Quality Measurement in the Wood Products Supply Chain

by

Omar A. Espinoza

Dissertation submitted to the faculty of the
Virginia Polytechnic Institute and State University in
partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Wood Science and Forest Products

Approved:

Brian Bond, Chair

Phil Araman | Deborah Cook

Earl Kline | Robert Smith

May 1st, 2009

Blacksburg, Virginia

Keywords: supply chain, supply chain management, quality, performance
measurement, six sigma

Quality Measurement in the Wood Products Supply Chain

Omar A. Espinoza

(ABSTRACT)

The purpose of this research is to learn about quality measurement practices in a wood products supply chain. According to the Supply Chain Management paradigm, companies no longer compete as individual entities, but as part of complex networks of suppliers and customers, linked together by flows of materials and information. Evidence suggests that a high degree of integration between supply chain members is essential to achieve superior market and financial performance. This study investigates the potential benefits from adopting supply chain quality management practices, focusing specifically on quality measurement.

A case-study was conducted to accomplish the objectives of the research. An exemplary wood products supply chain was studied in great detail. The current state was compared with best practices, as reported in the literature. Supply chain quality metrics were used to assess current performance and a simulation model was developed to estimate the impact of changes in significant factors affecting quality, such as production volume, on the supply chain's quality performance.

Quality measurement practices in the supply chain of study are described in detail in this dissertation. A high degree of internal integration was observed in the focal company, attributed in great part to the leadership of management, which formulates comprehensive quality planning, specifying quality measurement practices and goals. These practices provide the company with a competitive advantage, and have undoubtedly contributed to its relatively strong market share and financial performance. Significant improvements in defect rate and on-time performance at all levels in the supply chain have been achieved in great part thanks to current initiatives. There is room for improvement, however, regarding external integration; the supply chain of study could benefit from more information sharing with its external suppliers and increasing its supplier development efforts. There is also a lack of true measures of supply chain quality performance that could facilitate tracing variances back to their origin upstream the supply chain. Supply chain metrics must reflect the contribution of each supply chain member to the overall performance, and span the entire supply chain.

This is the first study that looks in depth at quality measurement practices from a supply chain perspective. It is also one of very few studies of supply chain management applied to the wood products industry. Examples are presented of how a supply chain performance measurement system can be developed. Results from this research show that it is important to adopt a supply chain perspective when designing a performance measurement system, not least to avoid sub-optimization. Poor quality at any point in the supply chain eventually translates into higher prices for the final customer, is detrimental to customer dissatisfaction, and hurts profitability; with the end result of declining competitiveness of the entire system.

Acknowledgements

My deepest appreciation and respect to my advisor, Dr. Brian Bond, who supported, guided, and encouraged me during five years of graduate studies.

Appreciation to my Committee members, Phil Araman, Dr. Deborah Cook, Dr. Earl Kline, and Dr. Robert Smith; for their guidance and suggestions, which contributed to improve this work.

Special thanks to the personnel at the companies visited during this study, for their time and patience.

Sincere thanks to my fellow graduate student Tim Stiess, for his friendship and valuable assistance during my research.

Finally, I would like to thank the staff at the Wood Science Department of Virginia Tech.

This dissertation is dedicated to my family.

Table of Contents

Chapter 1. Introduction and Literature Review 1

1.1 Industry Background 1
1.2 Problem Statement 5
1.3 Research Questions 6
1.4 Purpose and Objectives 7
1.5 Research Contributions 7
1.5.1 Contributions to the field of Wood Science and Forest Products 7
1.5.2 Contributions to the field of Supply Chain Management 7
1.5.3 Practical Contributions 8
1.6 Literature Review 9
1.6.1 Supply Chain Management 9
1.6.2 Supply Chain Integration 12
1.6.3 Performance Measurement 15
1.6.4 Supply Chain Performance Measurement 18
1.6.5 Quality Framework 21
1.6.6 Quality Improvement 28
1.6.7 Quality Management 31
1.6.8 Supply Chain Quality Management 33
1.6.9 Impact of Supply Chain Quality Management on Performance 38
1.6.10 Summary of the Literature Review 41

Chapter 2. Research Methods 43

2.1 Overview of Case Study Research 44
2.2 Overview of Value Stream Mapping 47
2.3 Overview of System Dynamics 49
2.4 Data Collection and Analysis 52
2.4.1 Supply Chain Framework 54
2.4.2 Quality Framework 54
2.4.3 Pareto Analysis and Histograms 55
2.4.4 Kolmogorov-Smirnov Goodness of Fit Test 56
2.4.5 Correlation and Regression Analysis 57

Chapter 3. Supply Chain Structure 59

3.1 Introduction 59
3.2 Value Creation Network 59
3.3 Final Customers 60
3.4 Product Lines 62
3.5 Species 63
3.6 Distribution Channel 64

3.7 Scope of the Study ... 65
3.8 Supply Chain Entities ... 66
3.8.1 Lumber Suppliers to the Door Plant ... 66
3.8.2 Door Plant ... 67
3.8.3 Assembly Plant ... 70
3.8.4 Retailer ... 73
3.8.5 Service Center and Construction Company ... 74
3.8.6 Construction Company ... 74
3.9 The Ordering Process ... 74
3.9.1 Orders from the Builder to the Service Center ... 75
3.9.2 Orders from the Retailer to the Assembly Plant ... 76
3.9.3 Orders from the Assembly Plant to the Door Plant ... 77
3.9.4 Orders from the Door Plant to Lumber Suppliers ... 77
3.10 Production Planning and Scheduling ... 78
3.11 Value Stream Map ... 80

Chapter 4. Quality Control and Measurement ... 84

4.1 Quality Control and Measurement at the Lumber Suppliers ... 85
4.1.1 Quality Control and Measurement at Lumber Supplier 2 ... 86
4.1.2 Quality Control and Measurement at Lumber Supplier 3 ... 87
4.1.3 Quality Control and Measurement at Lumber Supplier 4 ... 88
4.1.4 Quality Control and Measurement at Lumber Supplier 5 ... 94
4.1.5 Lumber Quality Attributes and Importance ... 95
4.2 Quality Control and Measurement at the Components Plant ... 97
4.2.1 Overview of Quality Control System and Practices ... 98
4.2.2 Quality Control of Incoming Lumber at the Door Plant ... 100
4.2.3 In-Process Audits ... 101
4.2.4 Controls at the Finishing Line and Color Consistency ... 102
4.2.5 Final inspection ... 103
4.2.6 Internal Quality Measures at the Door Plant ... 104
4.2.7 External Quality Measures at the Door Plant ... 110
4.2.8 Quality Improvement at the Components Plant ... 110
4.3 Quality Control and Measurement at the Assembly Plant ... 112
4.3.1 In-Process Quality Control and Measurement ... 112
4.3.2 Final Inspection at the Assembly Cells ... 112
4.3.3 External Measures at the Assembly Plant ... 114
4.4 Quality Control and Measurement at the Retailer ... 115
4.5 Quality Control and Measurement at the Service Center ... 116
4.5.1 Internal Quality Control and Measurement ... 116
4.5.2 External quality measurement ... 118
4.5.3 Quality Control and Improvement ... 121
4.5.4 Quality Attributes ... 122
4.6 Customer Satisfaction Survey ... 123
4.7 Quality Reporting at the Corporate Level ... 123

4.8 Communication of Quality Issues in the Supply Chain 124

Chapter 5. Quality Performance in the Supply Chain 125

5.1 Quality Performance at the Lumber Supplier 125
5.1.1 Grading Accuracy 125
5.1.2 Grade Mix of Lumber Purchased by the Door Plant 129
5.1.3 Grade Mix from Supplier 4 131
5.1.4 Supplier Evaluation 132
5.2 Quality Performance at the Door Plant 136
5.2.1 In-Process Audit Results 136
5.2.2 First Time Yield (FTY) and Rolled Throughput Yield (RTY) 137
5.2.3 Defect Rate Per Million at the Final Inspection 139
5.2.4 On-Time Delivery to the Assembly Plant 142
5.2.5 Impact of Current Practices on the Door Plant's Performance 143
5.3 Quality Performance at the Assembly Plant 144
5.3.1 Defects per Million at the Final Inspection 144
5.3.2 On-Time Complete (OTC) and Eyes-of-the-Customer (EOTC) 146
5.3.3 Impact of Current Practices on the Assembly Plant's Performance 148
5.4 Quality Performance at the Service Center 149
5.4.1 On-Time Complete 150
5.4.2 Quality Issues after Initial Installation 151
5.4.3 Customer Satisfaction Survey 152
5.4.4 Impact of Current Practices on the Service Center's Performance 152
5.5 Customer Satisfaction Survey 153
5.6 Supply Chain Quality Performance Relationships 154
5.6.1 Relationship between Defect Rate and Production Volume 154
5.6.2 Defect rate and Quality of Inputs 162
5.7 Summary 171

Chapter 6. Current State Analysis 174

6.1 Map of Current Supply Chain Causes 174
6.2 Quality Strategy and Internal Integration 176
6.3 External Integration in the Kitchen Cabinets Supply Chain 178
6.4 Suppliers Quality Management 181
6.5 Quality Measurement and Position in the Supply Chain 185
6.5.1 Quality data and reporting 186
6.5.2 Process control 189
6.5.3 Quality strategy and workforce management 189
6.5.4 Customer relationship – Measuring customer satisfaction 190
6.5.5 Supplier involvement and assistance to suppliers 190
6.6 Attribute Importance throughout the Supply Chain 191
6.6.1 Product and Service Quality Attributes vs. Performance Measures 192
6.6.2 Critical Quality Attributes vs. Performance Measures Used 194

6.7 Effect of Intermediate Inventories and Feedback Delays ... 198
6.8 Alignment of Current Measures with Customer Needs ... 200
6.9 Implications for the Secondary Wood Products Industry ... 201
6.10 Summary ... 202

Chapter 7. Supply Chain Quality Performance ... 204

7.1 Need for Supply Chain Measures ... 204
7.2 Six-Sigma measures for Supply Chain Quality Measurement ... 208
7.3 Computational Process ... 209
7.4 Measures for Supply Chain Performance ... 213
7.4.1 Defects Definitions ... 214
7.4.2 Time Performance Calculation ... 214
7.4.3 Product Quality Performance Calculation ... 218
7.4.4 Customer Satisfaction Calculation ... 224
7.4.5 About Sigma Scores ... 225
7.5 Simulation of Performance Measurement System ... 227
7.5.1 First Iteration: Baseline case ... 230
7.5.2 Second Iteration: Testing Model under Different Inputs ... 243
7.5.3 Third Iteration: Addition of a Defect Category ... 249
7.5.4 Connecting Supply Chain Performance with Customer Satisfaction ... 253
7.6 Summary ... 257

Chapter 8. Conclusions and Future Research ... 259

8.1 Conclusions ... 260
8.1.1 Determine quality performance measurement practices in a secondary wood products supply chain ... 260
8.1.2 Evaluate the impact of these practices on supply chain's performance ... 261
8.1.3 Investigate the impact of alternative practices on performance ... 262
8.2 Study Limitations ... 264
8.3 Recommendations for Future Research ... 266

Literature Cited ... 268

Appendix A: Lumber Supplier Questionnaire ... 280

Appendix B: Example of a Quality Control Plan ... 285

Appendix C: Validation Run Results ... 286

List of Figures

Figure 1-1. Inventory-to-shipments ratio of some U.S. durable goods manufacturers 4
Figure 1-2. Generalized wood products supply chain 10
Figure 1-3. Supply chain for wood furniture..... 11
Figure 1-4. Arc of supply chain integration 14
Figure 1-5. Four stages of supply chain integration 15
Figure 1-6. Characteristics of selected NHLA lumber grades..... 24
Figure 1-7. Model for quality management practices and performance..... 32
Figure 1-8. Critical areas and practices of supply quality management 34
Figure 1-9. Control process for logistics operations 36
Figure 1-10. Model for strategic quality and production planning in a supply chain 37
Figure 1-11. Interaction between supply chain members on time performance 40
Figure 2-1. Research process, methods, and results 44
Figure 2-2. Case study research process..... 45
Figure 2-3. Classic supply chain model (numbers represent time delays) 52
Figure 2-4. Interpretation of values of correlation coefficient..... 57
Figure 2-5. Examples of scatter plots and linear regression results 58
Figure 3-1. Kitchen cabinets value creation network 60
Figure 3-2. Species mix of lumber used by the components plant during year of analysis 63
Figure 3-3. Share of species throughout the supply chain of study..... 64
Figure 3-4. Supply chain path selected for the study 66
Figure 3-5. Production process at the door plant 68
Figure 3-6. Simplified view of the production process at the assembly plant 71
Figure 3-7. Order process from builder to service center 75
Figure 3-8. Order process from builder to retailer 76
Figure 3-9. Inventory management and scheduling in the cabinets supply chain 78
Figure 3-10. Illustration of a MAX-MIN inventory control system..... 80
Figure 3-11. Value stream map for the kitchen cabinets company..... 81
Figure 3-12. Supply chain response matrix (lead times as seen by the customer) 82
Figure 4-1. Framework for quality measurement..... 84
Figure 4-2. Sample of performance report at Supplier 4 93
Figure 4-3. Wood defects and profile sample displays at the door plant 100
Figure 4-4. Process and inspection diagram 107
Figure 4-5. Diagram representing sanding and finishing processes at the door plant. 108
Figure 4-6. Normal distribution and specification limits for a control attribute..... 108
Figure 4-7. Illustration of sigma score drift 109
Figure 4-8. General view of the DMAIC model 111
Figure 5-1. Overall grading and tally accuracy at Lumber Supplier 4 126
Figure 5-2. Major grading accuracy indicators for three years at Lumber Supplier 4 .. 127
Figure 5-3. Lumber grade mix for Lumber Supplier 4..... 128
Figure 5-4. Grading accuracy by wood defects as percentage of lumber volume 129

Figure 5-5. Average lumber mix purchased by the door plant during the year of analysis 129
Figure 5-6. Monthly lumber grade mix purchased by the door 130
Figure 5-7. Red oak lumber grade mix from Supplier 4 131
Figure 5-8. Cherry lumber grade mix from Supplier 4 131
Figure 5-9. Soft maple lumber grade mix from Supplier 4 132
Figure 5-10. Hard maple lumber grade mix from Supplier 4 132
Figure 5-11. Historic percentage of 2-Common lumber from Suppliers 3 and 4 133
Figure 5-12. Frequency of 2-Common cherry lumber deliveries to the door plant 134
Figure 5-13. Average defect rate for the door plant's processes 137
Figure 5-14. First-time yield and throughput yield at the finishing department 138
Figure 5-15. Rolled throughput yield vs. process complexity at four levels of individual yields 139
Figure 5-16. Defects per million opportunities at the door plant 139
Figure 5-17. Pareto chart of defects at the door plant's final inspection 140
Figure 5-18. Average number of defects per door at the door plant's final inspection. 141
Figure 5-19. Defects per door by species, door plant's final inspection 142
Figure 5-20. On-time delivery from door to assembly plant 143
Figure 5-21. Impact of improvement on in-process and final defect rate 144
Figure 5-22. Non-conforming parts per million at the assembly plant's final inspection145
Figure 5-23. Pareto chart of defects at the assembly plant's final inspection, year of analysis 145
Figure 5-24. On-time complete and eyes-of-the-customer, assembly plant 146
Figure 5-25. Pareto chart for on-time complete issues by cause and product, year of analysis 147
Figure 5-26. Pareto chart for after-shipment quality issues at assembly plant, year of analysis 148
Figure 5-27. Impact of improvement on scrap and on-time shipping 149
Figure 5-28. On-time complete at the Service Center, year of analysis 150
Figure 5-29. Pareto chart of variances at the service center for year of analysis 151
Figure 5-30. Relative difference between attribute importance and performance 153
Figure 5-31. Demand and workload pressure 155
Figure 5-32. Partial look of main feedback loops model of production ramp-ups 156
Figure 5-33. Relationship between final defect rate and production volume at the door plant 157
Figure 5-34. Relationship between external and internal defect rates and production volume at the assembly plant 158
Figure 5-35. Relationship between defect rate and orders at the service center 158
Figure 5-36. Relationship between assembly plant's backorder rate and door production 159
Figure 5-37. Number of defects per board foot for three lumber grades 164
Figure 5-38. Relationship between defect rate and percent of 2-Common lumber at the door plant 165
Figure 5-39. Relationship between defect rate and central panels defect rate at the door plant 166

Figure 5-40. Relationship between internal defect rates at the assembly plant and the door plant 167
Figure 5-41. Relationship between external and internal defect rates at the assembly plant 168
Figure 5-42. Relationship between defect rates at the service center and at the assembly plant 170
Figure 5-43. Relationship between damage defect rate at the service center and visual defects at the assembly plant 171
Figure 6-1. Supply chain current causes map 175
Figure 6-2. Effect of intermediate inventories and feedback delay 199
Figure 7-1. Supply chain quality measures development process 205
Figure 7-2. Importance and satisfaction of customer satisfaction components 206
Figure 7-3. Key measurement areas and critical factors of quality 207
Figure 7-4. Calculation for supply chain rolled throughput 212
Figure 7-5. Supply chain metrics: time performance 213
Figure 7-6. Supply chain metrics: product quality 213
Figure 7-7. Supply chain time performance – Defect rate and sigma score 215
Figure 7-8. Supply chain time performance– Rolled throughput yield 216
Figure 7-9. Supply chain time performance – Causes for late deliveries 217
Figure 7-10. Supply chain product quality performance – Defect rate and sigma score 221
Figure 7-11. Supply chain product quality performance – Rolled throughput yield 222
Figure 7-12. Individual and collective throughput yields. 222
Figure 7-13. Supply chain product quality performance - Causes 223
Figure 7-14. Customer satisfaction measures of performance 225
Figure 7-15. Monte Carlo simulation for supply chain quality performance measurement 228
Figure 7-16. Iterations of the supply chain performance measurement model 230
Figure 7-17. Production volume generator validation results for 12 months 231
Figure 7-18. Defect generator process. 232
Figure 7-19. Validation results for the door plant's defect generator 233
Figure 7-20. Validation results for the door plant's defect generator - DPMO 234
Figure 7-21. Validation results for the assembly plant's defect generator 234
Figure 7-22. Validation results for the assembly plant's defect generator - DPMO 235
Figure 7-23. Validation results for the 2-Common lumber content generator 236
Figure 7-24. Validation results for the lumber supplier error rate generator 237
Figure 7-25. Validation results for assembly plant time performance 238
Figure 7-26. Validation results for supply chain time performance (throughput yield) . 239
Figure 7-27. Validation results for supply chain time performance (defect rate per million) 239
Figure 7-28. Validation results for the final defect rate at the door plant 240
Figure 7-29. Validation results for supply chain product quality performance (throughput yield) 241
Figure 7-30. Validation results for supply chain product quality performance (throughput yield, excluding lumber suppliers) 241

Figure 7-31. Validation results for supply chain product quality performance (sigma score) ... 242
Figure 7-32. Supply chain time performance at different levels of demand ... 243
Figure 7-33. Supply chain product quality performance at different levels of demand 244
Figure 7-34. Door plant defect rate at different percentages of 2-Common lumber ... 246
Figure 7-35. Supply chain defect rate at different percentages of 2-Common lumber 247
Figure 7-36. Product quality throughput yield at different levels of supplier error rate. 248
Figure 7-37. Inspection and detection rate in the cabinets supply chain ... 250
Figure 7-38. Share of defects at final inspection at different in-process detection levels ... 252
Figure 7-39. Defect rate per million units at different in-process detection levels ... 253
Figure 7-40. Link between supply chain performance and customer satisfaction ... 254
Figure 7-41. Relationship between overall customer satisfaction and satisfaction with logistics performance ... 255
Figure 7-42. Results for simulation of impact of supply chain performance on customer satisfaction ... 256

List of Tables

Table 1-1. Traditional metrics used in the wood products industry 16
Table 1-2. Data envelopment analysis in the forest products industry 18
Table 1-3. Performance measures for supply chain 20
Table 1-4. Balanced score card for a supply chain and sample metrics 21
Table 1-5. American Lumber Standard programs 25
Table 1-6. Quality standards for finished wood products 27
Table 1-7. Critical factors for quality management 32
Table 1-8. Components of supply chain quality management 34
Table 1-9. TQM practices factors and performance measures impacted 38
Table 2-1. Partial view of matched research strategy and theory-building matrix 45
Table 2-2. Tactics to assure case research quality 47
Table 2-3. Value stream mapping tools 49
Table 2-4. Research applications of system dynamics on quality and quality improvement 51
Table 2-5. Required information and data gathering techniques 52
Table 2-6. Interviews and communications log 53
Table 3-1. Results of Lean Manufacturing at the Company's door plant (Company, 2007) 59
Table 3-2. Customers segments identified by the Company 61
Table 3-3. Sample of consumer research results carried out by the Company 61
Table 3-4. Product lines and options available 62
Table 3-5. Main characteristics of lumber suppliers contacted for the study 67
Table 3-6. Inventory quantities at the assembly plant 71
Table 3-7. Lead times for orders from the retailer 77
Table 3-8. Lead time and inventory levels throughout the supply chain 80
Table 4-1. Demographic information of lumber suppliers to the door plant 86
Table 4-2. Quality control items and measures at Supplier 4 89
Table 4-3. Quality attributes importance questionnaire 96
Table 4-4. List of quality control items for internal processes at the door plant 99
Table 4-5. Requirements for lumber purchases 101
Table 4-6. Sample for in-process audit record for the moulder operation 102
Table 4-7. Attributes and tolerances for the final inspection at the door plant 104
Table 4-8. Relationship between sigma score and defects per million opportunities .. 110
Table 4-9. Control items for final inspection at the assembly cells 113
Table 4-10. Sources of variances for on-time-complete calculation 114
Table 4-11. Non-conformances recorded to calculate eyes-of-the-customer (EOTC). 115
Table 4-12. Installation inspection checklist 118
Table 4-13. Variances recorded to calculate On-time-complete (OTC) 119
Table 4-14. Customer satisfaction survey 120
Table 4-15. Quality attributes importance for the construction company 122
Table 4-16. Customer satisfaction survey, functions and attributes 123
Table 5-1. Grading accuracy by species 128

Table 5-2. Service center customer satisfaction survey for one month 152
Table 5-3. Summary of effect of production volume on defect rate 160
Table 6-1. Advantages and disadvantages of a single supplier system 182
Table 6-2. Quality management factors that relate to quality measurement 186
Table 6-3. Product, process, and service attributes, and their measures.................... 193
Table 6-4. Critical lumber and supplier attributes and measures used........................ 195
Table 6-5. Customer satisfaction attributes and quality measures in the supply chain 196
Table 7-1. Defect definitions for time delivery and product quality 214
Table 7-2. Calculation of supply chain measures of time performance 215
Table 7-3. Sample calculation for lumber suppliers' quality performance.................... 219
Table 7-4. Calculation of lumber suppliers' quality performance 220
Table 7-5. Calculation of supply chain measures of product quality............................ 220
Table 7-6. Customer satisfaction computation and results.. 224
Table 7-7. Sigma score and 226
Table 7-8. Distribution fits and goodness-of-fit test of quality variables....................... 229
Table 7-9. Inputs to the second iteration: changing inputs 243
Table 7-10. Existing and new defect categories at the assembly plant's final inspection 251
Table 7-11. Supply chain time performance and customer satisfaction 256
Table 8-1. Improvement from current practices throughout the supply chain.............. 261

Chapter 1. Introduction and Literature Review

1.1 Industry Background

The U.S. forest products industry employs 1.3 million people and is among the ten top manufacturing employers in 42 states (American Forest and Paper Association, 2005). Wood products manufacturers alone (comprising chiefly lumber, engineered wood, pallets and containers, millwork, and veneer), reported a total value of shipments of $US 103.4 billion and employed 535,246 people, according to the 2004 Annual Survey of Manufacturers (U.S. Census Bureau, 2005). The United States is currently the largest producer and importer of wood products globally. However, like most of the manufacturing sector in the US, the wood products industry has been affected by low-cost producers from other countries, and has steadily been losing ground to imports. From 1995 to 2005, imports of wood products have grown by 60 percent (American Forest and Paper Association, 2005). Only considering household furniture, 54 percent of products sold in the US in 2004 were imported (Grushecky, Buehlmann, Schuler, Luppold, & Cesa, 2006). The effects of these developments has led to the creation of government agencies which purpose is to alleviate the negative outcomes of increasing imports (The Economist, 2007) on employment, and efforts by companies to improve the industry's competitiveness.

