from manufacturer
152	Cost of packaging station	C_{pack}	[\$]	(3.52)		250	250	C_{pack}	equipment cost	obtained from manufacturer
153	Clamp force safety factor	f_{safe}	(%)	(3.54)		1.5	1.5	f_{safe}	processing parameter	chosen based on safety needs
154	Projected area of part A	A_{partA}				0.264	12	A_{part_A}	part geometry	CAD model file of part
155	Projected area of part B	A_{partB}	[in ²]	(3.55)		0.316	4.33	A_{part_B}		

156	Projected area of gating system A	$A_{gatingA}$	[in ²]	(3.55)	0.058	1.2	A_{gating_A}	mold geometry	CAD model file of mold
157	Projected area of gating system B	$A_{gatingB}$			0.082	0.309	A_{gating_B}		
158	Interest rate	I	[%]	(3.56)	5%		I	investment parameter	set based on investment practices
159	Number of payments	n_{pay}	[#]	(3.56)	60		n_{pay}	investment parameter	set based on investment practices
160	Hourly cost of space	\tilde{C}_S	[\$/(ft ³ ·hr)]	(3.57)	1.68E-04		\tilde{C}_{ilde_S}	factory rate	historically estimated
161	Space used by injection machine A	A_{injA}	[ft ²]	(3.58)	95	125	A_{inj_A}	machine specification	obtained from manufacturer
162	Space used by injection machine B	A_{injB}			95	95	A_{inj_B}		
163	Space used by injection machine AB	$A_{inj,AB}$			147	147	A_{inj_AB}		
164	Space used by assembly station	A_{assem}	[ft ²]	(3.58)	25	25	A_{asem}	machine specification	obtained from manufacturer
165	Space used by inspection station	A_{insp}	[ft ²]	(3.58)	15	15	A_{insp}	machine specification	obtained from manufacturer
166	Space used by packaging station	A_{pack}	[ft ²]	(3.58)	30	30	A_{pack}	machine specification	obtained from manufacturer

Appendix B – MATLAB Files

A slightly simplified version of the cost estimation model was implemented into a MATLAB program. After the necessary input values are defined, the code simply evaluates all of the model's equations and plots the cost of both variants as a function of production quantity.

The program is structured as two separate m-files: 1) the main code which symbolically stores each equation and then later combines them and numerically evaluates them, and 2) a secondary code which simply stores all the values of the input variables. The main code is run and it calls the secondary code to obtain numeric values for all the symbolic variables. It can then find the total cost as a function of Q_d and ϕ . It then plots the output as a series of cost-quantity curves. Because the program for the second case study is the same as the first (with only the values of the input variables changed), only the two codes for the first case study are reproduced below:

"Thesis_Model_Code1.m"

```
clear all; close all; clc;

%% loading all relevant equations as symbolic expressions
%% Eq. 3.1 - Switching variable
syms phi;

%% Eq. 3.2 - Total cost
syms C_M C_T C_BO C_CI C_S;
C=C_M+C_T+C_BO+C_CI+C_S;

%% Eq. 3.3 - Effective production time
syms Q_1 Q_2 Q_3 Q_4 Q_5 Q_6 Q_7 Q_8;
syms Qdot_1 Qdot_2 Qdot_3 Qdot_4 Qdot_5 Qdot_6 Qdot_7 Qdot_8;
Theta_1=(1/3600)*Q_1/Qdot_1; Theta_2=(1/3600)*Q_2/Qdot_2; Theta_3=(1/3600)*Q_3/Qdot_3;
Theta_4=(1/3600)*Q_4/Qdot_4; Theta_5=(1/3600)*Q_5/Qdot_5; Theta_6=(1/3600)*Q_6/Qdot_6;
Theta_7=(1/3600)*Q_7/Qdot_7; Theta_8=(1/3600)*Q_8/Qdot_8;

%% Eq. 3.4 - Production Quantities
syms Q_d r_d_A r_d_B;
Q_1=Q_d/(1-r_d_A); Q_2=Q_d/(1-r_d_B); Q_3=2*Q_d; Q_4=Q_d; Q_5=Q_d;
Q_6=Q_d/((1-r_d_A)*(1-r_d_B)); Q_7=Q_d; Q_8=Q_d;

%% Eq. 3.5 - Production Rates
syms n_cav t_mold_B t_mold_AB t_insp_A t_insp_B t_insp_AB t_assm t_pack;
Qdot_1=n_cav/t_mold_A; Qdot_2=n_cav/t_mold_B; Qdot_3=1/(t_insp_A+t_insp_B);
Qdot_4=1/t_assm;
Qdot_5=1/t_pack; Qdot_6=n_cav/t_mold_AB; Qdot_7=1/t_insp_AB; Qdot_8=1/t_pack;
```

```

%% Eq. 3.6 - Molding times
syms t_inj_A t_cool_A t_inj_B t_cool_B t_reset_A t_reset_B t_reset_AB max_t_mold;
t_mold_A=t_inj_A+t_cool_A; t_mold_B=t_inj_B+t_cool_B;
t_mold_AB=max_t_mold+t_reset_AB;

%% Eq. 3.7 - Injection times
syms P_inj_A P_inj_B V_shot_A V_shot_B Pi_inj_A Pi_inj_B;
t_inj_A=2*P_inj_A*V_shot_A/Pi_inj_A;
t_inj_B=2*P_inj_B*V_shot_B/Pi_inj_B;

%% Eq. 3.8 - Cooling times
syms tau_max_A tau_max_B alpha_A alpha_B T_inj_A T_inj_B T_mold_A T_mold_B T_eject_A
T_eject_B t_extra_A t_extra_B;
t_cool_A=tau_max_A^2/(pi^2*alpha_A)*log(4*(T_inj_A-T_mold_A)/(pi*(T_eject_A-
T_mold_A)))+t_extra_A;
t_cool_B=tau_max_B^2/(pi^2*alpha_B)*log(4*(T_inj_B-T_mold_B)/(pi*(T_eject_B-
T_mold_B)))+t_extra_B;

%% Eq. 3.9 - Assembly time
syms t_handle_A t_handle_B sum_t_fasteners;
t_assm=(1-phi)*(t_handle_A+t_handle_B+sum_t_fasteners);

%% Eq. 3.10 - Material cost
syms c_resin_A c_resin_B c_fasteners c_misc;
C_M=(1-
phi)*(Q_1*c_resin_A+Q_2*c_resin_B+Q_d*c_fasteners)+phi*Q_6*(c_resin_A+c_resin_B)+Q_d*c_mi
sc;

%% Eq. 3.11 - Resin cost
syms V_shot_A V_shot_B gamma_A gamma_B p_resin_A p_resin_B;
c_resin_A=V_shot_A*gamma_A*p_resin_A/n_cav;
c_resin_B=V_shot_B*gamma_B*p_resin_B/n_cav;

%% Eq. 3.12 - Shot volumes
syms V_part_A V_part_B f_rg_A f_rg_B V_gating_A V_gating_B;
r_gating_A=V_gating_A/(n_cav*V_part_A+V_gating_A);
r_gating_B=V_gating_B/(n_cav*V_part_B+V_gating_B);
V_shot_A=n_cav*V_part_A+(1-phi)*(r_gating_A-f_rg_A)*V_gating_A;
V_shot_B=n_cav*V_part_B+(1-phi)*(r_gating_B-f_rg_B)*V_gating_B;

%% Eq. 3.13 - Gating volumes
syms V_sprue_A V_sprue_B V_runners_A V_runners_B;
V_gating_A=V_sprue_A+V_runners_A;
V_gating_B=V_sprue_B+V_runners_B;
V_gating_AB=0;

%% Eq. 3.14 - Gating volume
syms f_vol_A f_vol_B;
V_gating_A=f_vol_A*V_part_A;
V_gating_B=f_vol_B*V_part_B;

%% Eq. 3.15 - Tooling cost
syms C_base C_mach C_tol C_finish C_eject C_cool C_SA C_HR C_SU;
C_T=C_base+C_mach+C_tol+C_finish+C_eject+C_cool+C_SA+C_HR+C_SU;

%% Eq. 3.16 - Mold base cost
syms C_base_A C_base_B C_base_AB;
C_base=(1-phi)*(C_base_A+C_base_B)+phi*C_base_AB;

%% Eq. 3.17 - Mold base cost
syms alpha_base A_base_A A_base_B h_base_A h_base_B Beta_base A_base_AB h_base_AB;
C_base_A= alpha_base*A_base_A*h_base_A^(2/5)+Beta_base;
C_base_B= alpha_base*A_base_B*h_base_B^(2/5)+Beta_base;
C_base_AB=alpha_base*A_base_AB*h_base_AB^(2/5)+Beta_base;

%% Eq. 3.18 - Mold base areas
syms l_A l_B w_A w_B f_A A_SA_A A_SA_B A_SA_AB;
syms max_lw;
A_base_A=n_cav*l_A*w_A*(1+f_A)+A_SA_A;
A_base_B=n_cav*l_B*w_B*(1+f_A)+A_SA_B;