Manufacturing enterprises are trying to improve their internal processes with initiatives such as lean manufacturing (Cumbo, Kline, & Bumgardner, 2006; Hunter, Bullard, & Steele, 2004) total quality management (Kozak & Maness, 2003), six sigma (Blanchard, 2006; Raisinghani, Ette, Pierce, Cannon, & Daripaly, 2005), and supply chain management (Bryan & McDougall, 1998; Buehlmann, 2004; D'Amours, Frayret, & Rousseau, 2004). Secondary wood products manufacturers, for example, identified better quality, timely delivery, and better control of manufacturing process as important factors to improve competitiveness of domestic producers (Bumgardner, Buehlmann, Schuler, & Christianson, 2004). In particular, interest has increased in the implementation of quality improvement; from the application of statistical process control

(Cook, 1992; Patterson & Anderson, 1996; Young & Winistorfer, 1999), and in the research about consumer perceptions of quality (Broman, 1995; Hansen & Punches 1996; Weinfurter & Hansen, 1999). There is extensive research documenting that quality improvement initiatives can have a positive impact on competitive position (Forker, Mendez, & Hershauer, 1997; Garvin, 1984a; Gunter, Rolf-Dieter, & Hans-Werner, 1994; Kannan & Tan, 2007; Kuei, Madu, & Lin, 2001).

Another important development in business management has been the emergence of the Supply Chain Management (SCM) paradigm. The fall of trade barriers, the innovations in transportation and information technologies, deregulation, and improvement in logistics management have made possible levels of integration between members of supply chains unseen before. Companies all over the world have recognized that they can no longer compete as isolated entities, but as parts of very complex networks of buyers and suppliers, known as supply chains (Lambert & Cooper, 2000). According to the supply chain management point of view, companies must closely integrate and collaborate with their suppliers and customers in aspects like logistics, information, quality management, and process flow management. The importance and benefits of this approach are extensively documented (Berry & Evans, 1999; Lambert & Cooper, 2000; Mason-Jones & Towill, 1997, 1999; Petersen, Handfield, & Ragatz, 2005; Tan, Kannan, Handfield, & Ghosh, 1999; Towill, 1996), for example:

- Supply chain integration is very difficult for competitors to imitate and leads to superior product quality, delivery reliability, process flexibility, and cost leadership (Rosenzweig, Roth, & Dean, 2003).
- An “outward-facing” supply chain strategy leads to better results in measures of: (1) market place (market share, profitability, and ROA); (2) productivity (manufacturing and overhead costs; manufacturing, changeover, procurement, and delivery lead times; inventory turnover and labor productivity); and (3) non-productivity measures (customer service and satisfaction; conformance quality, speed of product development, on-time delivery, and supplier quality) (Frohlich & Westbrook, 2001).

- A higher level of relationships' quality (defined by communication, cooperation, commitment, trust, interdependence, and adaptation) in a supply chain result in higher levels of design and conformance quality, which in turn leads to improved customer satisfaction (Fynes, Voss, & Burca, 2005).

Increasing global competition and supply chain management practices have resulted in shortened lead times, improved value for the customer, transparency in logistics operations, and greatly reduced costs. For example, fashion companies can design, produce and deliver garments in fifteen days, very unusual in the fashion industry, where a period of several months is common (Ferdows, Lewis, & Machuca, 2004). Personal computer and footwear companies use mass-customization to offer products that fit the customers' specific requirements at reasonable costs. Logistics operations have become increasingly transparent and on-line tracking of parcel and post is becoming the industry's standard. Greatly increased efficiency made it possible for low-cost retailers, such as Wal-Mart, to prosper (Robinson & Malhotra, 2005). However, the secondary wood products industry, comprising value-added wood products like furniture, cabinets, flooring, paneling, running trim, and millwork; has been slow to adopt supply chain management practices (Buehlmann, 2004). This is evident, for example, looking at the inventory-to-shipments (I/S) ratio for U.S. manufacturers of durable goods from 1992 to 2006 (Figure 1-1), which gauges how long (in months) do inventories sit in factories, warehouses, or showrooms; a lower I/S ratio suggests a more efficient operation and/or strong market demand. This ratio has changed very little for wood products compared with other industries (at a -0.25 percent annual rate, compared with -1.75 average of non-wood durable goods included in Figure 1-1)

There are signs, however, that firms are trying to improve their business practices; for example, working harder to develop long-term relationships with their customers to face the new challenges (Buehlmann, Bumgardner, Schuler, & Barford, 2007). Some success stories of integrating supply chain processes in the industry exist, particularly in the kitchen cabinet industry (Buehlmann, 2004), which resulted in shortened lead times, more choices available to customers, and streamlined processes.

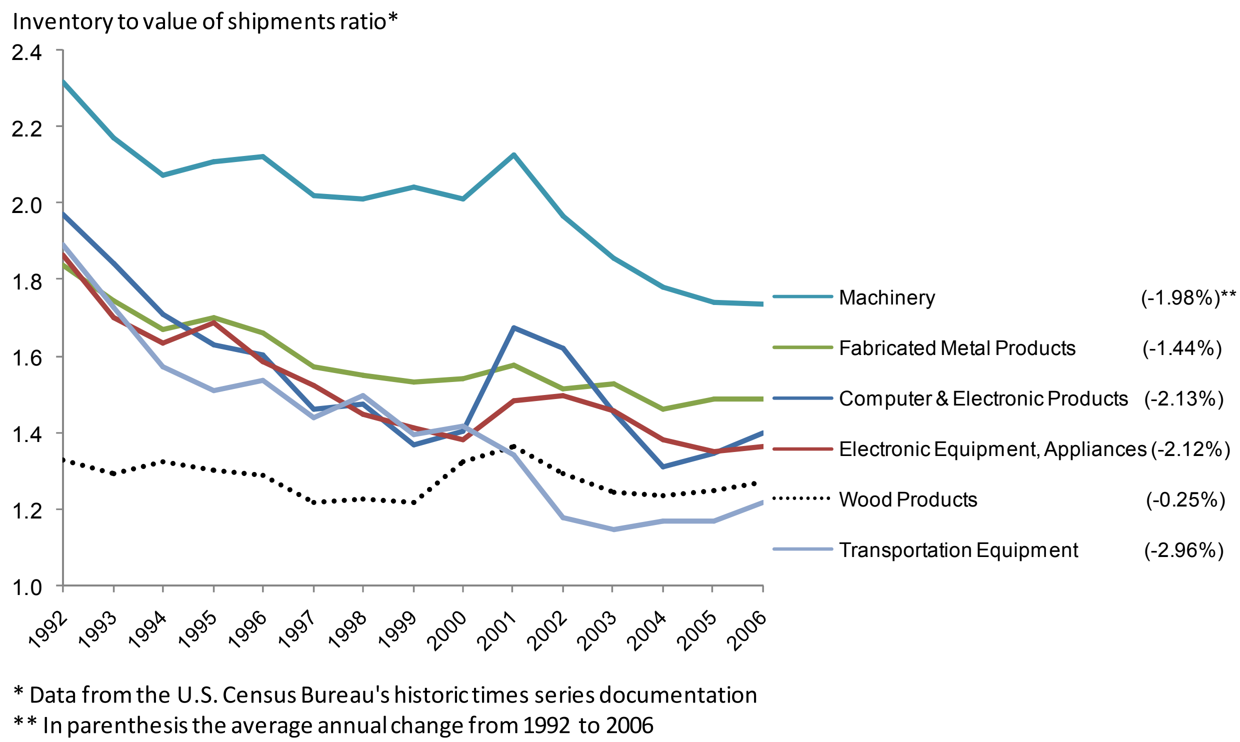


Figure 1-1. Inventory-to-shipments ratio of some U.S. durable goods manufacturers

This study focuses on the potential of combining supply chain management principles and effective quality performance measurement practices as an approach to improve the competitive position of wood products manufacturers. It is proposed that significant improvements in quality performance are possible when there is a high degree of integration between buyers and suppliers for planning, controlling and improving the quality of products and services provided. The first part of this dissertation consists in a literature review about supply chain management, performance measurement, and quality management (Chapter 1). Secondly, the quality measurement practices in an exemplary secondary wood products supply chain were studied in detail, in order to evaluate the effectiveness of these practices and their impact on the supply chain's performance (Chapter 4, Chapter 5, and Chapter 6). Opportunities for improvement are identified throughout Chapter 6 and Chapter 7. Finally, Chapter 7 contains the results of a simulation model, developed in order to illustrate the relationships found in the study and to evaluate how improvement affect performance.

1.2 Problem Statement

Extensive research exists about quality measurement of tangible attributes of wood products. As with most construction materials, standards and quality grading systems for wood products were extensively developed. For example, the American Society of Testing and Materials' Committee D-7 has been developing standards for testing wood-related materials and processes for over a hundred years on aspects such as physical properties or preservation treatments (Green, Ethington, King, Shelley, & Gromala, 2004). Performance standards exist for almost each major wood product category. However, research is less abundant regarding measurement of dimensions like perceived quality, serviceability, and aesthetics. Service quality was investigated in the softwood and hardwood lumber industries to some extent (Bush, Sinclair, & Araman, 1991; Forbes, Sinclair, Bush, & Araman, 1994; Hansen & Bush, 1996; Hansen & Bush, 1999; Hansen, Bush, & Fern, 1996); and there are only a handful of documented studies on consumer behavior and aesthetics of wood products (Anderson, Fell, Smith, Hansen, & Gomon, 2005; Broman, 1995; Pakarinen, 1999). Furthermore, the interactions between supply chain members in regards to quality measurement of wood products have received very little or no attention.

Only recently has the application of supply chain management principles in the secondary wood products industry received attention from researchers and industry practitioners (Buehlmann, 2004; D'Amours, et al., 2004; Vlosky, Wilson, Cohen, Fontenot, & et al., 1998; Winistorfer, 2005), in part due to the big challenges the domestic industry is facing from global competition. Particularly, research on quality performance measurement in a wood products supply chain environment has been found to be minimal. This could mean that companies are not currently leveraging the benefits of supply chain management in regards to quality measurement and control. Research in other industries suggests that sound supply chain quality management practices are closely associated with superior organizational performance (Beamon & Ware, 1998; Choi & Rungtusanatham, 1999; Forker, et al., 1997; Kannan & Tan, 2007; Kuei, et al., 2001; Robinson & Malhotra, 2005; Sila, Ebrahimpour, & Birkholz, 2006). Closely connecting the final customer and the suppliers, one of the principles of SCM, is only possible if the quality performance measures used are aligned with the needs and wants of that final buyer. This study attempts to address the need for research in this area by determining the current state of quality performance measurement in the wood products supply chain and identifying valid approaches for improvement.

1.3 Research Questions

Based on the needs identified in the problem statement, the following questions guided this research:

- *How is quality defined, measured, and communicated in a secondary wood products supply chain?* This question implies finding out which dimensions of quality are more important in the supply chain of interest, and how this importance changes with the position in the supply chain. A detailed analysis allowed determining the quality performance measures currently used by the supply chain entities. Also of interest was assessing the degree of collaboration in the establishment of quality policies and measures, and how members ensure their consistency with the supply chain's goals.
- *How do current practices of quality measurement impact the performance of the wood products supply chain?* It has been established from the literature review that successful supply chains align their quality management practices with customer requirements. How effectively do quality measurement practices contribute to this purpose? What is the impact of these practices on the supply chain's performance?
- *How can the answers to the previous questions be used to help companies improve supply chain quality performance?* Are there any alternatives to current quality measurement practices that could assist firms in the supply chain of interest to improve its overall performance? If so, can the impact of these alternatives be assessed?

It is proposed in this dissertation that significant improvements in quality performance are possible when there is a high degree of integration between supply chain partners for measuring the quality of products and services provided. Integration is encouraged when common measures of performance are used throughout the supply chain. When a company embraces its customers and suppliers, it is better positioned to identify real customer demand and requirements.

1.4 Purpose and Objectives

The purpose of this research was to increase the understanding of quality performance measurement practices in the secondary wood products supply chain. Specifically, the objectives of the study were to:

1. Determine quality performance measurement practices in a secondary wood products supply chain
2. Evaluate the impact of these practices on the supply chain's performance
3. Investigate the impact of alternative practices on performance

1.5 Research Contributions

The results of this research contribute to the body of knowledge in the fields of Wood Science and Forest Products and Supply Chain Management. An explanation follows.

1.5.1 Contributions to the field of Wood Science and Forest Products

This study enhances the knowledge in Wood Science and Forest Products by investigating the inter-firm interactions in regards to quality measurement from a perspective that has thus far received little attention in this industry: a supply chain management viewpoint. While there is extensive research about quality measurement of physical attributes of wood products, the effect of these practices on the supply chain's interactions and overall performance have not been investigated until now.

1.5.2 Contributions to the field of Supply Chain Management

This dissertation contributes to the field of supply chain management (SCM) by providing information about an industry sector that has received very little attention in the SCM literature. It describes in great detail the supply chain structure, material and information flows, and major processes. The analysis of the degree of internal and external integration in the supply chain of study is also an important addition to the SCM literature. Some specific categories of SCM to which this study contributes are:

- *Customer Relationship Management and Supplier Management*. The degree of integration/collaboration between suppliers and buyers in regards to quality measurement. How the customers' requirements are connected with the quality metrics used, from lumber suppliers to the last seller.
- *Supply Chain Performance Measurement*. The measures currently used were studied and evaluated in the context of a supply chain and approaches to the supply chain's quality performance measurement were proposed.
- *Supply Chain Quality Management*. How buyers and suppliers define, measure and communicate quality. This includes quality control of suppliers, involvement of suppliers and customers in the development of quality measures, statistical process control, and degree of self inspection. The relative importance of product and service quality attributes across the supply chain of interest was investigated.
- *Supply Chain Performance Measurement*. This study builds on what Lambert and Pohlen (2001) identified as a need to develop measures that reflect the performance of the supply chain as a whole, rather than intra-organizational performance. Also, it contributes in building measures that complement modern manufacturing practices, like lean manufacturing and six-sigma; a need identified by Shepherd and Günter (2006).

1.5.3 Practical Contributions

Current quality measurement practices were evaluated from a supply chain perspective, and specific improvements were suggested. New metrics could be used by firms to assess quality performance of the supply chain as a single entity and the contributions of individual companies. The research provides a practical example of applying six sigma measures to asses overall supply chain performance.

1.6 Literature Review

1.6.1 Supply Chain Management

A supply chain is “a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via de feed-forward flow of materials and the feedback flow of information” (Towill, 1996). According to the Council of Logistics Management, supply chain management (SCM) is the “systematic, strategic coordination of the traditional business functions and tactics across these businesses functions within a particular organization and across businesses within the supply chain for the purposes of improving the long-term performance of the individual organizations and the supply chain as a whole” (Li, Rao, Ragu-Nathan, & Ragu-Nathan, 2005). Managing a supply chain requires planning, executing and controlling the following activities: customer relationships and services, demand management, order fulfillment, manufacturing flow, procurement, product development, commercialization, and returns (Lambert & Cooper, 2000). The final goal of supply chain management is to synchronize the needs of its final customers with the flow of products and information through the different levels of the supply chain; helping to achieve high levels of customer satisfaction and reduced costs, two apparently conflicting objectives (Stevens, 1989). High levels of integration, a recurring theme in supply chain management, positively impact on performance, measured in metrics such as return on assets, market share and growth, product quality, customer service and competitive position (Tan, et al., 1999). Supply chain management practices are therefore important for the long-term success of a firm. Figure 1-2 illustrates a generalized supply chain of forest products adapted from D’Amours, et al. (2004) . A short description of the supply chain follows.

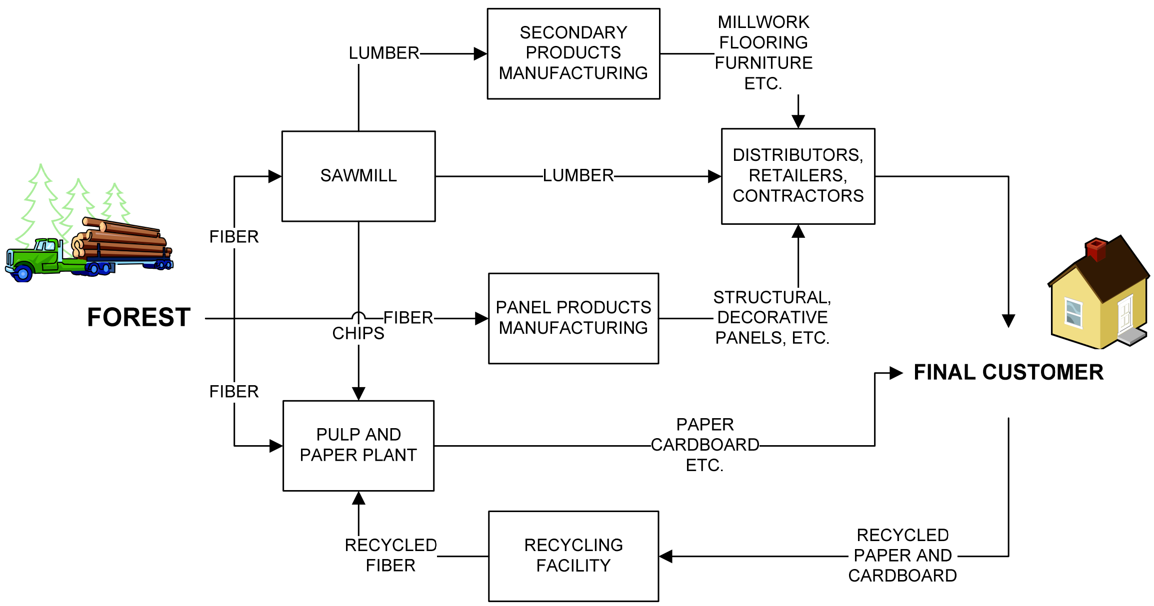


Figure 1-2. Generalized wood products supply chain

Logs are harvested and merchandised to maximize their market value. According to their quality, logs can be designated for pulp and paper products, construction lumber, veneer or panel products and lumber for further processing into value-added products. After conversion, wood products are sold to wholesalers, retailers or contractors, who in turn sell to the final customer. Different channels of distribution are used for each product category. For example, according to a study, about half of household furniture is sold through independent retailers, seven percent to wholesalers, and the remainder is sold in manufacturer-owned stores (Meyer, Michael, & Sinclair, 1992). The complexity of the supply chain depends on the sector of the industry: loggers and sawmills are basically suppliers of commodity products (raw materials). Housing contractors can be supplied by wholesalers, retailers, and directly from manufacturers. Figure 1-3 shows a typical supply chain configuration for furniture manufacturing. Note that suppliers of hardware, finishing materials, accessories, packaging materials, and adhesives are not included.

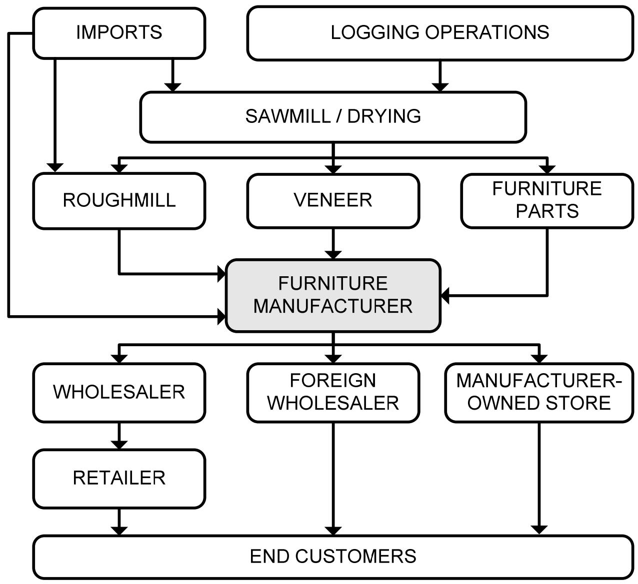


Figure 1-3. Supply chain for wood furniture.

Some sectors of the wood products industry, particularly kitchen cabinet manufacturers, have successfully implemented supply chain management practices to reduce lead times, reduce work-in-process and inventory, and build a reliable supply chain. In part as a result of these efforts, and contrary to the general trend, kitchen cabinets sales have increased in the last decade, keeping imports at less than five percent (Buehlmann, 2004). This is illustrated by the inventory-to-shipments ratio (I/S), which had a value of 0.81 for wood cabinets, 1.95 for non-upholstered furniture, and 1.24 for the wood products industry in 2004 (the latter includes sawmills, veneer, engineered wood, millwork, and pallets), a 1 to 2.4 to 1.5 relationship (U.S. Census Bureau, 2005). However, most of the industry has yet to leverage the benefits of supply chain management. Practices such as integration-collaboration between buyers and suppliers, Just-in-Time (JIT) deliveries, information visibility, and total cost focus can contribute to improve the global competitiveness of the American wood products industry (Buehlmann, 2004). Partnering relationships, a very important SCM component, have shown to have a higher degree of correlation with firm overall performance than the traditional transactional/competing relationships among wood products distributors and manufacturers (Fontenot, Vlosky, Wilson, & Wilson, 1998; Vlosky, et al., 1998). Product quality and timely delivery, closely associated with SCM practices, are cited among the most important factors for keeping a strong domestic competitive position in a survey of US wood products executives (Bumgardner, et al., 2004).

Information technology, one of the most important enablers of SCM, is playing an increasingly important role in business-to-business relationships in the wood products industry. Internet technologies and the use of electronic data interchange (EDI) are playing increasingly important roles in integrating and coordinating the relationships between businesses in wood products supply chains, helping to reduce lead time and inventories (D'Amours, et al., 2004; Dupuy & Vlosky, 2000; Punches & Vlosky, 1998).

1.6.2 Supply Chain Integration

One of the tenets of Supply Chain Management (SCM) is the proposition that strong performance is strongly associated with a high degree of integration among supply chain constituents. Integration in this context is understood as the "process of interaction and collaboration in which manufacturing, purchasing and logistics work together in a cooperative manner to arrive at mutually acceptable outcomes for their organizations" (Pagell, 2004). According to the SCM literature, a company should integrate its key business processes with its customers and suppliers, in order to create value for the customer and eliminate waste in the form of, for example, excessive inter-plant inventory or capacity (Frohlich & Westbrook, 2001; Lambert & Cooper, 2000). Examples of processes that foster supply chain integration are: close collaboration with customers in planning, forecasting, and replenishment activities (downstream integration); and sharing production plans with suppliers and joint development of quality requirements (upstream integration). A considerable amount of research appears to support the link between supply chain integration and performance (Aryee, Naim, & Lalwani, 2008; Fabbe-Costes & Jahre, 2008; Levy, Bessant, Sang, & Lamming, 1995; Lummus, Vokurka, & Krumwiede, 2008; Rahman, 2006; Simatupang & Sridharan, 2008). Fabbe-Costes and Jahre (2008) carried out a review of the literature about supply chain integration and its relationship with performance; finding that with very few exceptions, all papers with empirical evidence analyzed support the assertion that more integration leads to better performance.

The basic dimensions of integration are scope and degree. The first dimension refers to which main activities are jointly planned and executed between supply chain partners. For example, Van-Donk and Van-der-Vaart (2005), listed four areas in which companies can develop integration with its supply chain partners in regards to logistics: flow of goods, planning and control, organization, and flow of information. Research is relatively abundant in regards to integration for procurement and logistics. The second dimension, degree, or level of integration, refers to the extent to which an integrated process is developed.

One method to portray and analyze the degree of supply chain integration (SCI) is to use the “arc of integration” (illustrated in Figure 1-4), developed by Frohlich and Westbrrok (2001) to analyze global manufacturers. In this approach, the angle of the arc represents the degree of SCI, and the direction of line segments shows a leaning towards customers or suppliers. The amplitude of the arc is determined using a set of integrative activities, ranging from the access to the planning system and production plans, to the common use of logistical equipment and third-party logistics providers. The researchers concluded that a wider “arc of integration” (supply chain integration) is associated with high performance, measured by indicators in three categories: marketplace, productivity, and non-productivity measures (Frohlich & Westbrook, 2001). Five levels of SCI were defined, listed from narrowest to a broadest “arc of integration”: inward-facing (very little integration with customers and suppliers), periphery-facing (moderate integration with customers and suppliers), supplier-facing (extensive integration with suppliers and moderate with customers), customer-facing (moderate integration with suppliers, extensive with customers), and outward-facing (extensive integration with suppliers and customers). The authors also found that most companies showed the “periphery-facing” integration, and conjectured that perhaps that is a natural equilibrium for supply chains.

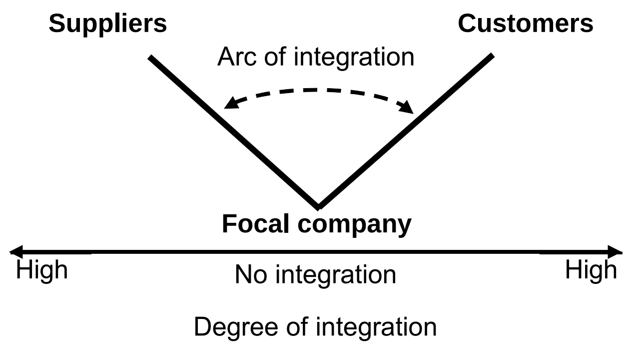


Figure 1-4. Arc of supply chain integration

Fabbe-Costes and Jahre (2008) defined the scope of supply chain integration differently that previously described. For these authors, scope refers to the “number of nature of organizations included in the integrated supply chain”; they list five scopes of SCI, referring to the nature and number of organizations included in the supply chain: (1) limited dyadic downstream, integration between focal company and its customers; (2) limited dyadic upstream, between company and suppliers; (3) limited dyadic, between company and its customers and suppliers, but separately; (4) limited triadic, same as previous but without differentiation; and (5) extended, including more than first-tier suppliers and customers. This classification bears similarity with Frohlich and Westbrook’s “arcs of integration”.

The ultimate goal of an integrated supply chain is “the removal of all boundaries, to facilitate the flow of material, cash, resources and information” (Naylor, Naim, & Berry, 1999), and one of the main drivers for integration is the reduction in uncertainty that close collaboration between supply chain partners helps to achieve. Stevens (1989) defined four stages of the integration process (listed in Figure 1-5) and stated that to achieve a higher service level all activities in the supply chain need to be in balance, avoiding thinking in terms of narrow functional areas.

Stage 1 - Baseline: Fragmented supply chain

- staged inventories
- independent control systems
- organizational boundaries

Stage 2 - Functional integration: focus on inward flow and cost reduction

- time-phased planning (MRP or MRPII)
- discrete business functions buffered by inventory
- high plant utilization and batch sizing
- reactive customer service
- distribution decoupled from manufacturing
- poor visibility of customer demand

Stage 3 - Internal integration: integration of process under the control of the company

- comprehensive internally integrated planning and control (DRP and JIT techniques)
- medium-term planning, focus on tactical issues
- emphasis on efficiency
- use of EDI for communication with customer
- reacting to demand

Stage 4 - External integration: extend integration outside the company, to suppliers and customers

- customer-oriented
- mutual support and cooperation with suppliers
- long-term commitment, eliminating the need of multiple sourcing

Figure 1-5. Four stages of supply chain integration

1.6.3 Performance Measurement

The last decades have seen a rapidly growing interest and practice of formal performance measurement among organizations and researchers. Neely et al. defines performance measurement as the “process of quantifying the efficiency and effectiveness of action”, and a performance measurement system as the “set of metrics” used to measure performance (Neely, Gregory, & Platts, 2005). Some of the causes for the “performance measurement revolution” are: increasing global and domestic competition, continuous improvement initiatives, national and international quality awards, ever-changing demands, and developments in information technology (Neely, 1999). A manufacturing company, challenged by domestic and international competition, might want to improve its competitive position by offering a higher level of product and service quality to its customers. For this purpose, the company may adopt a specific quality improvement methodology, such as total quality management (TQM) or six-sigma and, in order to successfully implement these initiatives, this hypothetical firm will need to adjust its systems to effectively measure, among other things, process and product quality, quality costs, and customer satisfaction.

Some of the most common challenges when designing performance measurement systems are: (1) having a balanced set of metrics, which means including all relevant metrics); (2) the alignment of metrics with strategic goals; (3) avoiding metrics that drive wrong behaviors; (4) the access to required information; and (5) the measurability of data (Beamon, 1999; Bourne, Neely, Platts, & Mills, 2002; Van-Aken & Coleman, 2002).

Regarding the wood products industry, metrics traditionally used quantify either financial performance or resource utilization. An example some of these metrics are listed in Table 1-1. Efforts to develop improved specific overall performance measures for forest products companies are described in the remaining of this section.

Table 1-1. Traditional metrics used in the wood products industry

Sector	Measure	Definition and reference
Sawmill	Lumber output	Amount of lumber output per time unit (Wang, 1988)
	Lumber recovery	Ratio between total lumber output volume and total log input (Wang, 1988)
	Lumber recovery factor	Ratio between board footage of lumber and cubic volume of logs (Steele, 1984)
	Overrun	Ratio of extra lumber recovered from a set of logs to the volume of those logs (Denig, 1993)
	Lumber thickness variation	Resulting combined variation of within and between-board thickness variation in sawing (Brown, 1982)
Drying	Drying degrade	Lumber value lost due to drying defects that lower its grade (Cuppett, 1966)
Rough-mill	Yield	Ratio between the amount of usable parts and the volume of lumber input (Mitchell, Wiedenbeck, & Ammerman, 2005)

A market value and risk-adjusted metric (MVRA) to measure financial performance of publicly owned forest products companies was proposed by Zinkhan (1988). Contrary to the generally used return on equity, which measures profits generated in relation to the investment made by shareholders, the proposed metric takes into account risk and encourages long-term planning (Zinkhan, 1988).

A process-oriented metric to measure performance of sawmills, the “4-F Performance Index”, thus named because it takes into account four factors: product mix, lumber recovery, log processing rate, and log diameter. The metric is calculated with a relatively complex algorithm, takes into consideration product mix, lumber recovery, processing rate, and log diameter. The index, claims the author, reflects the most important factors in sawmill operation performance, unlike other more traditional metrics like lumber recovery, value recovery, or gross profit (Wang, 1988).

Data Envelopment Analysis (DEA) has received the attention of some researchers to measure the relative efficiency performance of forest products operations. This technique is a non-parametric approach to evaluate efficiency, based on linear programming, which is especially useful in systems with multiple outputs and inputs. A virtual most-efficient producer is defined and compared with the real producer (decision making units), which is regarded as inefficient if it cannot produce outputs as efficiently as the virtual best producer. Data envelopment analysis “indicates the level of resource savings or service improvements for each inefficient unit if it is to achieve the level of efficiency of the best practice units” (Sowlati, 2005). DEA enables a fair comparison across units without assuming a best mode of production; allows identifying reference peers and source of inefficiency; and can incorporate multiple inputs and outputs. Table 1-2 shows some of applications of DEA in the forest products industry.

Table 1-2. Data envelopment analysis in the forest products industry

Decision Making Units	Inputs	Outputs	Reference
Forest districts in Taiwan	Budget, initial stocking, labor, land	Timber production, by-products, soil conservation	(Kao & Yang, 1991)
Forest owners associations in Japan	Staff, assets, costs	Revenue	(Shiba, 1997)
Logging contractor in U.S. south	Capital, labor, consumables	Tons of wood	(Sowlati, 2005)
Public forestry boards in Finland	Labor expenses, traveling, materials costs	Different outputs for each activities	(Viitala & Hänninen, 1998)
Forest and paper industries in different countries	Interest expenses, total costs and expenses	Total sales	(Lee, 2005)
Line-board mills in North America	Fiber, chemicals, fuel, power, labor, materials, delivery	Annual production	(Yin, 1998)
Pulp producers in the world	Fiber, energy, labor, materials	Annual production	(Sowlati, 2005)
Sawmills in Greece	Capital, labor	Production	(Sowlati, 2005)
Sawmills in Norway	Capital, labor, electricity, fuel, oil, lumber for planning saw-logs	Lumber, planed lumber, chips and residues	(Nyrud & Baardsen, 2003)
Wood products manufacturing sub-sectors in Canada	Employees, materials, energy	Revenues	(Vahid & Sowlati, 2007)

1.6.4 Supply Chain Performance Measurement

Performance measurement in a supply chain environment presents additional challenges to the ones mentioned in the previous section. Supply chains are larger and more complex systems and overall measures should be consistent with each component's strategic goals. Simatupang and Sridharan (2008) state that performance measurement systems are key elements of supply chain collaboration, since metrics drive behavior, and measures must be common across the supply chain members to be meaningful. A brief explanation of some proposed approaches and instruments to measure supply chain performance follows.

Some authors favor few and simple measures for supply chain performance. Lapide (2000) states that the *availability* of products and the *total costs* to the point of consumption are the most important overall performance measures for a supply chain (Lapide, 2000). The *perfect order* is a measure that connects supply chain's logistics performance and customer satisfaction. While different companies will include different components to the perfect order definition, in general this metric represents the percentage of orders that meet customers' expectations perfectly. The perfect order might be defined as delivering the right quantity of required products, in proper conditions, at the correct location, when it is needed, and at the right cost for the company and the customer (Novack & Thomas, 2004). Although a simple concept, implementing the perfect order metric presents many challenges, like having the appropriate information in a timely manner, the impact of backorders or substitutions, and the effect of customer request date. It is claimed that a well implemented perfect order measure can help the company to meet customer expectations, reduce lead times, reduce variability, identify where problems occur in the order cycle, and improve service flexibility.

Towill (1996) asserts that focusing on reducing *lead time*, known as *time compression*, at all echelons of a supply chain is the best way to achieve supply chain improvements. The logic is that to collapse lead time, the company must streamline the flow of material, information, and cash; and that compressing time also reduces the effects of uncertainty as the time horizon for forecasting and planning is also compressed. One benefit of time compression is quicker defect detection, and consequently improvement of overall quality. Three main tactics are followed when collapsing time in a supply chain: (1) provide members with better and timely information (2) help members to shorten work cycle times in bottleneck operations, and (3) balance lead time and capacity. Common tools to achieve time compression are industrial and production engineering, information technology, operations engineering (Denis R. Towill, 1996), and lean manufacturing tools.

Other authors state that a good performance measurement system for supply chains should include metrics for all relevant aspect of performance. According to Beamon (1999), in order to have a balanced and inclusive approach, performance measures used for a supply chain should reflect *resources*, *outputs*, and *flexibility*. Specific measures proposed by the author in each of these categories are shown in Table 1-3.

Table 1-3. Performance measures for supply chain

Performance measurement area	Metrics	
Resources	• Total cost • Distribution cost • Manufacturing cost	• Inventory • Return on investment (ROI)
Outputs	• Sales • Profit • Fill rate • On-time deliveries • Backorders / Stock-outs	• Customer response time • Manufacturing lead time • Shipping errors • Customer complaints
Flexibility	• Volume flexibility • Delivery flexibility	• Product mix flexibility • New product flexibility

Li et al. developed a measurement instrument to assess overall supply chain management performance. The authors grouped SCM practices in six categories: (1) strategic supplier partnership, (2) customer relationship, (3) information sharing, (4) information quality, (5) internal lean practices, and (6) postponement (Li, et al., 2005). The instrument is a survey questionnaire based on qualitative information that can be used to assess overall SC management performance. Its ability to predict SC performance was evaluated comparing its results with performance as measured using the Supply Chain Operations Reference (SCOR) model, developed by the Supply Chain Council (Supply-Chain Council, 2008). Results showed that the effective implementation of supply chain management practices did improve performance as defined by the reference model.

Brewer and Speh (2000) combined the framework of supply chain management with Kaplan and Norton's balanced scorecard to measure SC performance. The authors listed some examples for specific metrics in each dimension, but managers can develop new metrics according to the specific needs of their supply chains. This measurement approach expands the benefits of the balanced scorecard from individual companies to supply chains: focus on strategy rather than control and cross-functional integration. It also recognizes the inter-firm nature of supply chains. Table 1-4 shows the proposed framework (Brewer & Speh, 2000).

Table 1-4. Balanced score card for a supply chain and sample metrics

Customer perspective		Innovation and learning perspective	
Goals	Measures	Goals	Measures
1. Customer view of product 2. Customer view of timeliness 3. Customer view of flexibility 4. Customer value	1. Number of customer contact points 2. Relative customer order response time 3. Customer perception of flexible response 4. Customer value ratio	1. Product/process innovation 2. Partnership management 3. Information flows 4. Threats and substitutes	1. Product finalization point 2. Product category commitment ratio 3. Number of shared data sets/total data sets 4. Performance trajectories of competing technologies
Customer perspective		Financial perspective	
Goals	Measures	Goals	Measures
1. Waste reduction 2. Time compression 3. Flexible response 4. Unit cost reduction	1. SC cost of ownership 2. SC cycle efficiency 3. Number of choices/ average response time 4. % of SC target costs achieved	1. Profit margins 2. Cash flow 3. Revenue 4. Return on assets	1. Profit margin by SC partner 2. Cash-to-cash cycle 3. Customer growth & profitability 4. Return on SC assets

1.6.5 Quality Framework

In order to provide a framework to investigate quality measurement in the wood products industry, this section reviews some quality definitions and relates them to quality of wood products. Typical quality measures and standards used by wood products manufacturers are also described.

Many definitions for quality have been provided in throughout the years, with approaches ranging from transcendent views ("innate excellence"), to the customer-oriented ("meeting or exceeding customers expectations"), to the very technical or manufacturing-oriented ("conformance to specifications"). Garvin stated that these sometimes conflicting views need to coexist, and identified eight dimensions necessary to define quality: (1) performance, or the operating characteristics of the product; (2) features, characteristics additional to the basic function of the product; (3) reliability, refers to the time that a product operates before failure; (4) conformance, or meeting accepted standards; (5) durability, the product life before it deteriorates; (6) serviceability, related to the quality of the repair service; (7) aesthetics, refers to how the customer perceives the looks, sound, smell or tastes of a product; and, (8) perceived quality, the most subjective together with aesthetics, represents the reputation and intangible features of a product (Garvin, 1984b).

The application of Garvin's eight quality dimensions to forest products was investigated in the office furniture and softwood lumber industries. Results from research in the office furniture industry (Sinclair, Hansen, & Fern, 1993) showed that most of Garvin's eight dimensions existed in the industry and that there is a strong association between service level and total quality perception. The authors suggested adding one economic dimension (price and value) and combining performance and features in one dimension and serviceability and perceived quality in another, since there is strong association between service and quality. In a similar work in the softwood lumber industry (E. N. Hansen, et al., 1996), the authors combined Garvin's eight product quality dimensions with the previously proposed components of service quality (Parasuraman, Zeithaml, & Berry, 1988) and came up with a twelve-dimension model with eighty items, which was tested by surveying home centers, truss manufacturers and wood treatment plants. Based on the results of the survey, the model was reduced to five-dimensions: (1) lumber characteristics, (2) supplier/sales person characteristics, (3) lumber performance, (4) supplier services, and (5) supplier facilities. Another survey among users of hardwood lumber showed that manufacturers of millwork, flooring, furniture, and cabinet manufacturers, based their buying decisions on grading accuracy, supplier's reputation, freedom from surface checks, competitive pricing, and lumber thickness consistency (Bush, et al., 1991). Thus, a company looking for a source of differentiation through superior quality should consider all dimensions of quality and determine the area they want to focus their efforts on. In wood products, although physical product quality attributes are listed among the most important determinants for buying decisions and perceived product quality, service quality, reflected on attributes like timely delivery or technical support, also plays a critical role.

The next section describes the quality standards and metrics used at several echelons of the generalized wood products supply chain. Each sector in the wood products industry has developed quality standards for their products. Quality standards provide the industry with a common language for trading and a basis for product quality measurement. Most of these standards categorize raw materials and products in quality classes, and some of them also prescribe methods for testing and evaluation. A description of quality standards for wood products, from logs to final products, follows.

1.6.5.1 Log Quality Standards

Tree species are divided in two broad categories: softwoods and hardwoods, based on botanic and anatomical differences. In general, hardwood lumber is used for flooring, architectural and interior woodwork, furniture, and pallets. Softwoods are generally processed for building components, such as studs, joists, scaffolding, and panel products for construction (Forest Products Laboratory, 1999b). Since processing and final uses for hardwoods and softwoods differ significantly, quality standards for these two groups vary as well. Softwood logs are typically traded by weight and are not individually graded.

Hardwood log quality is evaluated based on the estimated volume and final product category (e.g. lumber, pulp, or veneer) that can be obtained when the log is processed. The output, known as yield, is estimated using log rules, which are mathematical relations or tables that estimate volume based on log diameter and length (Freese, 1973), a measurement process known as log scaling. The log quality class, known as grade, is evaluated by determining its most profitable use (construction, lumber, veneer, pulp) and the quality and quantity of the products to be potentially obtained from the log (Rast, Sonderman, & Gammon, 1973). Log quality or grade is assigned based on surface characteristics that might indicate a loss of potential yield or reduction of utility, like rot, knots and cracks. There are no industry-wide accepted standards for log scaling and grading; it is common to find individual districts or buyers using their own preferred set of standards; one author found that there were more than ninety five log rules used in United States and Canada (Freese, 1973).