```

```

A_base_AB=2*n_cav*max_lw*(1+f_A)+A_SA_AB;

%% Eq. 3.19 - Mold base heights
syms h_A h_B h_AB f_h h_SA_A h_SA_B h_SA_AB;
h_base_A=h_A*(1+f_h)+h_SA_A;
h_base_B=h_B*(1+f_h)+h_SA_B;
h_base_AB=h_AB*(1+f_h)+h_SA_AB;

%% Eq. 3.20 - Mold base areas
syms h_AB;
A_A=l_A*w_A; A_B=l_B*w_B; V_A=A_A*h_A; V_B=A_B*h_B;
syms max_lw;
A_AB=max_lw; V_AB=A_AB*h_AB;

%% Eq. 3.21 - Machining cost
syms rdot_mach t_mach_A_plus_t_mach_B t_mach_AB;
t_mach=(1-phi)*(t_mach_A_plus_t_mach_B)+phi*t_mach_AB;
C_mach=rdot_mach*t_mach;

%% Eq. 3.22 - Machining times
syms t_cavity_A t_cavity_B t_core_A t_core_B t_gating_A t_gating_B;
syms t_core_AB t_gating_AB;
t_mach_A= n_cav*(t_cavity_A+t_core_A)+t_gating_A;
t_mach_B= n_cav*(t_cavity_B+t_core_B)+t_gating_B;
t_mach_A_plus_t_mach_B=t_mach_A+t_mach_B;
t_mach_AB=n_cav*(t_cavity_A+t_cavity_B+2*t_core_AB)+t_gating_AB;

%% Eq. 3.23 - Machining times
syms V_mill Vdot_mill t_gating_A_plus_t_gating_B;
t_mach_A_plus_t_mach_B=n_cav*(V_mill/Vdot_mill)+t_gating_A_plus_t_gating_B;
t_mach_AB=n_cav*(V_mill/Vdot_mill)+t_gating_AB;

%% Eq. 3.24 - Machining volumes
syms V_cav_A V_cav_B V_core_A V_core_B;
V_mill=V_cav_A+V_cav_B+(1-phi)*(V_core_A+V_core_B)+phi*2*V_core_A;

%% Eq. 3.25 - Part volumes
syms V_convex_A V_convex_B V_concave_A V_concave_B;
V_part_A=V_convex_A-V_concave_A;
V_part_B=V_convex_B-V_concave_B;

%% Eq. 3.26 - Cavity volumes
syms f_shrink_A f_shrink_B;
V_cav_A=V_convex_A*(1+f_shrink_A);
V_cav_B=V_convex_B*(1+f_shrink_B);

%% Eq. 3.27 - Core volumes
syms h_core_A h_core_B;
V_core_A=h_core_A*(A_A*(1+f_A))-V_concave_A;
V_core_B=h_core_B*(A_B*(1+f_A))-V_concave_B;

%% Eq. 3.28 - Gating machining time
t_gating_A_plus_t_gating_B=(V_gating_A+V_gating_B)/Vdot_mill;
t_gating_AB=0;

%% Eq. 3.29 - Tolerance costs
syms rdot_tol t_tol n_tol;
% t_tol_j=
C_tol=n_cav*rdot_tol*t_tol;

%% Eq. 3.30 - Number of surfaces for tolerancing
syms n_tol_A n_tol_B n_tol_ABcavA n_tol_ABcavB n_tol_ABcore;
n_tol=(1-phi)*(n_tol_A+n_tol_B)+phi*(n_tol_ABcavA+n_tol_ABcavB+n_tol_ABcore);

%% Eq. 3.31 - Tolerancing time
syms d_rough alpha_tol Beta_tol ldot_tol;

%% Eq. 3.32 - Finishing costs
syms rdot_polish rdot_texture t_polish t_texture;
C_polish=rdot_polish*t_polish;
C_texture=rdot_texture*t_texture;

```



```

C_finish=n_cav*(C_polish+C_texture);

%% Eq. 3.33 - Number of surfaces to be polished
syms n_polish_A n_polish_B n_polish_ABcavA n_polish_ABcavB n_polish_ABcore;
n_polish=(1-
phi)*(n_polish_A+n_polish_B)+phi*(n_polish_ABcavA+n_polish_ABcavB+2*n_polish_ABcore);

%% Eq. 3.34 - Surface polishing time
syms alpha_polish Beta_polish Adot_polish;
%

%% Eq. 3.35 - Texturing time
syms f_texture;
t_texture=f_texture*t_mach;

%% Eq. 3.36 - Ejector system costs
syms alpha_pins Beta_pins n_pins;
C_eject=alpha_pins*n_pins+Beta_pins;

%% Eq. 3.37 - Number of ejector pins
syms n_pins_A n_pins_B;
n_pins=n_cav*((1-phi)*(n_pins_A+n_pins_B)+phi*2*n_pins_A);

%% Eq. 3.38 - Number of ejector pins
syms alpha_area Beta_area;
n_pins_A=alpha_area*A_A^Beta_area;
n_pins_B=alpha_area*A_B^Beta_area;

%% Eq. 3.39 - Cooling system costs
syms rdot_drill t_drill;
C_cool=rdot_drill*t_drill;

%% Eq. 3.40 - Drilling time
syms ldot_drill l_cool;
t_drill=l_cool/ldot_drill;

%% Eq. 3.41 - Cooling lengths
syms l_cool_1 l_cool_2 l_cool_3 l_cool_4 l_extra;
l_cool=n_cav*((1-
phi)*(l_cool_1+l_cool_2+l_cool_3+l_cool_4)+phi*(2*l_cool_1+l_cool_2+l_cool_4))+l_extra;

%% Eq. 3.42 - Number of undercuts
syms n_ext_A n_ext_B n_int_A n_int_B n_ext_ABA n_ext_ABB n_int_A n_int_B n_int_AB;
n_ext=(1-phi)*(n_ext_A+n_ext_B)+phi*(n_ext_ABA+n_ext_ABB);
n_int=(1-phi)*(n_int_A+n_int_B)+phi*2*n_int_AB;

%% (unnumbered Eq.)
syms A_int_j A_ext_k;
%

%% Eq. 3.43 - Side action costs
syms alpha_int Beta_int alpha_ext Beta_ext;
% Eq. 3.48 is computed in variable file, "Thesis_Model_Vars_1.m"

%% Eq. 3.44 - Side action costs
syms C_SA_j C_SA_k;
C_SA=n_cav*(sum(C_SA_j)+sum(C_SA_k));

%% Eq. 3.45 - Hot runner costs
syms C_HR_A C_HR_B C_HR_AB
C_HR=(1-phi)*(C_HR_A+C_HR_B)+phi*(C_HR_AB);

%% Eq. 3.46 - Hot runner costs
syms alpha_HR Beta_HR;
C_HR_A=alpha_HR*A_base_A+Beta_HR;
C_HR_B=alpha_HR*A_base_B+Beta_HR;
C_HR_AB=alpha_HR*A_base_AB+Beta_HR;

%% Eq. 3.47 - Setup costs
syms C_SU_A C_SU_B C_SU_AB;
C_SU=(1-phi)*(C_SU_A+C_SU_B)+phi*C_SU_AB;