1.6.5.2 Commercial Lumber Quality Standards

Unlike log grading, lumber grade standards are widely recognized and used by the industry. Hardwood lumber grading is based on the surface area free of defects (clear cuts) and size of the pieces that can be obtained after cutting individual pieces of lumber. Inspection of hardwood lumber is typically done visually, but there is some incipient commercial application of automated grading by using lumber scanning systems. Softwood lumber is mostly graded based on its mechanical properties; which can be carried out visually (looking for major defects that may limit the strength and stiffness) or mechanically (by performing non-destructive tests to determine mechanical properties). Both hardwood and softwood lumber grading are typically carried out at the sawmill; and the development, upgrading and enforcement of standards is generally the responsibility of the manufacturers' association or a national organization.

The National Hardwood Lumber Association (NHLA) developed grades for hardwood lumber by the end of the nineteenth century. The NHLA grading rules sort lumber in different grades based on a visual assessment of the amount of the usable material, or cuttings free of defects (e.g. rot, knots or splits) (National Hardwood Lumber Association, 2003). The upper grades under the NHLA rules are more suitable for long, wide clear cuts; thus, manufacturers of moldings, doors, frames will more likely prefer these grades. Lumber of grades Number 1 Common and Number 2A Common yield more narrower and short clear cuttings, more suitable for flooring, kitchen cabinets (American Hardwood Export Council, Undated). Figure 1-6 illustrates requirements for selected grades (Cassens & Fischer, 1978).

Minimum board sizes	Minimum sizes of cuttings
W 6" x L 8'	W 4" x L 5' or W 3" x L 7'
W 3" x L 4'	W 3" x L 3' or W 4" x L 2'
W 3" x L 4'	W 3" x L 2'

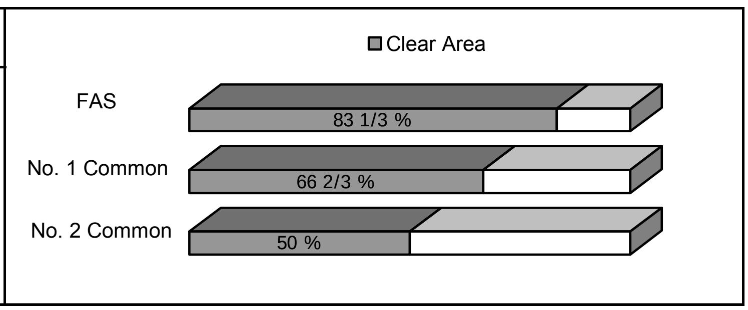


Figure 1-6. Characteristics of selected NHLA lumber grades

Softwood lumber grade standards are administered by the American Lumber Standard Committee (ALSC), which administers the accreditation program for the grade marking of lumber and maintains the American Softwood Lumber Standard (ALS). Most softwood lumber is used as structural components in construction, and most building codes dictate that each piece be individually marked with the logo of the applicable accredited agency. The ALSC is the basis for trading ninety eight percent of softwood lumber consumed in the U.S (American Lumber Standard Committee, 2001-2006). The programs and standards are shown in Table 1-5.

Table 1-5. American Lumber Standard programs

American Lumber Standard		
Lumber Program	Treated Wood Program	Wood Packaging Materials Program
• Standard Grading Rules for Northeastern Lumber (NeLMA) • Standard Grading Rules (NSLB) • Standard Specifications for Grades of California Redwood Lumber (RIS) • Standard Grading Rules for Southern Pine (SPIB) • Standard Grading Rules for West Coast Lumber (WCLIB) • Western Lumber Grading Rules (WWPA) • Standard Grading Rules for Canadian Lumber (NLGA)	American Wood Preservers Association (AWPA) Standards • Use Category System (UCS) • Preservatives (P) Standards • Commodities Standards (C) • Non-Pressure (N) Standards • Analytical (A) Standards • Miscellaneous Standards (M)	International Plant Protection Convention (IPPC) Guidelines for Regulating Wood Packaging Material International Trade (ISPM 15)

(Based on information from the American Lumber Standard Committee's website, 2001-2006)

Since most of softwood lumber is used for structural and construction purposes, visual grading consists in separating individual pieces by strength and stiffness, based on the size and location of the defect that most limit these mechanical properties, like knots, splits, wane and pith. For softwood lumber that is machine-graded (known as Machine Stress Rated), individual pieces of lumber are tested for modulus of elasticity and its grade is determined and stamped automatically.

1.6.5.3 The Grade Standard - Customer Perception Gap

There is a fair amount of literature regarding performance measurement and how it has to be aligned with the company’s strategy (Beamon, 1999; Chan, 2003; Gunasekaran, Patel, & McGaughey, 2004; Neely, 2005). Some common problems of performance measures are (1) having too much data and measures but of little value, (2) measures not balanced, with financial measures usually more represented, (3) counterproductive measures, (4) measures that lead to optimization of system components but sub-optimization of the system, (5) measures that do not support decision making, and (6) measures not sufficiently communicated (Van-Aken, 2004). These problems also apply of course to quality measures.

Some producers and researchers have investigated whether focusing solely on meeting industry grade standards is enough to satisfy customers' needs, realizing a gap between the customer's perception of quality and what is defined as acceptable quality by the industry standards (Hansen & Punches, 1996). This gap affects the customers' evaluation of the firm's quality (Parasuraman, 1985). Some firms consider acceptable quality just passing a re-inspection or receiving few complaints from the customer (Bishop, 1990) and with stumpage prices growing, some firms push grade limits to maximize yield. These trends have resulted in customers' dissatisfaction with the lumber quality. In a survey to lumber buyers, a great majority answered that lumber quality was decreasing (Hansen & Bush, 1996). It appears that achieving customer satisfaction can no longer be considered only meeting industry-defined grade standards.

The lumber industry shows characteristics of a mature and stalemate market: low transactional complexity and technology designed for large batches. In such a market there are few differentiation opportunities and little potential for competitive advantage, and therefore competition is based mostly on price (Calori & Ardisson, 1988; De Vasconcellos, 1991). However, even in this kind of market, differentiation through "total quality" and strong cost controls can lead to important competitive advantages. Total quality in this context means focusing on all dimensions of quality.

Some lumber producers have realized this differentiation opportunity and, for example, have expanded their product offerings and include proprietary grades, to serve the particular and special needs of their customers (Taylor, 1989), thus generating niche markets and closing the grade standard-customer perception gap. Investigation on the economics of offering proprietary grades found that important benefits for both the producer and the buyer could be achieved with this approach (Reeb & Massey, 1996). Proprietary grades are usually developed in close cooperation with specific customers and some companies include these grades in their normal offering, advertising high levels of yield.

1.6.5.4 Final Product Quality Standards

Regarding final wood products, the use of grade standards is generally limited to members of the organization that administers the standards. Some standards for final value-added and structural products are listed in Table 1-6.

Table 1-6. Quality standards for finished wood products

Product	Product/scope	Standard	Organization
Intermediate products	Dimension & components*	Rules and Specifications for Dimension & Woodwork	Wood Component Manufacturers Association
Value-added products	Cabinet, countertops and decorative laminate products	KCMA/ANSI A161.1	Kitchen Cabinet Manufacturers Association
	Wood flooring	NOFMA grades	Wood Flooring Manufacturers Association
	Wood flooring (maple)	MFMA-RL, MFMA-FJ, MFMA-PQ	Maple Flooring Manufacturers Association
	Interior architectural woodworks	AWI Quality Standards	Architectural Woodwork Institute
Structural components	Construction and industrial plywood and wood-based structural-use panels	PS 1-95 PS 2-04	National Institute of Standards and Technology, Engineered Wood Association
	Engineered wood products	PRI-400 I-joists, PRR-401 Rim Board®, PRL-501 LVL	Engineered Wood Association

*Lumber processed into specific dimensions, semi- or completely machined

The criteria used to assign grades for end products vary widely. Grading of structural components is based on mechanical properties and durability. Others, like the AWI standards contain guidelines to assess levels of product, finishing and installation quality. Standards for dimension and components contain guidelines for specify products, along with tolerances and allowances. Grades for flooring are assigned based on allowances for natural characteristics and manufacturing marks.

1.6.5.5 Final Consumer Perceptions

It is the end customer who finally makes the final purchase decision, therefore, it is critical to understand how he/she decides which product to buy and under what criteria.

All efforts to measure and improve quality in previous steps of the value chain would be of little value if the metrics used do not align with the customers' definition of quality. Much of the research on customers' perceptions in the wood products industry deals with intermediate consumers, like lumber users and furniture buyers (Bush, et al., 1991; Dunn, Shupe, & Vlosky, 2003; Forbes, et al., 1994).

Although limited, there has been some interest in understanding final consumer behavior in the forest products industry (Anderson, et al., 2005). One example is one study about the relative importance of environmental certification as in purchase decisions (Anderson & Hansen, 2004), results showed that little importance is placed on environmental certification as a product attribute; but among those who rated certification as the most important attribute, there was a willingness to pay more for these products. In another research effort, the attitudes and feelings toward wood features were investigated and identify the overall blending of wood features and the divergent features that mismatch in the surface as the most important factors in the visual impression of wood (Broman, 1995).

1.6.6 Quality Improvement

There are four general approaches for quality assurance and improvement (Kozak & Maness, 2003): 1) in-house quality programs, which may consist of any existent improvement technology (e.g., lean manufacturing, six-sigma) or one developed by the company; 2) a quality certification system, like the ISO quality standards, which makes use of quality standards developed by some internationally recognized and evaluated by an independent party; 3) an award mechanism, and 4) an industry-specific logo. This section describes the most common quality improvement technologies in the wood products industry.

1.6.6.1 In-house Quality Programs

The last IW/MPI (Industry Week and Manufacturing Performance Institute) Census of Manufacturers (Blanchard, 2006) lists as the most popular improvement methods lean manufacturing, with 40.5 percent of companies choosing it as their primary improvement method, followed by lean-six sigma (12.4 percent), and total quality management (9.9 percent) in third place. Regarding improvement technologies, the wood products industry reflects the trends identified in the U.S. manufacturing sector. In a survey to a variety of secondary wood manufacturers (Cumbo, et al., 2006), 55 percent answered that they were currently implementing lean manufacturing (LM), with kitchen cabinets and upholstered furniture companies the most enthusiastic (56 and 71 percent of companies, respectively). Lean manufacturing philosophy considers defects or low quality as a one of the “seven wastes” and recognizes the need for its elimination. One-piece flow (a goal of LM) facilitates the discovery of errors and their causes; and helps to avoid the mass production of defects. Numerous success stories can be found in trade journals about results from LM implementation, and most outcomes are stated in terms of reduced lead-time and increased production, as a result of improvements in availability, performance, and quality.

The potential of Statistical Process Control (SPC) to improve quality by reducing variation in wood products has long ago been recognized by producers and researches. Maybe the best example of SPC application in the wood products industry is the control of lumber thickness variation in sawing operations, where a reduction of a thousandth inch in the target thickness can save the sawmill important amounts of resources by improved recovery. This can only be accomplished by carefully monitoring thickness variation between and within individual pieces of lumber to detect changes in process and their causes (Brown, 1979). The potential of SPC for controlling variability in the lumber drying process has been also investigated (Maki & Milota, 1993) but is not widely applied. SPC is also used by plywood and other panel products manufacturers (Young & Winistorfer, 1999).

1.6.6.2 Quality Certification

The most internationally recognized quality certification program is the ISO 9000. It provides international recognition that a company can understand, meet, and enhance customer requirements; achieve continuous improvement of performance; and meet applicable regulatory requirements (International Organization for Standardization, 2004). ISO 9000 does not certify a specific product but rather the quality management system in place. The adoption of the ISO 9000 quality standards is limited among U.S. wood products companies. Main drivers to apply for certification are to use it as a framework for Total Quality Management (TQM), to gain competitive advantage through an improved perception of quality by customers, and by customers requirements (Ruddell & Stevens, 1998).

Environmental certification has been a hot subject during the last decade. It was conceived as a market-based approach to better management of forests. The Forest Stewardship Council (FSC) is an independent non-governmental organization that sets international standards for responsible forest management, and is a widely recognized certification entity. Being FSC-certified gives a company’s products the right to bear the certification logo and allegedly access to new markets and higher prices. However, environmental certification is not yet a highly valued product attribute among U.S. consumers, nor it allows manufacturers to charge significant premiums for environmentally- certified wood (Ozanne & Vlosky, 2003; Stevens, Mubariq, & Ruddell, 1998). Nevertheless, the United States has, after the United Kingdom, the largest number of chain of custody certifications, and the fourth largest certified forest area in the world (Forest Stewardship Council, 2003).

1.6.6.3 Quality Awards

The most prominent quality award in the U.S. is the Baldrige Award for Quality, which lays out guidelines for assessing an organization’s performance in seven areas: organization and leadership, strategy, customer focus, measurement and analysis, human resources, process management, and results. Among the twenty seven manufacturing award-winning companies, there is one wood flooring products firm recipient of the award (U.S. Commerce Department's Technology Administration, 2006). Every State has its own version of the award to recognize excellence in quality. Also, industry-specific quality awards exist in every major wood products category, usually administered by an industry association or a recognized trade magazine. Examples are the Safety Excellence Awards (American Forest & Paper Association), the Outstanding

Mill Achievement Award (Northwest Pulp and Paper Association), and the Metz Award (Wood and Wood Products Magazine).

1.6.6.4 Industry-specific Mark or Logo

The Wood Products Quality Council in Canada provides companies with a framework for quality management that covers management commitment, quality plan, continuous improvement, traceability, inspection of incoming material, training and measurement of in-progress work (Kozak & Maness, 2003). Companies that successfully apply these principles are awarded the certification (Kozak & Maness, 2003) and the right to bear the Woodmark logo on their products. Eight companies are currently listed as Woodmark-certified (Wood Products Quality Council, 2006).

In the U.S., the Architectural Woodworking Institute (AWI) has a quality assurance tool for interior architectural woodworks called the AWI Quality Certification Program (QCP). Applicants have to demonstrate the ability to manufacture, finish and/or install woodworks in compliance with the Quality Standards Illustrated. The certification process includes a questionnaire about the QSI, references from owners, contractors and architects, and a plant and project inspections. There are currently 440 firms and professionals certified in this program (Architectural Woodwork Institute, 2006).

1.6.7 Quality Management

Quality management, as stated in the “Juran’s trilogy”, includes the processes for planning, controlling and improving quality (Gryna, De Feo, & Juran, 2007). Deming, credited for starting the total quality management (TQM) movement, laid down fourteen principles for quality management (Deming, 1986). In a broad sense, quality management could be regarded as *all the business management activities aimed at meeting customer requirements* and doing so in a way to maximize profit (Earl, 1989). Eight factors were identified by Saraph et al. (1989) from the literature as critical for quality management (QM). The factors and a brief explanation are shown in Table 1-7.

Table 1-7. Critical factors for quality management

Critical factors	Description
1. Role of management leadership and quality policy	Acceptance of responsibility by department heads. Participation in quality improvement efforts. Specificity of quality goals. Importance attached to quality in relation to cost and schedule. Comprehensive quality planning.
2. Role of the quality department	Visibility and autonomy of the quality department. The quality department's access to top management. Use of quality staff for consultation. Coordination between quality department and other departments.
3. Training	Provision of statistical training. Trade training, and quality-related training for all employees.
4. Product design	Thorough scrub/down process. Involvement of all affected departments in design reviews. Clarity of specifications. Emphasis on quality, not roll/out schedule. Avoidance of frequent redesigns.
5. Supplier quality management	Fewer dependable suppliers. Reliance on supplier process control. Strong interdependence of supplier and customer. Purchasing policy emphasizing quality rather than price. Supplier quality control. Supplier assistance in product development.
6. Process management	Clarity of process ownership, boundaries, and steps. Less reliance on inspection. Use of statistical process control. Selective automation. Fool-proof process design. Preventative maintenance. Employee self-inspection.
7. Quality data and reporting	Use of quality cost data. Feedback of quality data to employees and managers. Timely quality measurement. Evaluation of managers and employees based on quality performance. Availability of quality data.
8. Employee relations	Implementation of employee involvement and quality circles. Open employee participation in quality decisions. Responsibility of employees for quality. Employee recognition for superior quality performance. On-going quality awareness of all employees.

The relationship between specific quality management (QM) practices and quality performance was investigated by Flynn et al. (1995) by constructing a framework based on the literature and validated by path analysis, using information from manufacturing plants. Figure 1-7 illustrates the revised model (Flynn, Schroeder, & Sakakibara, 1995).

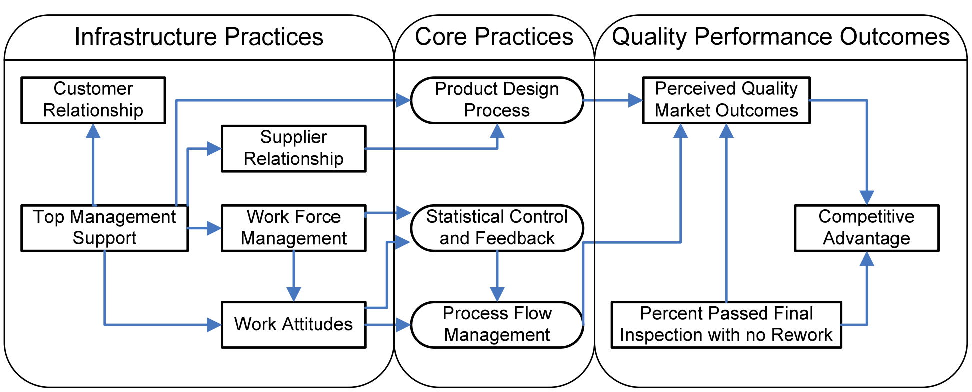


Figure 1-7. Model for quality management practices and performance

The model includes “core” QM practices (process flow management, product design, statistical control), which directly impact performance; and “infrastructural” QM practices (supplier relationship, work attitudes, workforce management, top management support), which create the environment that allows and supports the core practices. The quality performance outcomes included in the model were perceived quality, percent of flawless products and competitive advantage. Some important findings about the relationships in the final model were: (1) perceived quality and percent of error-free products could not explain most of the competitive advantage variance, thus suggesting that other factors contribute to competitive advantage; (2) product design is very important for perceived quality and process flow, and statistical quality control contribute mostly to the physical quality of the product; (3) conformance quality is an order qualifier, while aesthetics and design are order winners, contributing to competitive advantage; (4) top management support is critical for core and infrastructure QM practices.

1.6.8 Supply Chain Quality Management

Supply chain quality management (SCQM), is “the formal coordination and integration of business processes involving all partner organizations in the supply channel to measure, analyze and continually improve products, services, and processes in order to create value and achieve satisfaction of intermediate and final customers in the marketplace” (Robinson & Malhotra, 2005). Table 1-8 shows the main components of quality management and supply chain management that are combined into a framework for SCQM.

Table 1-8. Components of supply chain quality management

Quality Management	Supply Chain Management
Customer focus	Relationships and partnerships
Strategic planning and leadership	Strategic management
Continuous improvement and learning	Transportation and logistics
Empowerment and teamwork	Marketing
Human resources	Continuous improvement and learning
Management structure	Organizational behavior
Quality tools	Best practices
Supplier support	Supply base integration
Framework for Supply Chain Management Quality Management	
Internal Supply Chain	External Supply Chain
Intra-Organizational Focus	Inter-Organizational Focus
• Internally Focused Process Integration & Management	• Externally Focused Process Integration, Management & Strategy
• Strategy	• Communication and partnership
• Quality leadership	• Supply chain quality leadership
• Quality practices	• Quality and supply chain practices

It should be noted that the strategy and process integration in the external supply chain are combined into a single theme because of their close relationship. Following some research models for quality planning and control in a supply chain environment are described, as well as attempts to explain the impact of SCQM practices on overall performance.

Ten critical practices in supply quality management were identified by Lo and Yeung (2006). Practices were grouped in three areas. Figure 1-8 shows the ten critical practices identified; grouped in three main areas of supply quality management by the aforementioned researchers.

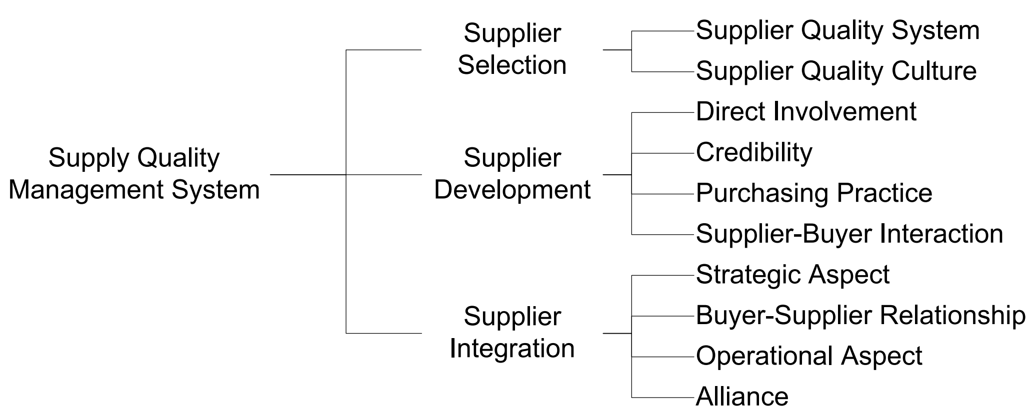


Figure 1-8. Critical areas and practices of supply quality management

In Figure 1-8, *supplier selection* refers to the shift towards long-term partnerships with suppliers, where selection is based on quality rather than price. Supplier characteristics to look for here are: a reliable quality assurance system, an effective control of operations, continuous quality improvement, awareness of quality policy, and quality certification (e.g., ISO, MBQA). In *supplier development*, the authors group activities aimed at helping suppliers develop the required quality, such as supplier evaluation, achievement recognition, supplier training, technical assistance, effective communication, and proactive attitude and commitment. Lastly, the *supplier integration* areas include all joint development activities with suppliers, like sharing strategic information, long-term relationships, mutual trust, supplier base reduction, joint problem solving, and improvement of quality in both sides (Lo & Yeung, 2006).

Sila et al. explored the relationships between quality management and supply chain management by surveying one-thousand U.S. companies that manufacture electric and electronic equipment, transportation equipment, and instruments and related products (Sila, et al., 2006). Component suppliers, major component suppliers and end product producers were included in the sample to represent the different echelons of a supply chain. The authors did not find significant differences in knowledge about suppliers and customers based on the position in the supply chain. Among price, quality and trust as important attributes in the relationships with customers and suppliers, most companies rated quality as the most important. Surprisingly, results show that quality systems are developed internally, without much consideration of customer input; and companies involve major customers in their improvement initiatives, but not major suppliers. Lastly, companies believe that SCQM does have a positive impact on product quality.

Similarly, another study explored quality management practices at different levels of the supply chain found no statistical difference in the level of quality management (Choi & Rungtusanatham, 1999). However, results do show differences in strategic quality planning depending on the industry, with auto manufacturers the most active (only automotive, electronics and metal coating industries were represented in the sample). The levels of supply chain were defined as final assemblers, top-tier suppliers, and tertiary-tier suppliers. The factors of quality management investigated were:

management of process quality, human resource development and management, strategic quality planning, and information and analysis.

Regarding specific components of supply chain quality management, Novack (1989) presented a control model for logistics operations that can be applied for quality control in supply chains. The author highlights the importance of matching the sophistication of the control system with the quality levels desired by the customer. Figure 1-9 shows an abbreviated version of the model for control process proposed.

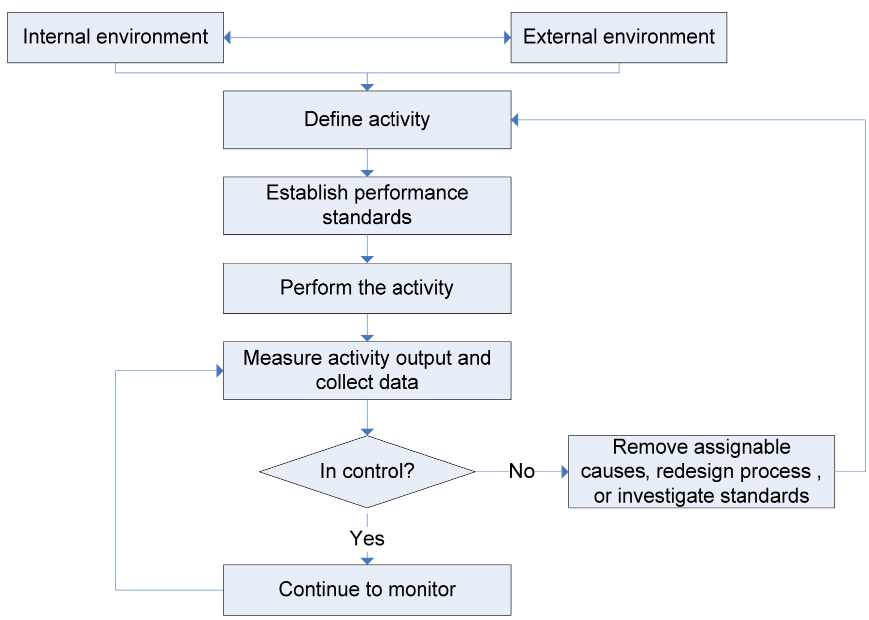


Figure 1-9. Control process for logistics operations

Batson and McGough (2006) developed a model for strategic quality planning of production and supply chain at the early stages of installing a new manufacturing plant (shown in Figure 1-10). Operations research and network simulation can be used to maximize supply chain efficiency, but only with quality planning can designers consider customers' needs. Juran's quality planning roadmap can be used for this purpose.

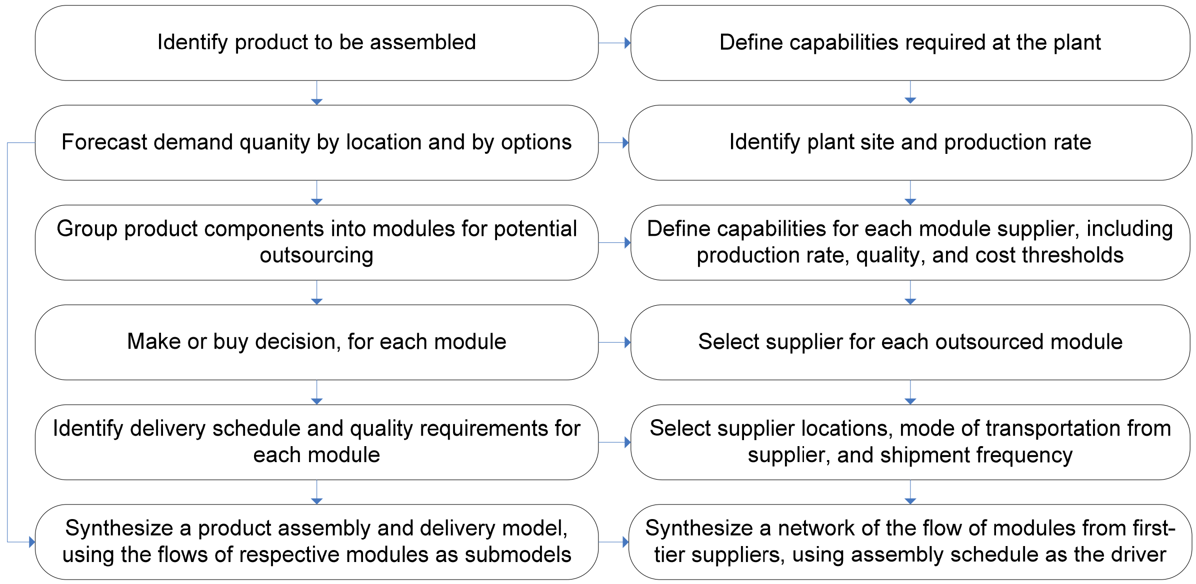


Figure 1-10. Model for strategic quality and production planning in a supply chain

Some researchers link SCQM with metrics typically used when implementing improvement methodologies such as six sigma, total quality management, and business system engineering. Dasgupta (2003) adapted typical six-sigma metrics to measure quality performance in a supply chain, such as the probability of filling an error-free order (*yield*), defects per unit (*dpu*), and sigma value (*z-value*). These metrics reflect the combined effect on quality of the inter-firm nature of a supply chain. Six-sigma metrics allow companies to measure supply chain quality performance and also identify the cause and probable sources of performance under six-sigma level.

Tan et al. (1999) studied total quality management (TQM) as part of supply chain management practices, along with competitive environment, supply chain base management practices, and customer relations; in an empirical study to determine the impact of these practices on performance. The seven TQM factors investigated are listed in Table 1-9. In the results, only the use of performance data had a significant impact on growth and return on assets (ROA), management commitment to quality, involvement of the quality department, and the social responsibility of management had a positive impact on overall performance.

Table 1-9. TQM practices factors and performance measures impacted

Factor	Performance Measure Impacted
Management commitment to quality	Overall performance
Use of performance data in quality management Use of quality related training	Growth and ROA
Involvement of quality department Use of operational quality practices	Overall performance
Social responsibility of management Delegation of responsibility	Overall performance

A similar study by Forker et al. (1997) aimed at determining the relationship between eight TQM practices, based on those defined by Saraph et al. (1989) and supply chain's quality performance. The quality performance measures studied were lot acceptance, piece part acceptance, and defective parts per million. Using data envelopment analysis (DEA), the authors found a non-linear relationship between TQM practices and quality performance. Five of the eight TQM practices were positively correlated to performance in firms that efficiently implemented these practices: supplier quality management, role of the quality department, training, quality data and reporting, and product design. Process management and the role of top management were not significant in the step-wise regression. The employee relations factor was positively correlated to quality performance regardless of efficiency in implementation (Forker, et al., 1997). In another study by the same authors, perceptions regarding quality improvement efforts by suppliers and buyers for a major electronic company were assessed. Results show that buyers consider quality more important when selecting suppliers than suppliers thought, and that buyers had more faith in their supplier qualification system that did the suppliers (Forker, Ruch, & Hershauer, 1999).

1.6.9 Impact of Supply Chain Quality Management on Performance

The impact of SCQM practices on organizational performance was investigated by surveying the perceptions of middle managers in about one hundred mid to large-sized companies in Taiwan (Kuei, et al., 2001). The instrument developed by Saraph et al. (1989) was used for the study. Organizational performance items were cost savings, productivity, sales growth, earnings growth, and employee satisfaction. Companies were classified in three quality performance clusters: high, medium and low quality.

Results show that improvements in organizational performance, as perceived by practicing managers, are related to improvements in supply chain quality management practices. High quality performance systems performed better in cost savings than low quality ones. Also, high quality systems had a better performance than medium quality system in productivity, earnings growth and sales growth. Employee satisfaction, productivity, and sales growth were higher in medium quality systems as compared with low quality systems.

The impact of operational quality management on supply chain quality performance was investigated by surveying purchasing and materials managers in manufacturing firms in the US (Kannan & Tan, 2007). The authors evaluated a model with five factors (customer input, supplier quality, design quality, JIT quality, and process integrity) and their effect on two quality performance measures (product quality and customer service). Items included in the QM factors are operational in nature and can be used tactically by companies in their interactions with customers and suppliers to improve overall quality. Only JIT did not have a significant impact on product quality; and as for customer service, supplier quality and process integrity did not significantly impact it. Results showed that quality efforts must not be only internally focused, but also take in consideration suppliers and customers. Significantly, customer input was very important for product quality and customer service. In summary, Kannan and Tan (2007) demonstrated that an externally-focused quality effort, this is involving a company's customers and suppliers, has a positive impact on product quality and customer service. This association comes from the fact that the quality delivered to the final customer is a product of the quality management efforts by all supply chain members (Rahman, 2006)

In a different approach, simulation was used by Persson and Olhager (2002) to assess different supply chain alternative designs. They constructed and simulated three SC designs with different levels of integration and synchronization, and three levels of quality yield. The alternatives were evaluated based on total SC costs, aggregate quality, and lead time (Persson & Olhager, 2002). The outcomes of the simulations consistently showed better results as the level of integration and synchronization of the SC increased. Some interesting relationships from the results were that total cost increased more than proportionally with lead-time and this non-linearity increased with poorer quality.

The impact of interactions between suppliers and customers on the supply chain's time performance (how fast and accurately products flow through the supply chain to the final customer) was investigated by Salvador et al. (2001). The model used by the authors is shown in Figure 1-11 (Salvador et al., 2001).

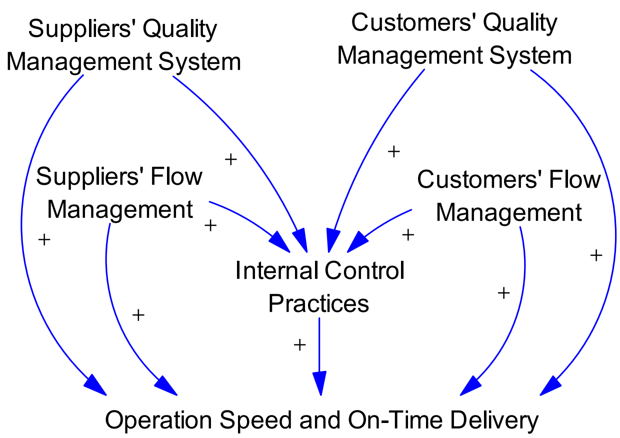


Figure 1-11. Interaction between supply chain members on time performance

Examples of flow interaction include commitment to time-phased orders in long-term purchase agreements, to allow for shorter order-to-delivery times; electronic data interchange (EDI) implementation; or internet-based commerce. Quality management interactions may include supplier certification and joint product design. The authors differentiate between improvements in time performance achieved only through supply chain interactions, and not necessarily improvements in companies' internal processes; and improvements driven by changes in internal activities. The first ones are considered as *direct effects* of supply chain interactions, and the later are known as *mediated effects* of internal practices. Two time performance metrics were used: punctuality of delivery and operations speed. The study was conducted collecting information in 164 manufacturing plants located in four countries (UK, USA, Germany, and Japan), and producing electronic products, machinery and transportation equipment. Results confirmed the hypotheses that supply chain interactions do have a positive impact on time-related performance. In the case of quality management, time performance improved as a result of internal activities. Interactions for flow management, on the other hand, had a direct impact on time performance (Salvador, et al., 2001).

1.6.10 Summary of the Literature Review

The most important ideas from the literature review can be summarized as follows:

- Companies no longer compete as separate entities, but as parts of complex networks known as supply chains. Companies that recognize this are better positioned to compete in the new global economy.
- Supply chain management requires the management of business processes that span the entire network, from supplier management to customer service. Supply chain management can help companies to reduce costs, achieve time compression, and improve financial performance.
- Supply chain integration leads to better performance in quality, delivery, and cost-effectiveness. These improvements come, in great part, from the reduction of uncertainty made possible by integration. New product development, for example, is more successful when suppliers and customers are involved in the designing process.
- Performance measurement systems are critical to the success of an organization. An effective performance measurement system is balanced, aligned with the strategy of the firm, drives the desired behavior, and avoids sub-optimization. The last characteristic is particularly important when measuring performance in a supply chain; a systems thinking must be adopted and the measurement system should span the entire supply chain.
- Quality has several dimensions, and to achieve customer satisfaction, organizations need to focus on all those dimensions critical to their customers. Service attributes are as important for customer satisfaction as product attributes.
- Quality management involves all the business processes aimed at meeting customer requirements. This concept can be extended to the supply chain when all partner organizations are included in a concerted effort, and when value is created for intermediate as well as final customers. Supply chain quality management practices

are associated with better performance in terms of lead time, costs, growth, productivity, and employee satisfaction.

Research is limited about specific aspects of quality management in the supply chain, particularly quality measurement. Some authors suggest supply chain measures of quality, mostly focusing on logistics performance (e.g., lead time, filling rate, and backorders). Little can be found, however, on the impact of poor quality throughout the supply chain. This is especially important if sub-optimization is to be avoided.

Likewise, very little research has been found concerning supply chain management principles applied to wood products enterprises in general, and none about supply chain quality measurement in particular. Considering that the wood products manufacturing sector has been negatively affected by global sourcing and competition of low-cost imports, it could benefit from knowledge about tools that have proved valuable in improving competitiveness in other industries.

From the literature review, it is well established that (a) companies are better off when collaborating and integrating with their supply chain partners, (b) performance measurement systems should be carefully designed to avoid sub-optimization, and that (c), quality is a powerful strategic tool to achieve competitive advantage. This study combines these ideas in order to investigate current quality measurement practices in a supply chain environment and the potential for improvement. Results from this dissertation contribute the body of knowledge of the fields of supply chain management, performance measurement, and wood science and forest products. The outcomes from this research could be useful in the development of supply chain performance measurement systems, particularly for quality measurement.

Chapter 2. Research Methods

To accomplish the objectives of this research, a single-case study was conducted, studying a wood products supply chain (SC) with great detail. Data collection techniques consisted of on-site visits to manufacturing plants, field studies, and semi-structured interviews with key personnel in order to request quality-related data. The information gathered was used to portray the supply chain in a Value Stream Map in order to have a better understanding of the relationships between SC entities and flows of materials and information. The focus of the data collection phase was to obtain in-depth knowledge of quality measurement practices across the supply chain of interest. To accomplish the second and third objectives of the research, a set of quality performance metrics at the supply chain level was used to assess the impact of current and alternative practices.

Figure 2-1 depicts a process flow showing the main phases of the research, the methods and tools used, and the main results of each phase. This process is a combination of value stream mapping process by Jones and Womack (2002), Beamon and Ware's (1998) process quality model, and Stuart et al. (2002) suggested five-step process for case study research. Following is an overview of case study research, value steam mapping, and the data collection and analysis techniques used.

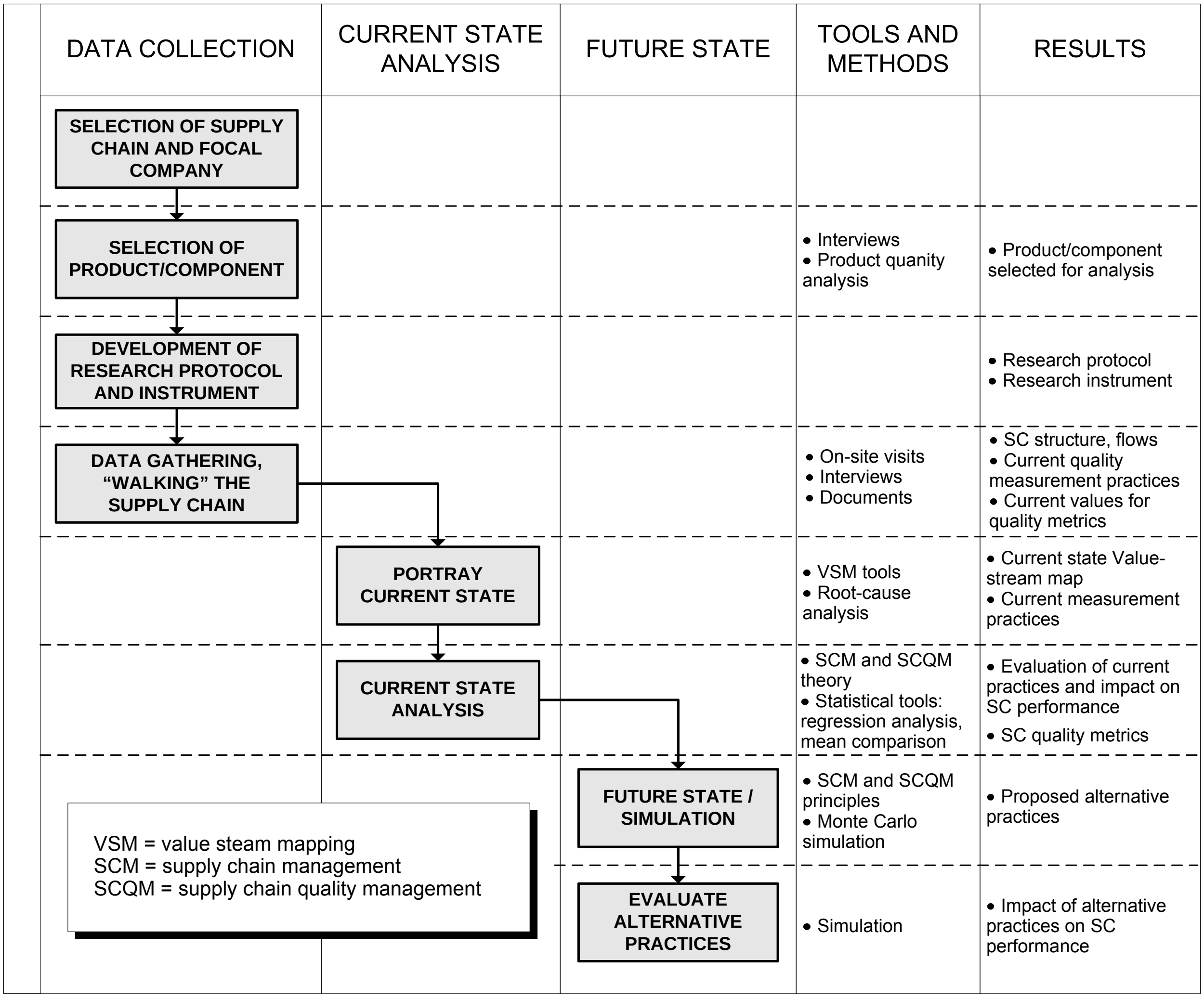


Figure 2-1. Research process, methods, and results

2.1 Overview of Case Study Research

A case study is "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident, and in which multiple sources of evidence are used" (Yin, 1984). Case study research is particularly appropriate when (1) the research questions are of the "how" and "why" types, (2) there is little or no control over the subject of the research, and (3) the activities performed by the system occur in the present (Stuart, McCutcheon, Handfield, McLachlin, & Samson, 2002). Table 2-1 shows a partial view of the research strategies and theory-building activities by Handfield and Melnyk (1998).

Table 2-1. Partial view of matched research strategy and theory-building matrix

Purpose	Research question	Research structure	Data collection techniques
Mapping	• What are the key variables? • What are the salient, critical themes, patterns, categories?	• Few focused case studies • In-depth field studies • Multi-site case studies • Best-in-class case studies	• Observation • In-depth interviews • History • Unobtrusive measures
Relationship building	• What are the patterns or linkages between variables? • Can an order in the relationships be identified? • Why these relationships exist?	• Few focused case studies • In-depth field studies • Multi-site case studies • Best-in-class case studies	• Observation • In-depth interviews • History • Unobtrusive measures

In this study, the current quality measurement practices were described (mapped) and an understanding was pursued of the relationships between supply chain members in regards to quality measurement activities (relationship building). A single case study allows the description of these activities and relationships with great detail and depth, this way facilitating the achievement of theoretical validity.

Case studies allow the identification and description of critical variables and thus are appropriate for the field of Supply Chain Management (Seuring, 2005). This methodology "can help to gather better information about the realities of supply chains and develop better, more complete theories about them" (Koulikoff-Souviron & Harrison, 2005) . Stuart et al. (2002) suggest a five-step process for a case study research. And a slightly modified version is illustrated in Figure 2-2.