```

```

%% Eq. 3.48 - Setup costs
syms alpha_SU Beta_SU_1 Beta_SU_2;
C_SU_A=alpha_SU*A_base_A+Beta_SU_1;
C_SU_B=alpha_SU*A_base_B+Beta_SU_1;
C_SU_AB=alpha_SU*A_base_AB+Beta_SU_2;

%% Eq. 3.49 - Basic overhead cost
syms Cdot_BO_1 Cdot_BO_2 Cdot_BO_3 Cdot_BO_4 Cdot_BO_5 Cdot_BO_6;
syms Cdot_BO_7 Cdot_BO_8;
C_BO=(1-phi)*(Theta_1*Cdot_BO_1+Theta_2*Cdot_BO_2+Theta_3*Cdot_BO_3+Theta_4*Cdot_BO_4...
+Theta_5*Cdot_BO_5)+phi*(Theta_6*Cdot_BO_6+Theta_7*Cdot_BO_7+Theta_8*Cdot_BO_8);

%% Eq. 3.50 - Basic overhead rates
syms f_OH_1 f_OH_2 f_OH_3 f_OH_4 f_OH_5 f_OH_6 f_OH_7 f_OH_8;
syms rdot_mold_A rdot_mold_B rdot_mold_AB rdot_oper rdot_insp rdot_assm rdot_pack;
Cdot_BO_1=(1+f_OH_1)*(rdot_mold_A+rdot_oper);
Cdot_BO_2=(1+f_OH_2)*(rdot_mold_B+rdot_oper);
Cdot_BO_3=(1+f_OH_3)*rdot_insp; Cdot_BO_4=(1+f_OH_4)*rdot_assm;
Cdot_BO_5=(1+f_OH_5)*rdot_pack; Cdot_BO_6=(1+f_OH_6)*(rdot_mold_AB+rdot_oper);
Cdot_BO_7=(1+f_OH_7)*rdot_insp; Cdot_BO_8=(1+f_OH_8)*rdot_pack;

%% (unnumbered Eq.)
syms rdot_mold_A rdot_mold_B rdot_mold_AB;

%% Eq. 3.51 - Capital investment cost
syms f_I f_L t_WO C_C_1 C_C_2 C_C_3 C_C_4 C_C_5 C_C_6 C_C_7 C_C_8;
C_CI=f_I/(f_L*t_WO)*((1-phi)*(Theta_1*C_C_1+Theta_2*C_C_2+Theta_3*C_C_3+...
Theta_4*C_C_4+Theta_5*C_C_5)+phi*(Theta_6*C_C_6+Theta_7*C_C_7+...
Theta_8*C_C_8));

%% Eq. 3.52 - Equipment costs
syms C_mach_A C_mach_B C_mach_AB C_insp C_assm C_pack C_platen;
C_C_1=C_mach_A; C_C_2=C_mach_B; C_C_3=C_insp; C_C_4=C_assm; C_C_5=C_pack;
C_C_6=C_mach_AB+C_platen; C_C_7=C_insp; C_C_8=C_pack;

%% Eq. 3.53 - Machine costs
syms C_press_A C_press_B C_inj_A C_inj_B C_press_AB;
C_mach_A=C_press_A+C_inj_A;
C_mach_B=C_press_B+C_inj_B;
C_mach_AB=C_press_AB+C_inj_A+C_inj_B;

%% (unnumbered Eq.)
syms C_press_A C_press_B C_press_AB;
%

%% Eq. 3.54 - Clamp forces
syms f_safe P_inj_A P_inj_B A_proj_A A_proj_B;
F_clamp_A=f_safe*P_inj_A*A_proj_A;
F_clamp_B=f_safe*P_inj_B*A_proj_B;
F_clamp_AB=f_safe*(P_inj_A*A_proj_A+P_inj_B*A_proj_B);

%% Eq. 3.55 - Projected areas
syms A_part_A A_part_B A_gating_A A_gating_B;
A_proj_A=n_cav*A_part_A+A_gating_A;
A_proj_B=n_cav*A_part_B+A_gating_B;

%% (unnumbered Eq.)
syms V_barrel_A V_barrel_B;
syms C_inj_A C_inj_B;
%

%% (unnumbered Eq.)
syms D_platen;

%% Eq. 3.56 - Interest factor
syms I n_pay;
f_I=I*(1+I)^n_pay/((1+I)^n_pay-1);

%% Eq. 3.57 - Space cost
syms Ctilde_S A_1 A_2 A_3 A_4 A_5 A_6 A_7 A_8;

```

```

C_S=Ctilde_S*((1-phi)*(Theta_1*A_1+Theta_2*A_3+Theta_3*A_3+Theta_4*A_4...
+Theta_5*A_5)+phi*(Theta_6*A_6+Theta_7*A_7+Theta_8*A_8));

%% Eq. 3.58 - Floor space
syms A_inj_A A_inj_B A_inj_AB A_insp A_assm A_pack;
A_1=A_inj_A; A_2=A_inj_B; A_3=A_insp; A_4=A_assm;
A_5=A_pack; A_6=A_inj_AB; A_7=A_insp; A_8=A_pack;
%%% done loading all relevant equations as symbolic expressions

%%% loading input values and override values
Thesis_Model_Vars1;
%%% done loading input values and override values

%%% evaluating Cost using input values
CSYM=eval(eval(eval(eval(eval(eval(eval(C)))))));
%% done evaluating Cost using input values

%%% plotting Cost verse production quantity
phi_j=[0 1];
Q_d_i=linspace(1,10E6,1000);

for j=1:2
    phi=phi_j(j);
    for i=1:length(Q_d_i)
        Q_d=Q_d_i(i);
        C_eval(j,i)=eval(CSYM);
    end
end

i_max=20;
figure(1); hold on;
plot(Q_d_i(1:i_max),C_eval(1,1:i_max),'b-');
plot(Q_d_i(1:i_max),C_eval(2,1:i_max),'b--');
xlabel('Production Quantity, Q_{d} [parts]'); ylabel('Total Cost, C [$]');
title('Plot Ia - Total Cost vs. Production Quantity');
legend('SMM&A','MMM',2);
axis equal tight; grid; hold off;

figure(2); hold on;
plot(log(Q_d_i),log(C_eval(1,:)./Q_d_i),'b-');
plot(log(Q_d_i),log(C_eval(2,:)./Q_d_i),'b--');
xlabel('log(Q_{d}) [log(parts)]'); ylabel('log(c=C/Q_{d}) [log($)]');
title('Plot Ib - Log-Log Plot of Unit Cost vs. Production Quantity');
legend('SMM&A','MMM',2);
axis equal tight; grid; hold off;
%%% done plotting Cost verse production quantity