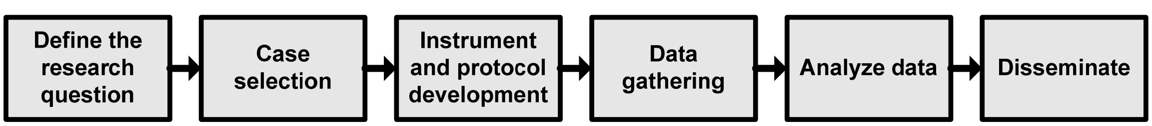


Figure 2-2. Case study research process

As with any other research strategy, the research questions have to be stated first. As mentioned before, case study is most appropriate for how- and why-type of research questions. Once these questions are formulated, a case (or multiple cases) should be selected. Case selection can follow several approaches. Many times case selection is opportunistic (i.e. companies near to the researchers' facilities, or good contacts with key personnel inside the companies), but care should be taken to avoid extraneous variations and the effect of company size, type of manufacturing process, and industry. The case selected does not need to be representative, but rather exemplary, since inferential statistics are not crucial (Stuart, et al., 2002). For a case study strategy, the selection of a case follows theoretical rather than statistical reasons (Koulikoff-Souviron & Harrison, 2005). As rationale for a single-case study, the same authors state that in Supply Chain Management, a single case might be selected "in order to research in great depth exemplary practices". However, single-case studies must be carefully investigated to assure access to information and minimize the chances that the case turns out not being what was expected, with the resulting waste of time and efforts. For this research, the unit of analysis for the proposed research was a wood products supply chain, and the subunits were the supply chain's entities or individual companies. Therefore, this research falls into the "embedded" single-case research design category (Yin, 1984), where in addition of the main unit of analysis, attention is also given to subunits.

After defining the research questions and selecting the case, a research protocol has to be developed. This step is very important for the reliability of the case study research. A case study protocol contains the instruments, procedures, and rules that are used in the data collection phase of the research. When developing the protocol, it should considered using multiple sources of evidence (Yin, 1984) and multiple data collection methods (Koulikoff-Souviron & Harrison, 2005), both contribute to increase construct validity.

A common criticism of the case study strategy is that it lacks rigor. This can be countered by carefully designing and documenting the research process and by taking measures to ensure the reliability and validity of the study (Stuart, et al., 2002). Some suggestions to ensure the quality of the case study are: (1) to establish a chain of evidence (for construct validity), (2) to use pattern matching and explanation building (for internal validity), (3) the use of replication (for external validity), (4) careful documentation of the process, (5) the use of rules of conduct to structure the research process, (6) to validate communication, and (7) the use of triangulation (Seuring, 2005; Yin, 1984). Table 2-2 lists the tactics that were used to ensure that this research meets the quality tests for a case study, based on the aforementioned authors. No tactic for internal validity was considered since the study is of a descriptive nature.

Table 2-2. Tactics to assure case research quality

Test	Tactic
Construct validity	• Use more than one source of information (interviews, documents, observation, literature) • Revision by key interviewed personnel • Carefully establish and document the chain of evidence for the conclusions derived from the study • Creating a model of the current state and using simulation for its validation
External validity	• Analytical generalization. Focusing on key elements of the supply chain of the study to comparison with similar supply chains. • The current state quality measurement practices will be compared with the "ideal" practices as described in the literature (e.g. highest level of collaboration and information sharing between supply chain members)
Reliability	• Carefully developed and documented research protocol • Create a database with all materials related to the study: field studies notes, interviews scripts, and documents from companies

2.2 Overview of Value Stream Mapping

Value stream mapping (VSM) is "the simple process of directly observing the flow of information and materials as they occur, summarizing them visually, and then envisioning a future state with much better performance" (Jones & Womack, 2002a). A value stream map can represent activities from product development to introduction in the market, or from a customer's order to its completion (Tapping, Luyster, & Shuker, 2002).

The process for problem solving with value stream mapping is (1) selecting a product family, (2) identifying the problem from the perspective of the customer and the organization, (3) walking along the value stream to map the current state, (4) mapping the current value stream for the selected product, and (5) mapping the future state. In mapping the future state, each activity of the process is assessed regarding whether it really creates value, and a continuous flow and leveled output are sought after (Womack, 2006). The purpose of mapping the current state is to identify all sources of waste in the system. Waste in this context can fall in the following categories (Hines & Rich, 1997; Tapping, et al., 2002):

- *Overproduction*, or producing more than is necessary to meet demand
- *Waiting*, when materials sit idle without any value being added
- *Transport*, time and resources wasted in moving materials or people
- *Inappropriate processing*, unnecessary or harmful to products or people
- *Unnecessary inventory*
- *Unnecessary motion*, movements that could be avoided
- *Defects* in finished goods or in-process materials

The first step in the research methodology was to select a product or major component. The value stream mapping literature suggests the selection of a single component to analyze the entire supply chain (Jones & Womack, 2002a). The assumption is that the "wastes" identified in the production of one component will be the same for all the other components. For product selection, the following criteria were suggested in order to maximize the generalization of the results to an industry market segment: (1) the product must be sold in a competitive market; (2) the product must be important for the operation of the buyer; (3) the purchase decision should involve several functions and levels of management; and (4) the product should be purchased by different type of business (Moriarty & Reibstein, 1986).

Ideally, a supply chain should have the following characteristics: everyone along the supply chain should be aware of the rate of customer consumption, little inventory of any kind, few transport links between processes, little information processing (pure signal and no noise), the shortest possible lead time, and changes for improvements should have minimum costs (Jones & Womack, 2002a). Some specific tools that can help to identify waste and formulate improvements are listed in Table 2-3.

Table 2-3. Value stream mapping tools

Tool	Description	Type of waste it helps to eliminate
Process activity mapping	A process is broken down into operations, inspections, transport. The goal is to identify non-value adding activity. A rearranged and improved process can then be proposed.	All types
Supply chain response matrix	Helps to portray time constraints in a process in two-dimensional graph. X-axis represents internal and external lead times, y-axis the average inventory in days. The supply chain response time is the sum of values on both axes.	Waiting, overproduction, inventory, motion
Production variety funnel	A portrayal tool to determine the levels of complexity along the supply chain activities in terms of number of inputs and outputs	Processing, inventory, waiting
Quality filter mapping	Helps to identify the type and where in the supply chain do defects occur. Processes are represented in the x-axis and a defect occurrence metric on the y-axis.	Defects, overproduction, processing
Demand amplification mapping	Derived from Forrester's industrial systems dynamics. This tool shows changes in demand in time and throughout the supply chain. Helps to reduce fluctuation.	Overproduction, waiting, inventory
Decision point analysis	A graphic technique that helps to show up to which point supply is driven by customer (pull) and from there by forecast (push)	Overproduction, waiting, inventory, processing

(Based on Hines & Rich, 1997; Wood, 2004)

Value stream mapping in research is mostly used to reduce inventories and streamline the flow of materials and information, thus reducing lead times. As mentioned previously, when lead times are reduced and the flow improved, quality is improved as a result. For example, principles of value stream mapping were used by researchers in UK's red meat industry to identify and improve the misalignments of activities and product attributes with consumers' needs (Zokaei & Simons, 2006). In the context of the proposed research, value stream mapping and its tools were used to portray flow of materials and information across the supply chain, and to identify and portray specific quality control activities in the supply chain.

2.3 Overview of System Dynamics

System dynamics is "*the application of feedback control systems principles and techniques to managerial, organizational, and socioeconomic problems. System dynamics seeks to integrate the several functional areas of an organization into a conceptual and meaningful whole, and to provide and organized and quantitative basis* *for designing more effective organization policy*" (Roberts, 1978). System dynamics takes into consideration not only the physical components of the organization, but also aspects like relationships and policies, and the links between the components are considered as critical as the design of the components (Wikner, Towill, & Naim, 1991). The central belief is that the response of the whole system is tightly linked to its structure. Organizational relationships in a system dynamics representation are of two types: *levels* (accumulation of resources) and *rates* (flows of efforts, information, or money). Level or rate variables can be tangible (materials) or intangible (information) (Roberts, 1978).

There is a significant amount of research on supply chain improvement using system dynamics, most of which focus on reducing lead times and inventory levels leaner supply chains (Forrester, 1961; Houlihan, 1985; Roberts, 1978; Towill, 1992; Wikner, et al., 1991). Wikner (1991) investigated five basic improvement strategies for supply chains using system dynamics, namely: (1) changing the decision rules, (2) reducing time delays, (3) removing distributors, (4) improving individual components design, and (5) integrating information flow. Combinations of two or more of these strategies are also possible.

A number of research efforts on system dynamics applied to the forest products exist (Buongiorno, 1996; Gunnarsson, Ronnqvist, & Lundgren, 2004; Jones, 2002). Buongiorno (1996) combined econometric and mathematical programming and system dynamics to analyze the U.S. forestry sector's policy and forecasting. Ina similar study, Jones et al. (2002) investigated the policy effectiveness to facilitate the sustainability of the forest products economy in the Northeastern United States. Table 2-4 shows some research applications of system dynamics to quality and quality improvement.

Table 2-4. Research applications of system dynamics on quality and quality improvement

Application	Reference
Simulating the behavior of quality costs in a manufacturing environment	(Burgess, 1996)
Simulating strategic policy-making process towards TQM implementation	(Khanna, Vrat, Shankar, & Sahay, 2004)
Quantifying the benefits from continuous quality improvement on market performance	(Visawan & Tannock, 2004)
Simulating of the effect on perceived quality of factors such as efforts for quality improvement, supply chain management, firm's reputation, warranty, and advertisement	(Wankhade & Dabade, 2006)
Design of effective performance measurement systems	(Akkermans & Oorschot, 2005)
Simulating the interaction between the factors of quality management on internal and external quality performance	(Mandal, Howell, & Sohal, 1998)
Exploring the interactions between operations, quality, and maintenance management	(Jambekar, 2000)
Investigating the influence that the decision-making structure in product development and quality improvement processes has on the supplier-manufacturer collaboration performance	(Kim & Oh, 2005)
Modeling quality issues in a manufacturing environment, to be used for policy evaluation and long term consequences on organization performance	(Mandal, Love, & Gunasekaran, 2002)

The steps for problem-solving in system dynamics are: (1) define the problem and goals, (2) describe the system, (3) develop a model of the system, (4) collect data needed for model operation, (5) model validation, and (6) test different policy changes and their effect on the proposed goals (Khanna, et al., 2004; Schlager, 1978). Three types of information are needed to construct a system dynamics model: the organizational structure of the supply chain, the delays in decisions and actions, and the policy on purchasing orders and inventories (Forrester, 1978).

Once the required information is collected, the system is represented in *causal loop diagrams*, where causal relationships (links) between variables are identified, as well as the direction of those relationships (positive or negative). A more formal representation with standardized symbols, known as *flow diagram*, is constructed in the following phase. Figure 2-3 shows Forrester's classic supply chain model (Forrester, 1961). The system representation phase is usually followed by manual or computer simulation, to better understand the relationships and flows and to test potential improvements to current policies.

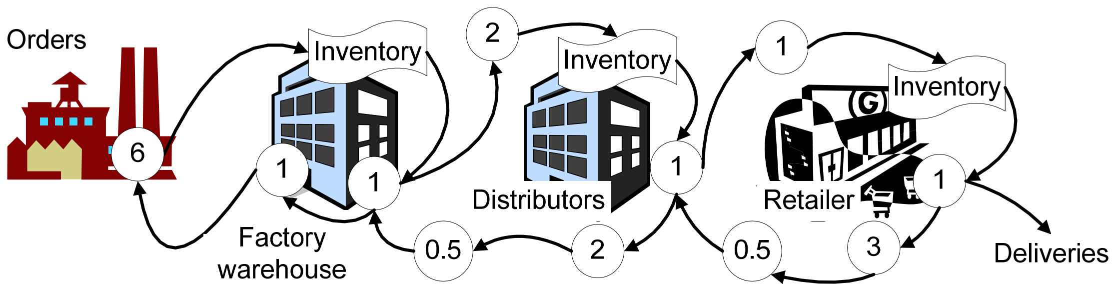


Figure 2-3. Classic supply chain model (numbers represent time delays)

In the context of the present research, system dynamics provides a useful tool to portray cause and affect relationships. Causal-loop diagrams are an excellent tool to visualize and understand the overall effect on quality performance of changes in manufacturing variables.

2.4 Data Collection and Analysis

Three main data collection techniques were used: interviews with key personnel, analysis of companies' documents, and plant visits. The interviews were carried out using both standardized and non-standardized questionnaires. Standardized interviews are considered appropriate for gathering quantitative and factual data, and non-standardized ones are better for qualitative and causal data (Healey & Rawlinson, 1994). The objective of the research implies gathering quantitative data like defect rates and production volumes; as well as qualitative data, like relationships between supply chain's entities. Specific data and the collection techniques used are listed in Table 2-5.

Table 2-5. Required information and data gathering techniques

Information	Data-gathering technique
Supply chain structure	Interview
Material and information flow	Interview, observation
Production volumes, products, raw materials, returns	Interview, observation, documents
Measurement and control of internal and external quality	Interview, observation, documents
Effects of changes in quality across the supply chain	Interview, observation, documents
Communication of quality requirements	Interview, documents
Communication of quality-related problems	Interview, documents
Supplier selection process	Interview, documents
Current quality improvement initiatives	Interview
Quality requirements development process	Interview
Relative importance of quality dimensions	Interview, questionnaire
Current quality performance of suppliers	Interview, documents

Numerical information (e.g., defect rate) was usually obtained in electronic spreadsheet format. Production and managerial documents were also collected during the visits. From August 2007 to January of 2009, visits and interviews were conducted to collect information about the structure of the supply chain, the flow of materials and information, and quality measurement practices. Table 2-6 shows date and location of interviews and visits.

Table 2-6. Interviews and communications log

Date	Location	Facility	Data collection method	Position/Function of interviewee
		-------- Supply chain structure, materials and information flow --------		
15-Aug-07	VA	Door plant	Personal interview	Continuous Improvement
24-Sep-07	VA	Door plant	Personal interview	Continuous Improvement
			Personal interview	Lumber Purchasing
			Personal interview	Material Manager
			Plant tour	
12-Nov-07	VA	Assembly plant	Personal interview and tour	Material Manager
			Personal interview	Traffic Manager
			Plant tour	Continuous Improvement
5-Dec-07	VA	Retailer	Personal interview	Office Manager
5-Dec-07	VA	Lumber supplier 1	Personal interview and tour	Sawmill Manager
9-Jan-08	VA	Door plant	Process observation	
15-Jan-08	VA	Door plant	E-maild questionnaire	Material Manager
11-Feb-08	VA	Door plant	E-maild questionnaire	Rough Mill Supervisor
		-------- Quality control, measurement, and performance --------		
24-Sep-07	VA	Door plant	Personal interview	Quality Control
10-Dec-07	VA	Door plant	E-maild questionnaire	Lumber Purchasing
9-Jan-08	VA	Door plant	Personal interview	Quality Assurance
25-Jan-08	VA	Assembly plant	Personal interview	Quality Assurance
14-Feb-08	VA	Assembly plant	E-maild questionnaire	Traffic Manager
19-Feb-08	PA	Lumber supplier 5	E-maild questionnaire	Lumber drying
26-Mar-08	NY	Lumber supplier 2	Personal interview	VP & Sawmill Manager
26-Mar-08	NY	Lumber supplier 3	Personal interview	Sawmill Manager
31-Mar-08	WV	Lumber supplier 4	Personal interview	Quality Control Manager
14-Apr-08	VA	Retailer	Personal interview	Project Coordinator
			E-maild questionnaire	Office Manager
20-May-08	NC	Service Center	Personal interview	Branch manager
30-May-08	VA	Door plant	Personal interview	Quality Assurance
5-Aug-08	VA	Door plant	Personal interview	Lumber Purchasing
12-Jan-09	VA	Door plant	Personal interview	Lumber Purchasing
			Personal interview	Quality Assurance
16-Jan-09	VA	Assemply plant	Phone interview	Continuous Improvement
20-Jan-09	NC	Service Center	Phone interview	Branch manager

In addition to these interviews and questionnaires, electronic mail and telephone calls were needed mostly for clarification and follow-up. Such communications are not listed in Table 2-6 but referenced in the text where relevant. In the next sections, the data analysis tools mostly used in this research are briefly explained, as well as the frameworks used for the data collection.

2.4.1 Supply Chain Framework

To describe the supply chain of interest, the conceptual framework provided by Lambert and Cooper (2000) was used. The framework entails understanding the supply chain's network structure, business processes, and level of integration. The *network structure* consists of (1) all members (primary or supporting) who are critical for the success of the supply chain; (2) the structural dimensions, which are defined by the number of tiers across the supply chain, the number of suppliers/buyers in each tier, and the position of the focal company; and (3) the process links between members. The *supply chain business processes* are: (1) customer relationship management, (2) customer service management, (3) demand management, (4) order fulfillment, (5) manufacturing flow management, (6) procurement, (7) product development and commercialization, and (8) returns. In this research, the aspects related to quality of some of these processes will be studied. As an example, for the procurement process, the role of quality considerations in the policies for supplier selection, development, and integration (Lo & Yeung, 2006) will be included in the analysis. Finally, the *level of integration* is determined by assessing to what degree supply chain management components are present. These management components can be classified in physical and technical management components (planning and control, work flow, organization, information flow, product flow); and managerial and behavioral management components (management methods, power and leadership, risk and reward, and culture).

2.4.2 Quality Framework

In order to analyze current quality measurement practices, the critical product and service quality dimensions have to be identified. This assessment was based on Garvin's eight product quality dimensions (Garvin, 1984b) and the service quality dimensions developed by Parasuraman et al. (1988). Specific items for these dimensions in the wood products industry were developed by several authors (Bush, et al., 1991; Forbes, et al., 1994; Hansen & Bush, 1996; Hansen & Bush, 1999; Hansen, et. al., 1996; Sinclair, et al., 1993), and along with input from faculty members, constituted the basic input for developing the data collection instruments for each link of the supply chain. Once the critical quality dimensions were established, the internal and external quality measurement practices and policies were examined, primarily by interviewing quality management personnel and by observation during plant visits.

2.4.3 Pareto Analysis and Histograms

Data on quality performance throughout the supply chain consisted chiefly of defect rate and defect relative frequency. The former gives a good measure of the overall performance of a process in terms of quality, and the latter can help explaining the origin of the quality issues. In analyzing defect occurrence it is important to know which are the most frequent since this leads to a better understanding of the process and helps identifying where improvement are most needed. A Pareto chart is a useful tool for this purpose, easy to construct and understand. A Pareto chart shows the frequency of a variable, in different categories or levels, arranged in order of descending frequency (Stevenson, 2000). The Pareto principle says that "...relatively few factors account for a disproportionally high share of the occurrences of an event..." (Stevenson, 2000); and is relevant in quality control, since typically relatively few issues account for most of defects occurring in a production or service process. Pareto charts are frequently used to help in deciding which improvement ideas to implement.

Histograms were used frequently during the data analysis to have a first view of the distribution of the data distribution. A histogram has the purpose of showing in a graphic fashion the distribution of a variable, by representing the frequency in the vertical axis and the response variable in the horizontal axis. The data is usually divided in same-sized bins or classes and then the number of data points that fall in each bin are counted and reflected on the height of each bar. A histogram helps to identify the center, spread, outliers, mode (or modes), and skewness of the data.

2.4.4 Kolmogorov-Smirnov Goodness of Fit Test

Part of the study involved the simulation of a response (e.g., defect occurrence). For such purpose, it is important to know if the response follows a specific probability distribution. The approach followed was to first construct a histogram, which is useful in narrowing down the potential distribution to a few candidates. Potential distributions can also be identified among those commonly found in practice; for example, time between successive failures can be approximated by a Weibull distribution, and exponential distribution is used to model random arrivals and breakdowns (Kelton, 2004).

Once a few distributions were selected, a goodness-of-fit test was used to decide which probability distribution best fitted the defect occurrence data at various points in the supply chain. One useful tool for this purpose is the Kolmogorov-Smirnov goodness-of-fit test. The advantage of this test is that it does not depend on the cumulative distribution being tested. The test is defined as follows (*NIST/SEMATECH*, 2006):

H0: The data follow a specified distribution

H1: The data do not follow the specified distribution

Test statistic:

$$D = \max_{1 \le i \le N} \left[F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right]$$

Where: i is the number of observation

Yi is the iid observation from the random sample

F is the theoretical cumulative distribution tested

N is the total number of data points

Acceptance criteria: H0 is rejected if D is greater than the critical value (from tables)

Several software products are available to run the K-S test. Specifically, SPPS® version 13.0, JMP7® version 7.0 (SAS Institute Inc.) and the Input Analyzer version 7.01(Rockwell Software) were used for this study.

2.4.5 Correlation and Regression Analysis

Correlation tells us the strength and sign of the linear relationship between two (or more) variables. One could be interested, for example, in knowing whether quality at a certain point in the supply chain (measured by defects per million) has a linear relationship with quality at a downstream process. Figure 2-4 shows different sets of data and their calculated correlation coefficient.

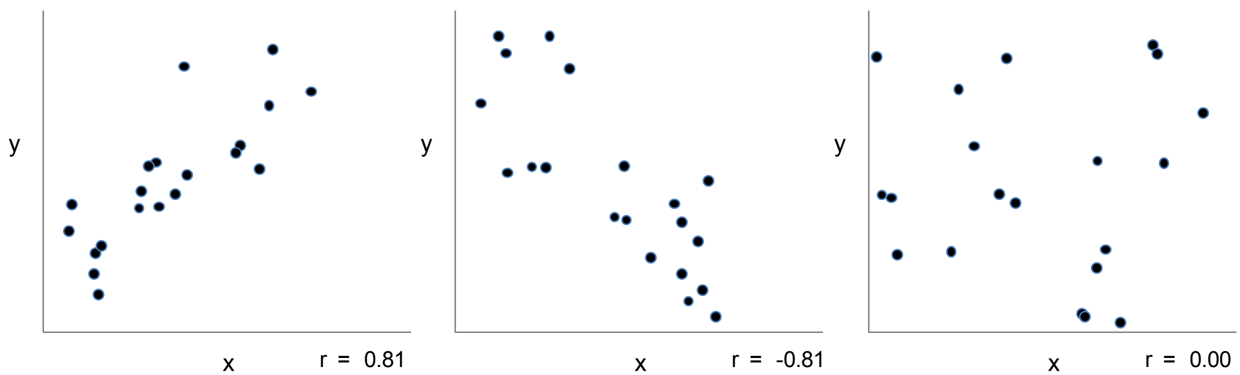


Figure 2-4. Interpretation of values of correlation coefficient

Regression analysis can help to elucidate how well changes in an independent variable can explain the behavior of a response variable. Regression models can be used for different purposes, namely: (1) description and explanation, (2) estimate parameters, (3) prediction, and (4) control (Montgomery, Peck, & Vining, 2001; Ott & Longnecker, 2001; pp. 11 and 531, respectively). Regression in the context of this study was utilized to describe how quality performance data changes with changes in some relevant variable, and also to try to explain such behavior.

Significance tests were also calculated to determine whether the linear regression equations were significant at $\alpha=0.05$ or, in other words, whether the slopes calculated were significantly different from zero. Figure 2-5 shows examples of two data sets, their scatter plots, and the linear regression equations.

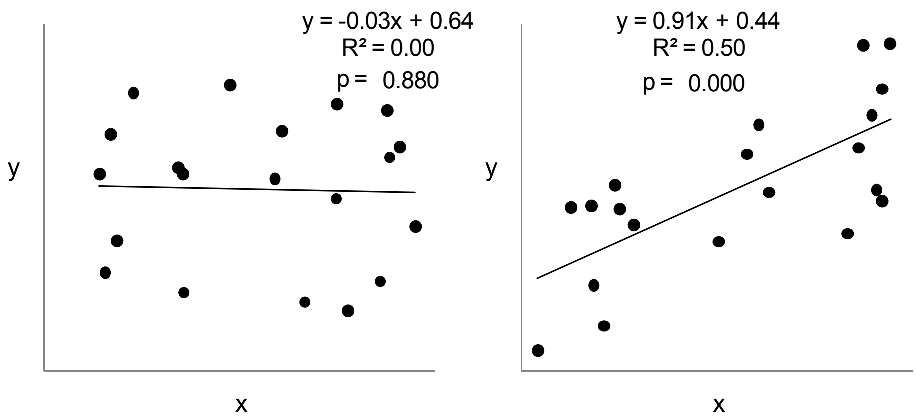


Figure 2-5. Examples of scatter plots and linear regression results

The p-value in Figure 2-5, indicates the probability of the relationship emerging randomly. A p-value of 0.05 means that there is a 95 percent chance that the relationship is real. The significance test is summarized as follows:

Based on a regression model $Yi = \beta0 + \beta1\ xi+$™i for i=1, 2,...,n

H0: $\beta1 = 0$ H1: $\beta1 \neq 0$

Test statistic:

$$f_0 = \frac{SSB}{SSW/(n-2)} = \frac{MSB}{MSW}$$

Where: SSB is the sum of squares between variables from ANOVA table
SSW is the sum of squares within variables from ANOVA table
MSB is the mean squares between variables from ANOVA table
MSW is the mean squares within variables from ANOVA table
N is the number of data points

Acceptance criteria: H0 is rejected if $f0 > F1,n\text{-}2,\alpha$

Software products are available to calculate correlation coefficient and conduct regression analysis. Specifically, SPPS® version 13.0, JMP7® version 7.0 (SAS Institute Inc.) and Microsoft Excel® were used for this study.

Chapter 3. Supply Chain Structure

3.1 Introduction

The company that was case-studied for this research is an integrated manufacturer of kitchen and bathroom cabinets with manufacturing facilities in several states. More than 5,000 employees work in several components and assembly plants. From this point on, the kitchen cabinet manufacturer will be referred simply as “the Company”.

In 1998, the Company started the implementation of Lean Manufacturing principles as part of its continuous improvement efforts. Lean Manufacturing (LM) is a production management philosophy based on the Toyota production system, which ultimate goal is the total elimination of “waste”. Waste in LM is understood as those processes that do not add value to the product from the customer’s point of view. Some results of this initiative cited by the Company are listed in Table 3-1. An award for operational excellence in the application of lean manufacturing principles was awarded to one of the company’s facilities located in 2003, as well as the ISO 14001.

Table 3-1. Results of Lean Manufacturing at the Company’s door plant (Company, 2007)

Species added	3
Lot size reduction (in pieces)	from 200 to 25
Number of SKUs	tripled
Increase in plant capacity with no capital	200%
Quality improvement (defect occurrence)	84%
In-process inventory reduction	80%
On-time shipments	99.7% of times
Equipment uptime	99%
Reduction in lead time	6 days to 13 hrs
Inventory turnover improvement*	18%
Cost improvement (as percentage of sales)*	10%

* Company-wide improvements

3.2 Value Creation Network

Based on initial interviews and secondary sources of information, the structure of the supply chain of interest can be represented in a value creation network diagram (Figure 3-1). As can be seen in Figure 3-1, a supply chain is rather a complex network of entities and relationships. For simplicity, some relationships and components are not shown, for example, logging and sawmill operations also sell wood fiber to manufacturers of packaging materials and pallet plants; and suppliers of materials and accessories, like sandpaper and hardware, do not supply only to the Company's facilities, but also to the service center and retailers.

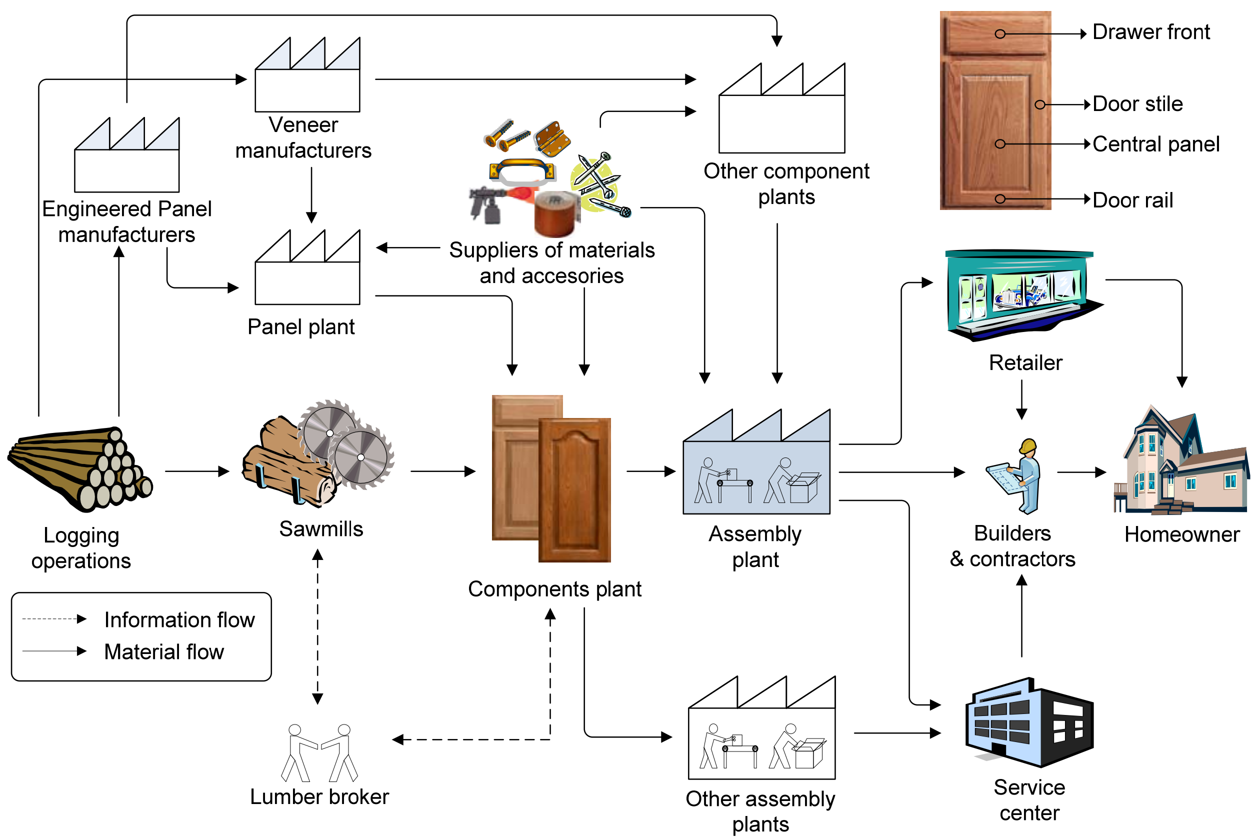


Figure 3-1. Kitchen cabinets value creation network

3.3 Final Customers

Although the Company does not sell directly to the final user of its products, it does invest in research about consumer behavior, which is important to design products that fit the needs and desires of different consumer segments, and also helps direct customers (i.e., dealers, distributors, and builders) to better tailor their product offerings to the final customer. Table 3-2 lists the four customer segments identified by a market research commissioned by the Company.

Table 3-2. Customers segments identified by the Company

Segment	Attributes
1	• High-income homeowners • Highly educated • Like trying latest products and fashions • Look for high-end feature in their kitchens
2	• Use the kitchen the most and for a variety of activities • Want a comfortable house, but not ostentatious • Like a traditional style and value reliable products that do not need much maintenance.
3	• Husband and wife work and have little free time • Spend a great deal of time in the kitchen • They value efficiency in any kitchen product or accessory, like organizational or storage solutions.
4	• The youngest of all segment customers, usually first-time home buyers • Location and price are the most valuable characteristics in a house • Kitchens are the least important for these homeowners • Use this space for working

The Company offers three product lines, each designed to accommodate each of the aforementioned segment's needs and tastes; not only in regards to price, but also functionality and potential uses of kitchen spaces (see more on this in the Product Lines section). The Company makes available to builders, contractors, and retailers (its direct customers) useful information about final consumer purchasing and living habits that can help them in their sales effort. A sample of this information is shown in Table 3-3.

Table 3-3. Sample of consumer research results carried out by the Company

Contents	Example of information contained in study
What people do in model homes? How much time do they spend? Major trends Reactions Emotional triggers Features of great interest	• 72% of home buyers shop in family • 36% shop because need a larger home • New home shopper is female (65%), married (87%), and college graduate (51%) • Spend 8:58 minutes spent in the home, and 1:23 in the kitchen • New home shoppers favor the bedroom (78%) and the kitchen (64%) • Cabinetry is the most examined part of the kitchen

Source: Company's webpage (2008)

The information about kitchen design and cabinet styles posted on the Company's website helps in creating awareness in the final customer. It also facilitates sales and final customer education on the Company's products.

3.4 Product Lines

The Company has three basic cabinet lines aimed at different customer segments identified in the market research. The number of options for species, finishing, glazing and paint finish are listed in Table 3-4. Two or three new products are launched every year.

Table 3-4. Product lines and options available

Product Line	Options				
	Door styles	Species / material	Finish options	Glazing*	Paint
Line 1	6	Maple, oak, and laminate	8	-	-
Line 2	20	Cherry, hickory, maple, oak, and laminate	13	7	-
Line 3	27	Birch, cherry, hickory, maple, oak, and laminate	44	51	3

*Glazing is a finishing technique where a semi-transparent glaze is applied to a door with base color and sealer, followed by a hand-wiping for an aged appearance

Combining door styles and finishes there are 1,762 possible options. This wide range of styles and finishing options, combined with options for glass, hardware, and accessories, results in more than 500,000 stock-keeping units (SKUs). Adding to the complexity, 88 percent of inventory items are made up of 20 parts or more.

Regarding species, the assembly plant handles maple, oak, cherry, and melamine lines. According to personnel interviewed for the study, maple products have experienced the largest growth and right now it constitutes the strongest market. Demand for oak products has stalled and is strong only in the eastern United States (Material Manager, personal interview, November 12, 2007).

The web page of the Company provides a considerable amount of information about product styles and finishes, as well as specifications and detailed installation instructions for its products. Users can save their preferences of door styles, and even rate models that they like.

3.5 Species

The focal facility processes four species: red oak, cherry, soft maple, and hard maple. Only hard maple is purchased kiln-dried. Figure 3-2 shows the percentage of each species processed at the door plant during the year of analysis.

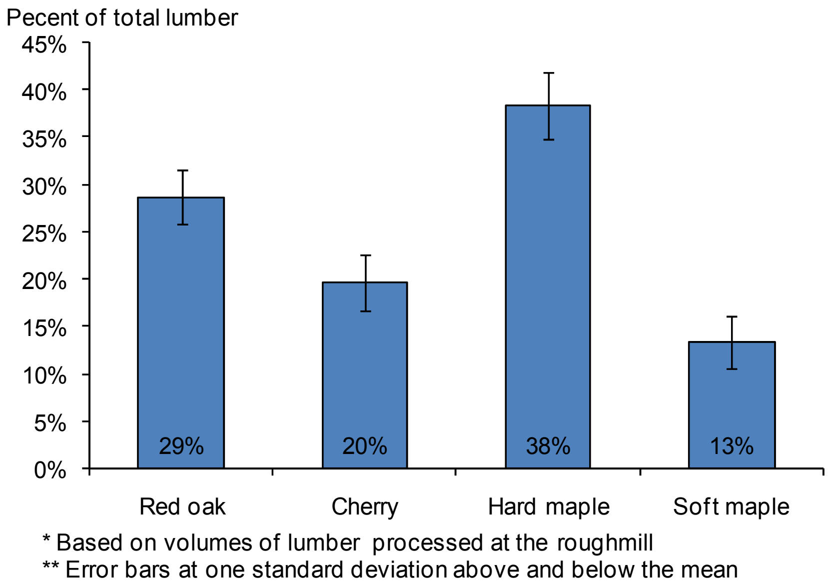


Figure 3-2. Species mix of lumber used by the components plant during year of analysis

Figure 3-3 shows the share of each species on the product mix throughout the supply chain of the study. The remaining four percent at the service center level consists of vinyl-based cabinets. As can be observed in Figure 3-3, the service center sells a disproportionally low percentage of red oak products, which suggests that the region served by this entity is not a strong market for red oak products or that red oak products might be overrepresented in the inventory at the assembly plant. The later assertion has support from the fact that at the time of the study there were 60 percent more days-worth of inventory for red oak than for maple or cherry. The opposite is true for cherry, with a higher percentage of cherry products sold at the service center than produced at previous stages in the supply chain. The species distribution departed significantly from what was reported by Olah, et. al in 2003 (Olah, Smith, & Hansen, 2003) as the industry average: 44 percent red oak, 29 percent maple, and 10 percent cherry.

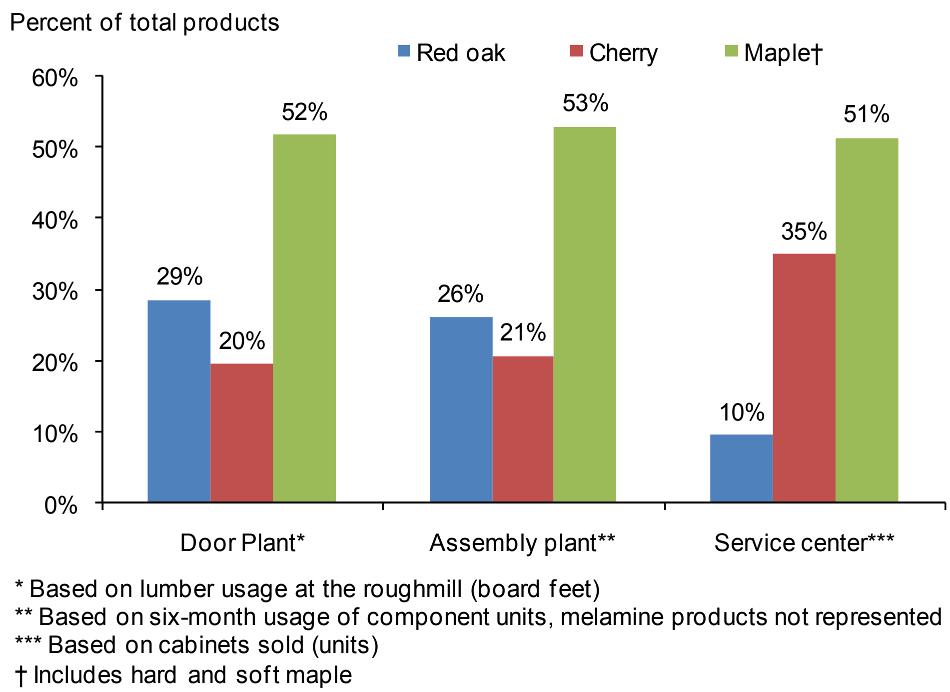


Figure 3-3. Share of species throughout the supply chain of study

3.6 Distribution Channel

The cabinet company sells to builders/contractors, retailers, and service centers. Retailers usually carry more than one brand and sell in turn to builders/contractors and a small percentage to final consumers. Service centers sell only the Company's products to construction companies and are also in charge of the installation. There is a considerable amount of information available to final consumers through the Company's website about styles, finishes, design solutions, accessories, and contact information for builders that use the Company's products. This combination of reaching not only immediate customers but also to final users creates a "pull" effect, potentially increasing the demand for the Company's products. A certification program for showrooms awards a distinction to customers who demonstrate creative design of cabinetry in their showrooms. Regarding sales operations, new sales and customer care is carried out through a number of Field Service Representatives, who visit potential and existing buyers.

In addition to selling to retailers and builders, the Company also operates “service centers”, which serve construction companies in specific regions. These centers bid for contracts with construction companies, order directly to the assembly plants and also install the cabinets. One service center was included in the study.

3.7 Scope of the Study

There can be as many value streams as different items in one company’s product mix. Therefore, a value stream map is better approached when a specific component is followed through the transformation process (Jones & Womack, 2002b; Tapping, et al., 2002). This is based on the assumption that wastes that occur in the manufacturing of a part or component are most likely replicated in the manufacturing of all other components. This research followed such approach in order to have a manageable unit of study, and given the time limitations of the study. The criteria used for selecting the value stream to be case-studied are listed below, and the supply chain path selected for the study is illustrated in Figure 3-4.

- The *component* selected should reflect the conversion process and the final product. In the case of kitchen cabinets, the door is probably the most complex component and the most representative of the final product, since the door style is the first decision a customer makes when purchasing a kitchen cabinet. Thus, the value stream for the door was selected for this study.
- Companies within a supply chain view the value creation network differently depending on their position in the system (Lambert, 2006); thus, a *focal facility* or *company* needs also to be selected as the starting point for the study. Since cabinet doors were selected as the component which transformation process was followed through the supply chain, this also determined the focal facility, which in this case is the components plant that makes the doors and drawer fronts.
- A cabinet door is typically made of a solid-wood frame and a central panel of engineered wood (see Figure 3-1). The latter is not manufactured at the focal facility, but at another components plant; therefore it was decided to focus only on the *solid-wood parts* (stiles and rails) of the door for the study.

- On the *customer's* side, the door facility's largest customer is an assembly plant located at a 250-mile distance, which receives about a third of the door plant's production. The assembly plant in turn sells to retailers and service centers. Lastly, retailers and service centers sell chiefly to construction companies, who are the last link before the final user of the product: the homeowner.

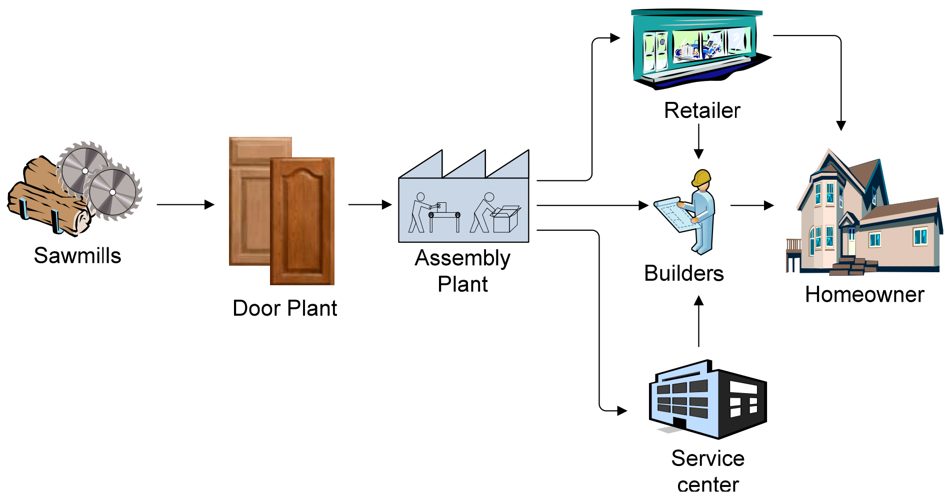


Figure 3-4. Supply chain path selected for the study

This study included a lumber supplier, the door plant, the assembly plant, the service center and one retailer. The service center and retailer in most cases install the product at the residence in construction, and receives direct feedback from the builder and from the final user. In this sense the service center and retailer can be considered as final links before the customer of the supply chain.

3.8 Supply Chain Entities

3.8.1 Lumber Suppliers to the Door Plant

The cabinet Company is part of one of the world's largest manufacturers of products for home improvement and new construction, with six cabinet-related companies. This gives the Company significant leverage when negotiating favorable terms for lumber purchases, due to the scale of its lumber needs. According to the person in charge of lumber purchasing at the door plant, transactions with lumber suppliers are based on long-term relationships (personal interview, September 24, 2007).. All lumber purchases are based on the National Hardwood Lumber Association grading rules, with additional requirements for lengths and species-specific features.

The door plant's lumber supplier base consists of 35 to 40 companies, and has not changed significantly for the last decade. An undisclosed number of suppliers provide lumber under contracts. Eighty percent of the lumber is bought directly from sawmills, and the rest from lumber brokers. The geographic location of suppliers influence sourcing decisions: most of the red oak is purchased from sawmills located up to 200 miles from the plant, hard maple and cherry from suppliers in Pennsylvania and New York; and soft maple from Ohio. Contact information for 5 suppliers was provided, which were asked for their participation; 4 accepted to be interviewed for the study. Table 3-5 summarizes the suppliers' characteristics.