```

"Thesis_Model_Vars1.m"

```

%%% Standard Input Variables
r_d_A=.023; r_d_B=.020; max_r_d=max(r_d_A,r_d_B);
n_cav=10;
t_insp_A=1.5; t_insp_B=1.5; t_insp_AB=2;
t_pack=.25;
t_reset_A=9; t_reset_B=11; t_reset_AB=13;
P_inj_A=15997; P_inj_B=17000;
Pi_inj_A=66000; Pi_inj_B=66000;
tau_max_A=.126; tau_max_B=.10;
alpha_A=.000125; alpha_B=.000155;
T_inj_A=540; T_inj_B=470;
T_mold_A=153; T_mold_B=80;
T_eject_A=165; T_eject_B=90;
t_extra_A=0; t_extra_B=0;
t_handle_A=1.6; t_handle_B=1.6;
t_insert_B=2.7;

```

```

t_insert_j=[]; % indexed expressions for Eq. 3.#
t_handle_j=[]; % indexed expressions for Eq. 3.#

n_fast=0;
c_fasteners=0;
c_misc=0;
gamma_A=.039; gamma_B=.024;
p_resin_A=2.00; p_resin_B=2.75;
V_part_A=.044; V_part_B=.033;
f_rg_A=0; f_rg_B=0;

% V_sprue_A= ; V_sprue_B= % not needed, using f_vol_i instead
% V_runners_A= ; V_runners_B= % not needed, using f_vol_i instead
f_vol_A=.22; f_vol_B=.26;

Beta_base=1000;
alpha_base=.45;
l_A=.579; l_B=.634;
w_A=.579; w_B=.634; max_lw=max(l_A*w_A,l_B*w_B);
f_A=1.65;
A_SA_A=0; A_SA_B=0; A_SA_AB=0;
h_A=.573; h_B=.567; h_AB=.567;
f_h=1.60;
h_SA_A=0; h_SA_B=0; h_SA_AB=0;
rdot_mach=50;
Vdot_mill=.09;
V_convex_A=.082; V_convex_B=.115;
V_concave_A=.038; V_concave_B=.081;
f_shrink_A=0; f_shrink_B=0;
h_core_A=.491; h_core_B=.567;
rdot_tol=50;
n_tol_A=0; n_tol_B=0;
n_tol_ABCavA=0; n_tol_ABCavB=0;
n_tol_ABcore=0;

A_j1=[]; % indexed expressions for Eq. #
d_j=[]; % indexed expressions for Eq. #

d_rough=.000984;
ldot_tol=60;
rdot_polish=50;
n_polish=0;
rdot_texture=50;
t_texture=0;
n_polish_A=0; n_polish_B=0;
n_polish_ABCavA=0; n_polish_ABCavB=0;
n_polish_ABcore=0;

A_j2=[]; % indexed expressions for Eq. #
s_j=[]; % indexed expressions for Eq. #

A_dot_polish=4.2;

syms alpha_polish; % need accurate value, but overridden below
syms Beta_polish; % need accurate value, but overridden below

f_texture=0;
alpha_pins=125;
Beta_pins=0;
alpha_area=1;
Beta_area=.5;
rdot_drill=50;
ldot_drill=10;
l_cool_1=15;
l_cool_2=17;
l_cool_3=15;
l_cool_4=17;
l_extra=11;
n_ext_A=0; n_ext_B=0;
n_ext_ABA=0; n_ext_ABB=0;
n_int_A=0; n_int_B=0; n_int_AB=0;

```

```

A_int_j=[]; % indexed expressions for Eq. 3.47
A_ext_k=[]; % indexed expressions for Eq. 3.47

syms Beta_int; % need accurate value, but overridden below
syms alpha_int; % need accurate value, but overridden below
syms Beta_ext; % need accurate value, but overridden below
syms alpha_ext; % need accurate value, but overridden below
syms alpha_HR; % need accurate value, but overridden below
syms Beta_HR; % need accurate value, but overridden below
syms alpha_SU; % need accurate value, but overridden below
syms Beta_SU1; % need accurate value, but overridden below
syms Beta_SU2; % need accurate value, but overridden below

f_OH_1=.37; f_OH_2=.37; f_OH_3=.10; f_OH_4=.10; f_OH_5=.10;
f_OH_6=.25; f_OH_7=.10; f_OH_8=.10;
rdot_oper=11;
rdot_assm=11;
rdot_insp=11;
rdot_pack=11;
rdot_misc=11;
rdot_mold_A=30; rdot_mold_B=30; rdot_mold_AB=36;
f_L=1;
t_WO=43800;
C_assm=250;
C_insp=250;
C_pack=250;
f_safe=1.5;
A_part_A=.264; A_part_B=.316;
A_gating_A=.058; A_gating_B=.082;
I=.05;
n_pay=60;
Ctilde_S=1.68E-4;
I=.05;
n_pay=60;
A_inj_A=95; A_inj_B=95; A_inj_AB=147;
A_assm=25;
A_insp=15;
A_pack=30;
%%% End of standard input variables

%% Override variables and equations
sum_t_fasteners=sum(t_insert_j)+sum(t_handle_j);

t_tol=0;
if length(d_j)>=1
    for j=1:length(d_j)
        t_tol_j(j)=A_j1(j)*(d_rough-d_j(j))^alpha_tol/(ldot_tol*Beta_tol);
    end
t_tol=sum(t_tol_j);
end

t_polish=0;
if length(A_j2)>=1
    for j=1:length(A_j2)
        t_polish_j(j)=A_j(j)*s_j(j)^alpha_polish/(Adot_polish*Beta_polish)
    end
t_polish=sum(t_polish_j);
end

C_SA_j=[]; C_SA_k=[];
if length(A_int_j)>=1
    for j=1:length(A_int_j)
        C_SA_j=alpha_int*A_int_j(j)+Beta_int;
    end
end
if length(A_ext_k)>=1
    for k=1:length(A_ext_k)
        C_SA_k=alpha_ext*A_ext_k(k)+Beta_ext;
    end
end
end

```

```
C_SA=sum(C_SA_j)+sum(C_SA_k);  
C_platen=60000;  
C_SU_A=200; C_SU_B=200; C_SU_AB=280;  
C_HR_A=0; C_HR_B=0; C_HR_AB=7000;  
C_mach_A=150000; C_mach_B=150000; C_mach_AB=220000;  
max_t_mold=t_mold_A;  
n_pins_A=ceil(eval(n_pins_A)); n_pins_B=ceil(eval(n_pins_B));  
%% End of override variables and equations
```

Appendix C – Engineering Drawings

The following figures are drawings for the products studied in Case Studies I & II. They are a little more detailed than the figures in Chapter 5 and include some important dimensions as well.

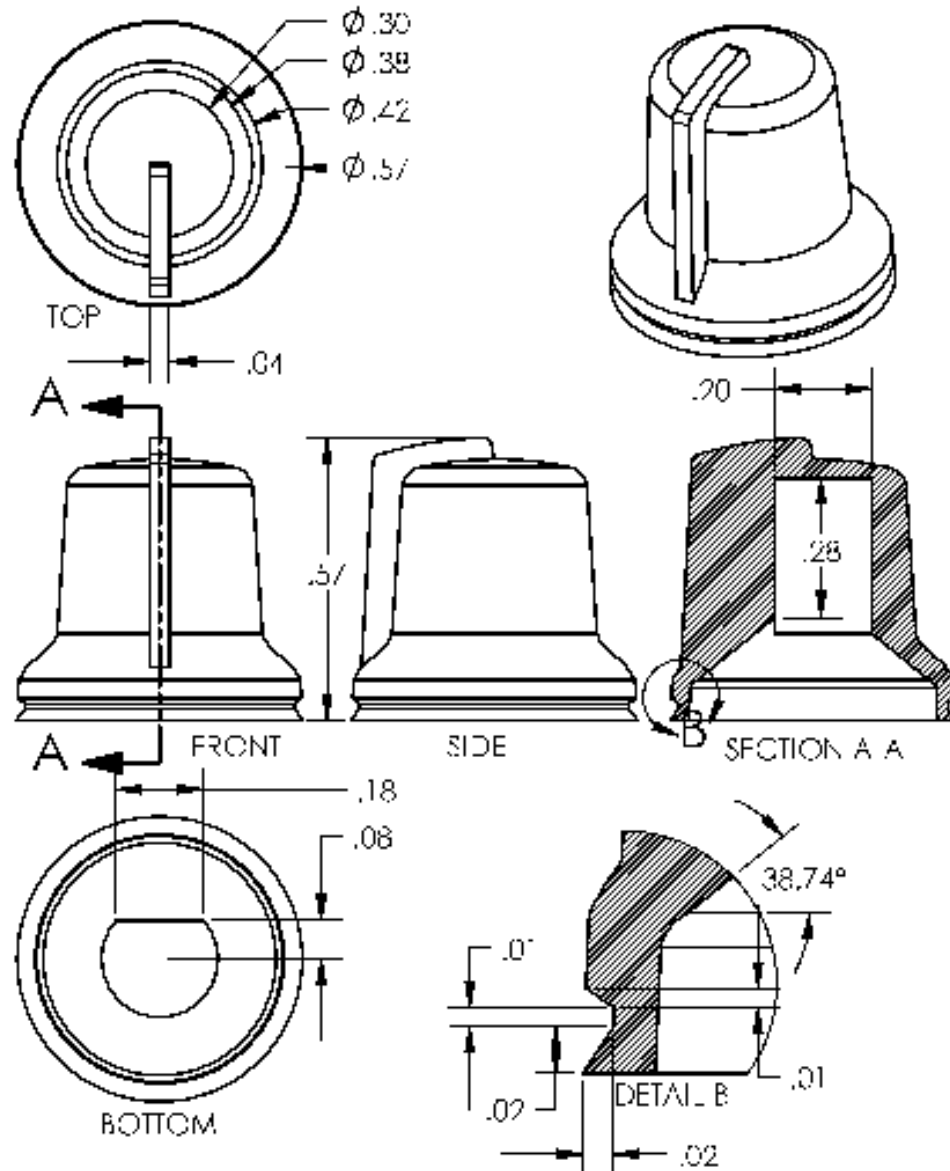


Figure C1 – Detailed drawing of SMM&A knob, Part A

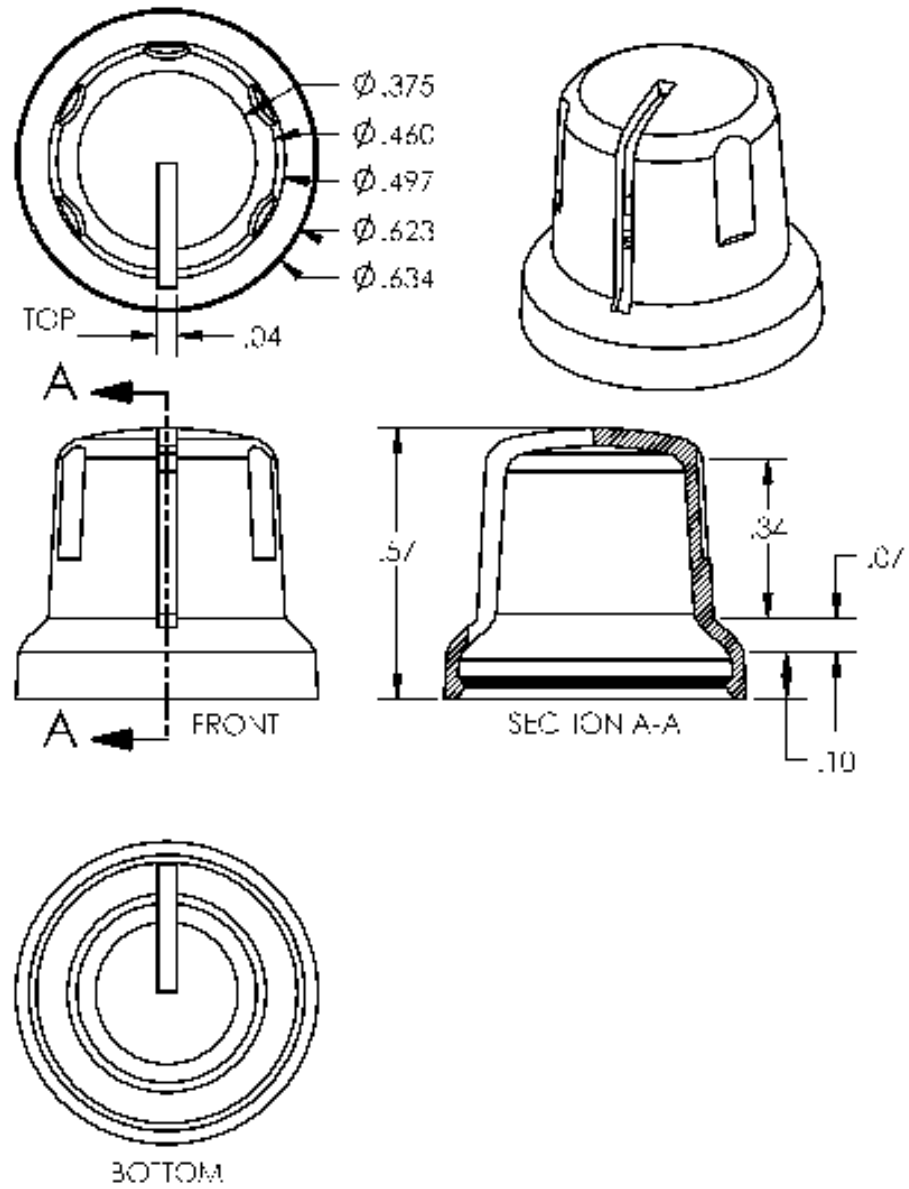


Figure C2 – Detailed drawing of SMM&A knob, Part B

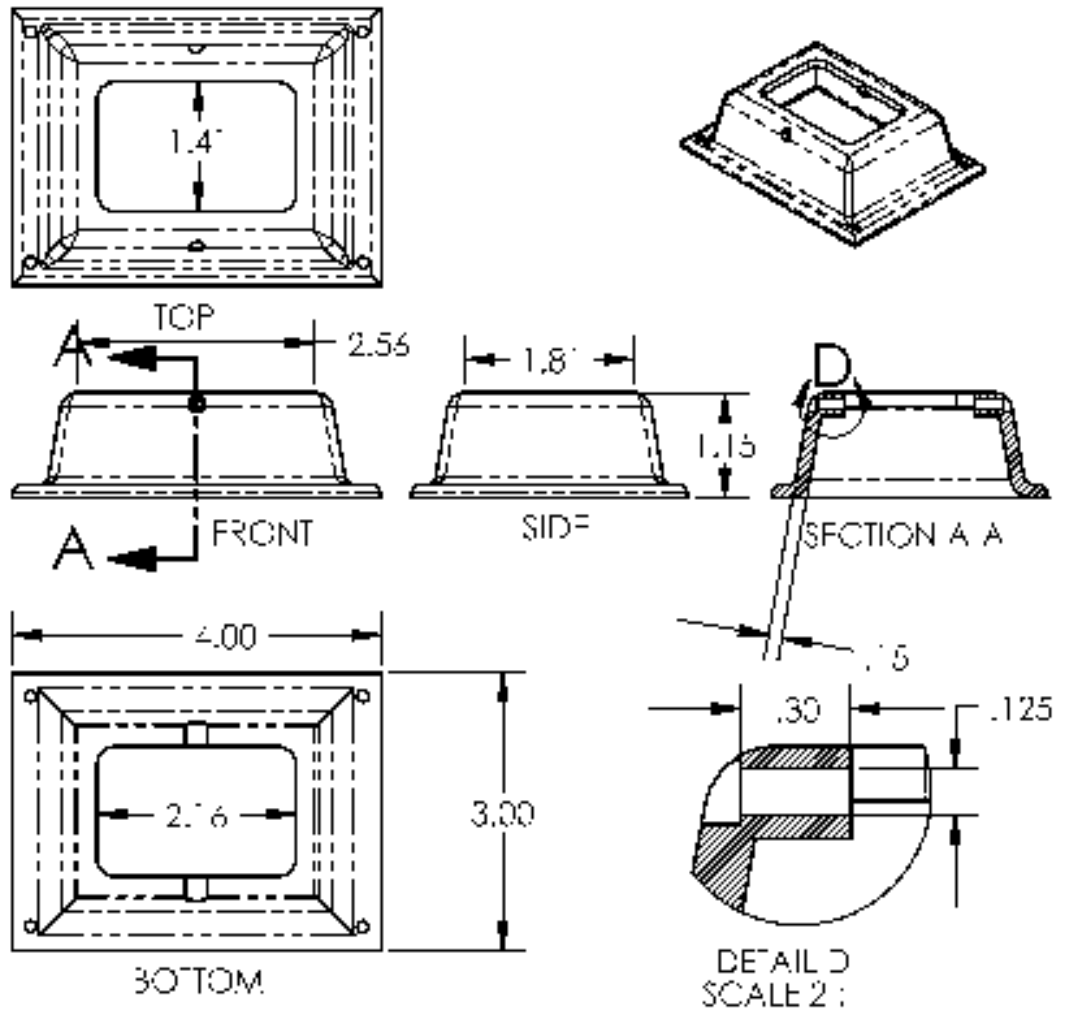


Figure C3 – Detailed drawing of SMM&A vent, Part A

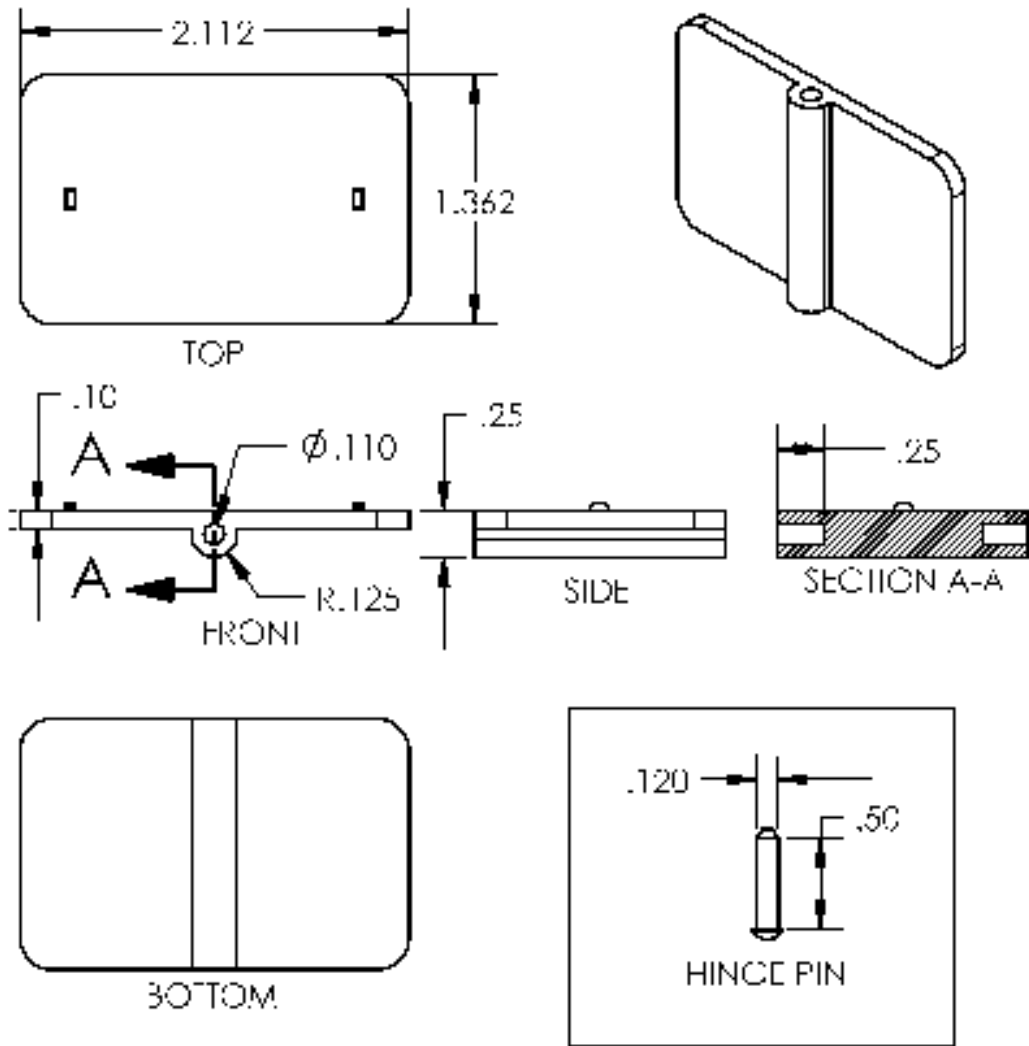


Figure C4 – Detailed drawing of SMM&A vent, Part B & hinge pin

Appendix D – FEA Loads & Restraints

The following two figures show how both variants of the vent's Part B were constrained and loaded for the FEA simulations of Section 5.2.3.2.

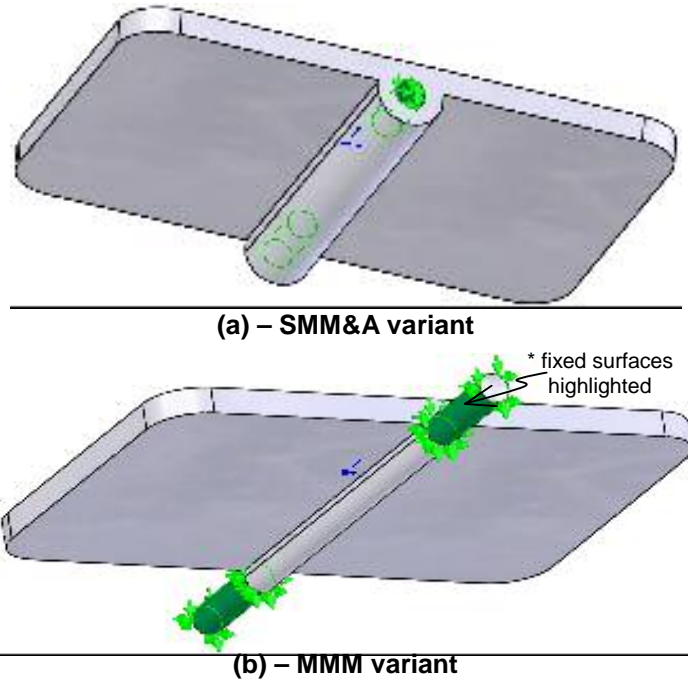


Figure D1 – Constrained surfaces for FEA analysis

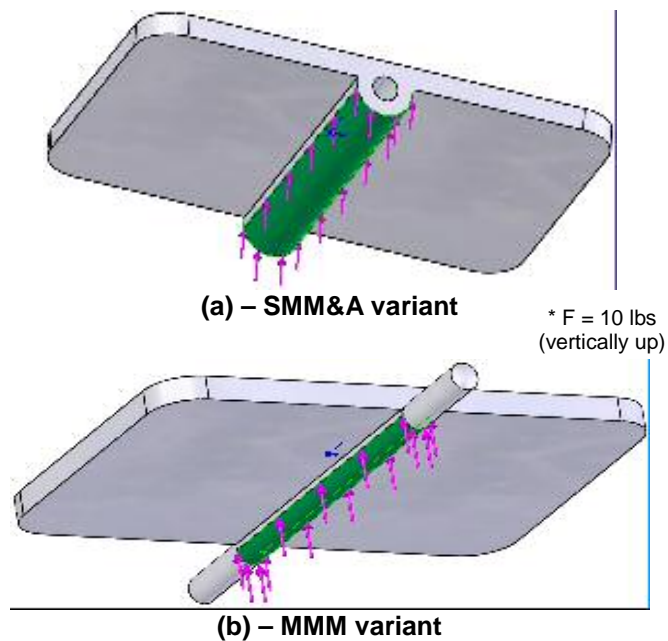


Figure D2 – Applied Loadings for FEA analysis

REFERENCES

- [1] Michael F. Ashby. *Materials Selection in Mechanical Design*. Butterworth-Heinemann: London, England, 1999.
- [2] W. M. Baker. Understanding Activity-Based Costing. *Industrial Management*, Vol. 36 (3/1994), pp.28-30.
- [3] J. Beaman, D. Bourell, B. Jackson, L. Jepson, D. McAdams, J. Perez, and K. Wood. Multi-Material Selective Laser Sintering: Empirical Studies and Hardware Development. In *Proceedings of the 2000 NSF Design and Manufacturing Grantees Conference*, January 2000.
- [4] Kurt A. Beiter, Brent Cheldelin, and Kosuke Ishii. Assembly Quality Method: A Tool in Aid of Product Strategy, Design, and Process Improvements. In *Proceedings of DETC'00: ASME 2000 Design Engineering Technical Conferences (DETC2000/DFM-14020)*. Baltimore, Maryland, September 2000.
- [5] David Ben-Arieh, and Li Qian. Activity-Based Cost Management for Design and Development Stage. *International Journal of Production Economics*, Vol. 83 (2003), pp.169-183.
- [6] Berkeley Integrated Manufacturing Lab. Manufacturing Advisory Service. *online software*, 3/31/1999. <http://cybercut.berkeley.edu/mas2/html/applet/index.html>.
- [7] J. T. Black. *The Design of Factory with a Future*. McGraw-Hill, Inc.: New York, New York, 1991.
- [8] Geoffrey Boothroyd. *Assembly Automation and Product Design*. Marcel Dekker, Inc.: New York, New York, 1992.
- [9] Geoffrey Boothroyd, Peter Dewhurst, and Winston Knight. *Product Design for Manufacture and Assembly*, 2nd Edition. Marcel Dekker, Inc.: New York, New York, 2002.
- [10] Ralph Brindle. Space Limited Inc., Baltimore, Maryland. *verbal interview*. 4/17/2003.
- [11] Douglas M Bryce. *Plastic Injection Molding, Vol. I: Manufacturing Process Fundamentals*. Society of Manufacturing Engineers: Dearborn, Michigan, 1996.
- [12] Douglas M Bryce. *Plastic Injection Molding, Vol. III: Mold Design and Construction Fundamentals*. Society of Manufacturing Engineers: Dearborn, Michigan, 1996.
- [13] Robin Cooper, and Robert S. Kaplan. Measure Costs Right: Make the Right Decisions. *Harvard Business Review*, Vol. 65 (5), April 15 2000, pp.96-103.
- [14] Robin Cooper, and Robert S. Kaplan. How Cost Accounting Distorts Product Cost. *Management Accounting*, April 2002.
- [15] S. Dhaliwal, S.K. Gupta, J. Huang, and M. Kumar. A Feature-Based Approach to Automated Decomposition of Multi-Piece Sacrificial Molds. Accepted for publication in *IMECE 2001 DFM Symposium*, 2001.

- [16] Amal M. Esawi, and Michael F. Ashby. Cost Estimation for Process Selection. In *Proceedings of DETC99: ASME Design for Manufacture Conference* (DETC99/DFM-8919). Las Vegas, Nevada, September 1999.
- [17] Esawi, Amal M., and Michael F. Ashby. Cost-Based ranking for Manufacturing Process Selection. In *Proceedings of IDMMME98: 2nd International Conference on Integrated Design and Manufacturing in Mechanical Engineering*. Compiegne, France, 1998. pp.1001-1008.
- [18] Adekunle Fagade, and David O. Kazmer. Early Cost Estimation for Injection Molded Components. *Journal of Injection Molding Technology*, September 2000, Vol. 4 (3), pp.97-106.
- [19] Adekunle Fagade, and David O. Kazmer. Economic Design of Injection Molded Parts Using DFM Guidelines - A review of Two Methods for Tooling Cost Estimation. 2000.
- [20] J. R. Fessler, A. H. Nickel, G. Link, F. B. Prinz, and P. Fussell. Functional Gradient Metallic Prototypes through Shape Deposition Manufacturing. In *Proceedings of the 1997 Solid Freeform Fabrication Symposium*. University of Texas at Austin, Austin, Texas. August 1997.
- [21] Frank. R. Field. Fundamentals of Process-Based Cost Modeling. *online presentation*, MIT Materials Systems Laboratory website. 9/5/2003.
http://ardent.mit.edu/real_options/RO_current_lectures/ESD%2003%20Slides/Process_CostModel03.pdf
- [22] Bruck, H. A., Fowler, G., Gupta, S. K., Valentine, T. M. Using Geometric Complexity to Enhance the Interfacial Strength of Heterogeneous Structures Fabricated in a Multi-Stage, Multi-Piece Molding Process. *Experimental Mechanics*, Vol. 44, 2004, pp.261-271.
- [23] Galorath Software. SEER DFM. *software*, version 5.0.
http://www.galorath.com/tools_manuf.shtm.
- [24] V. Goodship and J.C. Love. *Multi-Material Injection Moulding*. Rapra Technology LTD.: Shawbury, UK, 2002.
- [25] Mikell P. Groover. *Automation, Production Systems, and Computer-Integrated Manufacturing*. Prentice-Hall: Upper Saddle River, New Jersey, 2001.
- [26] John Hahn. Case Study for Multi-Shot. *SPE ANTEC Papers*, #78, 1999.
- [27] Robert B. Hare. Technical Multicolor/Component Injection Molding to Enhance Product, Reduce Cost. In *Proceedings of Multi-Shot Injection Molding* (CM97-210). Chicago, Illinois, 8/25/1997.
- [28] Wallace J. Hopp, and Mark L. Spearman. *Factory Physics. Foundations of Manufacturing Management*. Irwin McGraw-Hill: New York, New York, 1996.
- [29] Weiyi Hu, and Corrado Poli. To Injection Mold, to Stamp, or to Assemble? Part I: A DFM Cost Perspective. In *Proceedings of DETC97: ASME Design Engineering Technical Conferences* (DETC97/DTM-3896). Sacramento California, September 1997.

- [30] Weiyi Hu, and Corrado Poli. To Injection Mold, to Stamp, or to Assemble? Part II: A Time-to-Market Perspective. In *Proceedings of DETC97: ASME Design Engineering Technical Conferences* (DETC97/DTM-3896). Sacramento California, September 1997.
- [31] Interplast Corporation. Advances in TPE Adhesion Technology from M.A. Hanna Engineered Materials Solve Overmolding Challenges. *online article*, 1998. <http://www.interplast.se/n10.htm>.
- [32] David Kazmer, Ruchi Karania, and Christoph Roser. Plastics Product and Process Design Strategies. Submitted for *Proceedings of DETC04: ASME Design Engineering Technical Conferences* (DETC04/DFM). 2004.
- [33] David Kazmer. Injection Molding Cost Estimator. *online software*, 6/1/2004. <http://www.ecs.umass.edu/mie/faculty/kazmer/imcost/imcost.html>.
- [34] John Kietzman. Rapid Prototyping Polymer Parts via Shape Deposition Manufacturing. *Ph.D. Thesis, Stanford University*, February 1999.
- [35] Carl Kirkland. Rediscovering, unleashing the value of coinjection. *IMM Magazine* (online version). 12/2001. http://www.immnet.com/article_printable.html?article=1766.
- [36] Malay Kumar. Automated Design of Multi-Stage Molds for Manufacturing Multi-Material Objects. *Master of Science Thesis, University of Maryland, College Park* 2001.
- [37] C.L. Li. A Feature-Based Approach to Injection Mould Cooling System Design. *Computer-Aided Design*, Vol. 33 (2001), pp.1073-1090.
- [38] Robert A. Malloy. *Plastic Part Design for Injection Molding: And Introduction*. Hanser Gardner Publications, Inc.: Cincinnati, Ohio, 1994.
- [39] Michelle Maniscalco. Basic Elements: Simplifying multicomponent design. *IMM Magazine* (online version). 3/2004. <http://www.immnet.com/articles?article=2343>.
- [40] Materials Systems Laboratory. Introduction to Technical Cost Modeling: Concepts and Illustrations. *Online Presentation*, MIT Materials Systems Laboratory website. 10/3/2001. <http://msl1.mit.edu/mib/dsp/curricula.mit.edu/~dsplan/Docs/Sessions/S6/s6a.pdf>.
- [41] R. Merz, F. B. Prinz, K. Ramaswami, M. Terl, and L. Weiss. Shape Deposition Manufacturing. In *Proceedings of the 1994 Solid Freeform Fabrication Symposium*. 1994.
- [42] MGS MFG. Group. Multishot Seminar. *seminar notes*, 4/23/2002. <http://www.multishot.com/seminars/seminars.htm>.
- [43] Panicos A. Nicolaou, and Deborah L. Thurston. Machining: Quality, Cost and Environmental Estimation and Tradeoffs. In *Proceedings of DETC'00: ASME 2000 Design Engineering Technical Conferences* (DETC2000/DFM-14010). Baltimore, Maryland, September 2000.
- [44] E. Oberg, et. al. *Machinery's Handbook*, 25th Edition. Industrial Press: New York, 1996.

- [45] Kevin Otto, and Kristin Wood. *Product Design: Techniques in Reverse Engineering and New Product Development*. Prentice Hall: Upper Saddle River, New Jersey, September 2000.
- [46] M. Özbayrak, M. Akgün, and A.K. Türker. Activity-Based Cost Estimation in a Push/Pull Advanced Manufacturing System. *International Journal of Production Economics*, Vol. 87 (1), January 2004, pp.49-65.
- [47] Kulwant S. Pawar, and Helen Driva. Performance Measurement for Product Design and Development in a Manufacturing Environment. *International Journal of Production Economics*, Vols. 60-61 (1999), pp.61-68.
- [48] John D. Pirkl. Automating the Multi-Component Molding Process. In *Proceedings of Technologies for Multi-Material Injection Molding* (CM98-206). Troy, Michigan, May 1998.
- [49] Hermann Plank. Overmolding-Stack-Mold Technology: An Innovative Concept in Multi-Component Injection Molding. *SME Technical Papers* (CM02-225), 2002.
- [50] Corrado Poli. *Design for Manufacturing, A Structured Approach*. Butterworth-Heinemann: Boston, Massachusetts, 2001.
- [51] Presma Corporation. Coinjection FAQ. *Online FAQ*, 3/31/2001. http://www.presma.com/c_coinjection/faqs.html.
- [52] A. Priyadarshi, and S.K. Gupta. Geometric algorithms for automated design of multi-piece permanent molds. *Computer Aided Design*, Vol. 36, No. 3 (2004). pp.241-260.36(3):241—260, 2004.
- [53] Sumaira Rehman, and Marin D. Guenov. A Methodology for Modelling Manufacturing Costs at Conceptual Design. *Computers and Industrial Engineering*, Vol. 35, Nos.3-4 (1998). pp.623-626.
- [54] Dominick V. Rosato, Donald V. Rosato, and Marlene G. Rosato. *Injection Molding Handbook, Third Edition*. Kluwer Academic Publishers: Boston, Massachusetts, 2000.
- [55] Dominick V. Rosato, Donald V. Rosato, and Marlene G. Rosato. *Plastics Design Handbook*. Kluwer Academic Publishers: Boston, Massachusetts, 2001.
- [56] Joseph Sarkis. Quantitative Models for Performance Measurement Systems - Alternate Considerations. *International Journal of Production Economics*, Vol. 86 (2003), pp.67-84.
- [57] P. Suwignjo, U.S. Bititci, and A.S. Carrie. Quantitative Models for Performance Measurement System. *International Journal of Production Economics*, Vol. 64 (2000), pp.231-241.
- [58] William Winchell. *Realistic Cost Estimating For Manufacturing: Second Edition*. Society of Manufacturing Engineers: Dearborn Michigan, 1989.
- [59] Armen Zakarian, and Andrew Kusiak. Process Analysis and Reengineering. *Computers & Industrial Engineering*, Vol. 41 (2001), pp.135-150.

- [60] S.K. Gupta, Y. S. Chen, S. Feng, and R. Sriram. A system for generating process and material selection advice during embodiment design of mechanical components. *SME Journal of Manufacturing Systems*, Vol. 22 (2003), pp.28-45.