Table 3-5. Main characteristics of lumber suppliers contacted for the study

Supplier	Type of facility and drying capacity (MMBF)					Annual lumber output (MMBF)	Number of employees
	Concentration yard	Sawmill	Air-drying yard	Pre-dryers	Kiln-dryers		
Supplier 1	-	x	-	-	-	15	ND
Supplier 2	-	x	x (0.50)	-	x (0.22)	18	75
Supplier 3	x	x	x (0.20)	1.00	x (1.50)	40	110
Supplier 4	x	-	-	-	x (1.00)	18	70
Supplier 5	x	-	x	x (ND)	x (ND)	ND	ND

ND: No data available

3.8.2 Door Plant

A simplified view of the production process at the door plant is shown in Figure 3-5. A brief explanation of the production process follows.

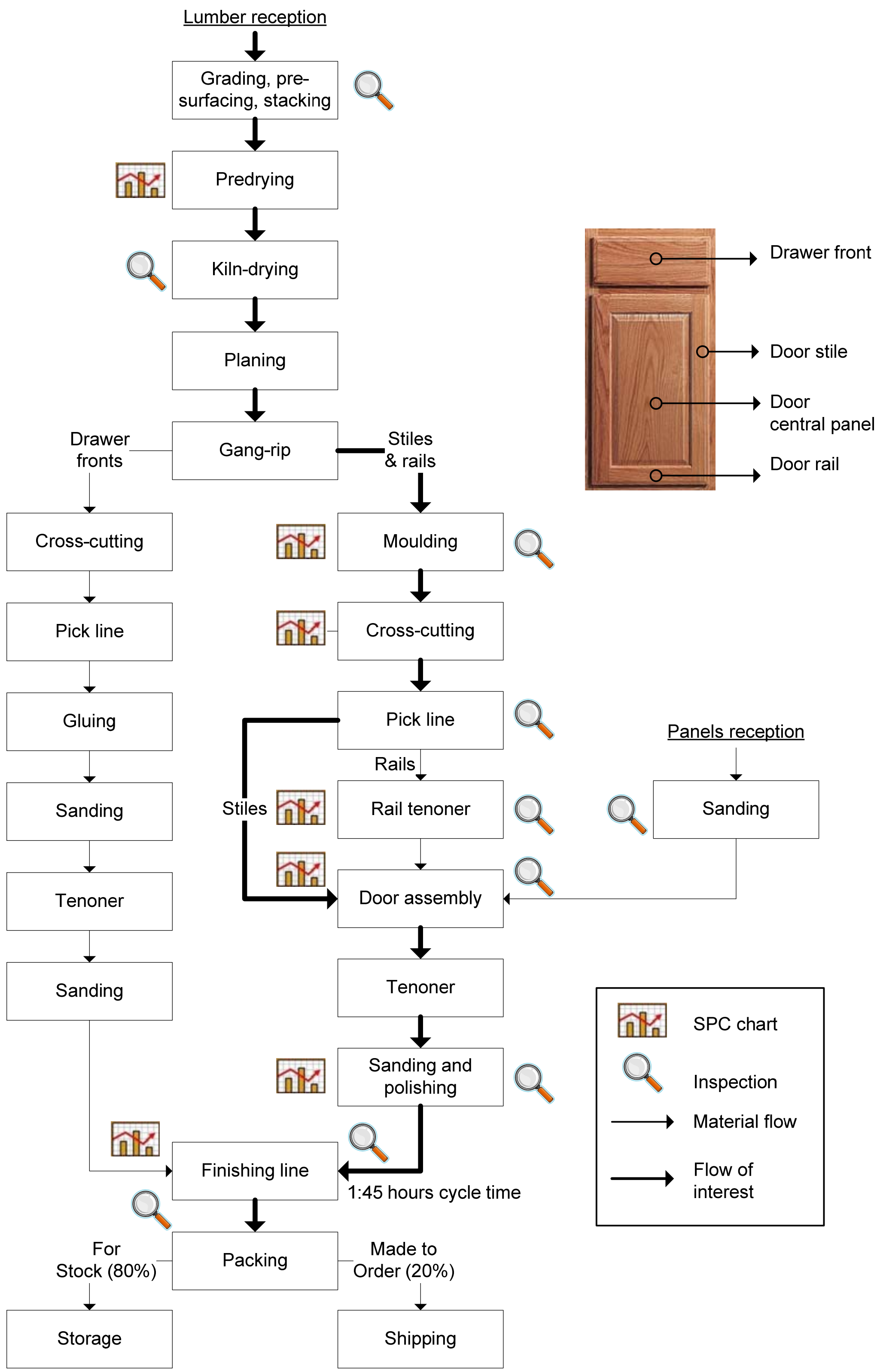


Figure 3-5. Production process at the door plant

The door plant produces sixteen styles from two of the three product lines offered by the Company, and works with four species: oak, hard and soft maple, and cherry. The central panels for the cabinet doors are not manufactured at the door plant; and come from another facility. Lumber for the door plant is purchased air-dried or green, with the exception of hard maple, which is bought kiln-dried, due to stain and color consistency issues. When lumber is received, it is graded, pre-surfaced and stacked. Payments to lumber suppliers are based on grade and tally as determined at the door plant. The material is then moved to two pre-dryers, which do not normally operate at full capacity. The target pre-drying times are 60 days for red oak, 25 days for cherry, and 20 days for soft maple. The target moisture content (MC) at the end of the pre-drying process is 20 percent or lower. After this, lumber is moved to five steam-heated kilns. Kiln-drying time depends on species and the initial MC; for oak at 20 percent MC, it takes approximately six days. A green lumber inventory equivalent to approximately two days-worth of production is kept at the lumber yard.

After drying, lumber is moved to a storage area with about half a million board feet of material. When hard maple is purchased, it is moved directly to the start of the roughmill process, where it is unstacked, surfaced, and cut into strips in a gang-rip saw. These strips are then manually selected and directed either to the production line for drawer fronts or for stiles and rails. Strips to be used for stiles and rails go through one of two moulders, where the appropriate profile is cut. Defects coming out from the moulders are marked and moved to a crosscut optimization saw. There are also two sets of manual chop-saws in this area, used for specialty orders or normal production, depending on the production schedule. From the crosscut saws, blanks (parts cut to standard dimensions and ready for further processing) are moved to a pick line with several bins, where operators inspect and classify each piece.

After the stiles and rails are classified at the pick line, door rails go to a tenoner, and the stiles are transported directly to the door assembly area. At this point the central panels coming from other plants join the production process. These panels are received, sanded and subject to inspection before entering the assembly area. There are five assembly booths, where doors are put together and pressed in tandem clamps. It takes two days from the start of the rough mill to the end of the finishing line, although processing time at the door plant is only 16 hours.

Once doors are assembled, they go into two consecutive double-end tenoners, where profiles are cut at their four sides, two at a time. Two belt sanders, and orbital sander and a brush sanding machine follow, with inspection and repair stations in between sanding operations. At the end of the sanding and polishing operations, operators pick up doors and inspect them. Doors are then moved to the finishing line, where they are hung to an overhead conveyor, using two perforations made previously in the back side of the door. The finish line conveyor is approximately one-mile long and the finishing process takes one hour and forty five minutes.

At the end of the finish line, doors and drawer fronts are inspected, wrapped, and placed on pallets. The majority of doors and fronts are made for stock, but a small percentage is directly loaded onto a truck. Doors for stock are placed on racks, identified by bar coding. The finish storage area maintains not only items made at the facility, but also doors and drawers fronts from other component plants, as well as accessories from external suppliers. This is part of the company's inventory strategy to improve responsiveness. About twelve days-worth of doors and drawer fronts are kept at the storage area, as well as quantities of cabinet frames (made at other plants) and cabinet accessories. Doors are shipped to the assembly plant using the Company's own trucks.

3.8.3 Assembly Plant

The assembly plant visited for this research puts together cabinets with components sent from the component plants and ships them to the customers. A significant part of the assembly plant area is dedicated to the storage of cabinet components and accessories, which arrive from other plants and external suppliers. Figure 3-6 shows a very simplified view of the production process at the assembly plant.

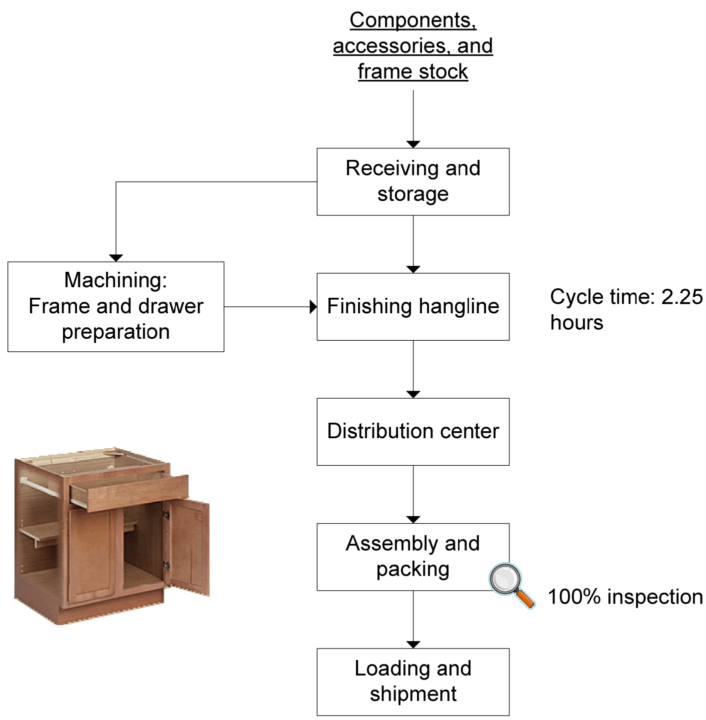


Figure 3-6. Simplified view of the production process at the assembly plant

In the receiving area, about eight trailers are unloaded daily. Items are scanned and placed in storage locations according to their priority. Low priority items are put in "random" locations, usually at higher levels in the storage racks. High priority items are placed at "pick-up" locations, at lower levels. Lot sizes and minimum order quantities are relatively small. Table 3-6 shows the average and standard deviation of inventory data for the assembly plant. Notice the large variability, reflected by the high standard deviation values.

Table 3-6. Inventory quantities at the assembly plant

Inventory parameter	Average*	Standard deviation
Average daily usage	4.49	10.11
On hand quantity	39.41	68.92
Lot size	51.78	60.35

Note: only non-zero quantities were included in the calculations
* Data changed to protect confidentiality

Each component that enters the finishing process is hung on an overhead conveyor with a tag showing its finish color and type. The cycle time in the finishing area is two hours and fifteen minutes. After the final coating dries, items are placed in individual slots at a distribution center location. A routing sheet allows picking up the correct items from the distribution center, and their later transfer to the assembly cells. The assembly plant is currently increasing the amount of finishing work currently carried out by the component plants, moving the final transformation step of the components closer to the customer. This practice is known as postponement, and consists in moving some operations or processes to a later point in the supply chain, thus increasing flexibility in responding to changes in demand and potentially achieving savings in inventory management (Li, et al., 2005). Postponing the finishing will also allow the plant to reduce inventory, especially of doors and fronts; simplify materials management (reducing SKUs handled); save costs on packaging, handling, and transportation; and maybe most importantly, shorten lead times.

The last processes before shipment are the assembly and packing of cabinets. There are nine assembly cells, where components are prepared, put together, inspected, put into boxes, and loaded into trucks. Each assembly cell is capable of processing one cabinet every fifty three seconds. There are no buffers between the intermediate steps in the assembly line, and components are picked up by “pullers” thirty minutes ahead to the start of the assembly. The pulling process takes about fifteen minutes to fill each cart. These very short time allowances make synchronization the most important feature of the assembly lines. The correct component must arrive at the correct time for its assembly into a cabinet without the need of buffers. Routing sheets and an in-house developed system of color-coded balls helps to determine which components are needed at the start of the assembly cell so the pace is not interrupted. There are several transparent pipes, each one representing a type of component (frame, side, door, drawers), and the colored balls are placed inside in the same sequence in which the components are needed. This system facilitates a smooth production flow in the assembly lines. There is a one-hundred percent inspection at the end of the cell, just before products are placed into their boxes and loaded into a truck. The assembly plant changes its production output by shutting off cells or by decreasing the number of personnel in each cell.

Each assembly cell produces about four hundred cabinets in an eight-hour shift. A cabinet is loaded on the truck five minutes after hinges are installed, and a regular truckload is filled in 3.5 to 4 hours. Several trucks are shipped every day, containing in average 10 kitchens (or 160 cabinets). Typically, a door that is picked up close to midnight from the door plant arrives to the assembly plant early morning the next day; at its arrival, doors and drawer fronts are placed in a mix-load or random location according to their priority. Some high-priority orders are placed under the “pick-and-pack” program, and can be shipped on the next day from the moment the order was placed. A cabinet is shipped typically on the fourth day after the order is received at the assembly plant. This speed makes inbound and outbound logistics critical in fulfilling customers’ orders

One rough measure of logistics efficiency is the proportion of less-than-truckload (LTL) shipments as compared with full truck loads (FTL). Not surprisingly, shipping partially-loaded trucks is much more costly than full truckloads, but it is sometimes necessary when there are urgent requests by the customer (a premium is charged), or when a certain item had to be reordered due to quality problems (cost incurred by the Company). At the assembly plant LTL shipments occur only three percent of the time, but represent up to six percent of the cost. The assembly plant’s largest customer, a kitchen and bath products retailer, receives eight to ten truckloads of cabinets per day at its various locations, one of which was visited for this study. Shipments to the service center, owned by the company, are made using a common carrier.

3.8.4 Retailer

A major customer of the assembly plant was interviewed for this study. This customer is a kitchen and bath products retailer, with warehouses and stores in four states of the Mid-Atlantic region. About four fifths of sales at this retailer go to builders and contractors, and the rest to walk-ins or retail sales. Although this customer carries other brands of kitchen cabinets, it supplies all its construction accounts with cabinets made by the Company. The particular store visited for this study serves fifteen building companies in its area. About one-half of the retailer’s sales include installation services.

3.8.5 Service Center and Construction Company

The Company owns fourteen service centers throughout the country. Each serves a region and sells to construction companies. Service centers are in charge of sales, installation, and customer service for their region; and sell only products made by the Company. The service center visited for this study serves approximately twenty construction companies in its area, and consists of a warehouse and office space. The staff of the service center is 43-strong and includes administrative personnel, supervisors, installers, warehouse personnel, and customer service associates. The warehouse has dedicated areas for cabinets, countertops and accessories.

3.8.6 Construction Company

A typical construction company's organizational structure includes (1) a purchasing manager that makes the decision of what cabinet company is going to supply its homes; (2) a construction manager that supervises building operations in a city or region; and (3) a construction superintendent that directly supervises the construction, service and warranty of individual homes in a community. All of them deal with both quality control and measurement practices before the product is turned over to the homeowner.

Although the service center only has contractual obligation with the construction company, it receives direct feedback from the homeowners, since they conduct the final inspection of the Company’s installed products. In this sense, the service center can be considered the last link of the supply chain before the final customer and no construction company was interviewed directly for this research.

3.9 The Ordering Process

The ordering process is explained in this section in the direction in which orders are usually made, this is from the customer (builder) to the lumber supplier. A timeframe for the ordering process in each link is also provided.

3.9.1 Orders from the Builder to the Service Center

The ordering process starts when the Purchasing Manager at the construction company decides on buying the Company's products. This is done through a bidding process. The builder purchasing agent at a national level provides local divisions the names of two potential vendors for the cabinets. A vendor is selected based mainly on price, since quality of construction and design was already considered when pre-selecting vendors. When the sales department at the construction company closes a house sale, the homeowner decides between different cabinet design options available. Once framing and rough mechanics are completed at the construction site, the construction superintendent releases an order for the cabinets to the service center. The ordering process from this point is illustrated in Figure 3-7.

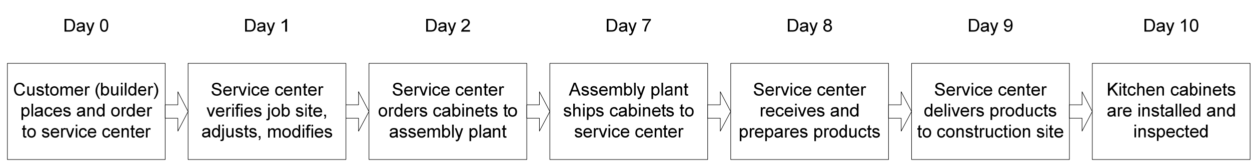


Figure 3-7. Order process from builder to service center

After an order is placed by the builder, a Field Service Representative from the service center goes to the construction site to take measurements and make sure the order is accurate or needs modification. After the order is verified or adjusted, the service center sends an order to the assembly plant for its construction. The assembly plant takes five days to deliver the product to the service center. Cabinet boxes are placed in trucks in the same order in which they will be needed, and personnel at the service center then unloads the truck and plastic-wrap whole kitchens ready for its delivery. The next day kitchens are delivered with all their accessories to the construction site and it takes another day complete the installation of the kitchen and bath cabinets. In average, from the moment an order is placed by the builder, it takes about ten days to complete the order, with installation included. If an item has to be reordered for any reason, the Company has an expediting program to rush orders through and it may take as little as two days for delivery.

3.9.2 Orders from the Retailer to the Assembly Plant

About eighty percent of purchase orders come from builders or contractors, and one-half of these orders include installation service. Figure 3-8 depicts the ordering process when the installation is not included.

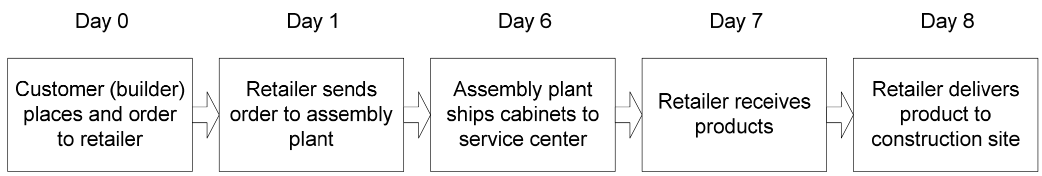


Figure 3-8. Order process from builder to retailer

Once a builder orders a cabinet to the retailer, a project coordinator is assigned to the purchase order. This person makes sure the order is correct and makes the necessary changes or adjustments. The order is then sent to the assembly plant by electronic data interchange (EDI), exactly seven days ahead of the day when it is estimated that the customer needs the product. Inventory is kept to a minimum and the store incurs a daily charge for items that spend more than ten days at the retailer's storage area. According to the office manager, the Company is its most up-to-date supplier regarding information technology (personal interview, December 5, 2007).

Products from the assembly plant arrive to the store typically seven days after placing an order for a standard finish (the assembly ships at the fifth day from receiving the order and the transit time is two days); some glazing options can take up to ten days, and hickory or laminate products take as long as sixteen days. It takes five to six weeks for an item from the customizable line of the Company (see Table 3-4). Depending on the day of the week, orders can be shipped the next day. When the store is in charge of installation, this work takes one or two days for a standard order, more for larger jobs. According to the office manager, the lead time from the assembly plant is very consistent and reliable. Table 3-7 summarizes the lead time information. The total lead time for a typical order with installation included, is approximately nine to fifteen days.

Table 3-7. Lead times for orders from the retailer

Type of finish	Typical lead time from the assembly plant to retailer	Delivery time from retailer to job site	Installation time
Standard finish	7 days	Depending on location, 1 or 2 days. Some locations only on certain days of the week	Typically 1-2 days Large jobs 3-4 days
Glazing option*	10 days		
Hickory	16 days		
Bisque (laminate)	16 days		

Source: electronic mail communication with office manager, June 2008
*Glazing is a finishing technique where a semi-transparent glaze is applied to a door with base color and sealer, followed by a hand-wiping for an aged appearance (Company's web page)

3.9.3 Orders from the Assembly Plant to the Door Plant

According to the materials manager at the assembly plant, most orders to the door plant are made based on a MIN-MAX system (Figure 3-10), and aimed at replenishing stock. Orders are sent to the door plant at six p.m. every day, and the lead time from the door plant is approximately six days, much shorter for orders under an expediting program. About half of the total inventory by value is consists of cabinet doors. The orders are sent through the corporate scheduling system. The door plant monitors its on-time delivery to the assembly plants very closely.

Two special programs for expediting orders exist: under the first program, small inventories of slow-moving items are replenished (a safety stock of 2 units of these items is kept at the assembly plants). The second program allows ordering an item at 10 A.M. and shipping it in the afternoon. Parts slips for these programs are printed in a characteristic color.

3.9.4 Orders from the Door Plant to Lumber Suppliers

All lumber purchase orders terms are based on NHLA grading rules and additional specifications stated by the Company. For planning purposes, a lead time of thirty days is considered when buying green lumber. Hard maple is purchased kiln-dried, and a much smaller lead time of one or two days is considered when planning purchases for this species. Due to its short lead time, hard maple is more conducive for just-in-time deliveries, and greatly reduces the on-hand inventory levels necessary to sustain production, since close to two-fifths of the lumber needs at the door plant are hard maple. For the same reason, planning of hard maple purchases is made more carefully than for other species, since a late delivery by a supplier (or suppliers) can lead to disruptions in the door plant's production schedules, a very costly proposition in a lean manufacturing environment. A three-day inventory of hard maple lumber is usually kept at the door plant to buffer against disruptions. With respect to red oak, cherry, and soft maple, there is usually enough lumber in the pipeline (pre-drying, kilns, and dry lumber inventory) to prevent shortages caused by late deliveries.

Purchasing needs are reviewed once a month and are determined considering inventory on hand, outstanding orders, and current demand information. Incoming lumber is re-graded, tallied, and pre-surfaced at the door plant. Payments to lumber suppliers are made based on grade and tally as determined at the plant.

3.10 Production Planning and Scheduling

Figure 3-9 shows a simplified view of the inventory management system. As the figure shows, customer orders drive operations up to the assembly plant, since cabinet assembly is started only against firm customer orders. However, the Company does not operate under a pure "pull" system, since internal production orders to the component plants are executed under a combination of forecast and demand-driven system. Lumber purchases by the door plant are determined using past usage values and expected sales. Sawmills (lumber suppliers) execute production orders for green lumber typically against firm customer orders and against forecasted demand for kiln-dry lumber.

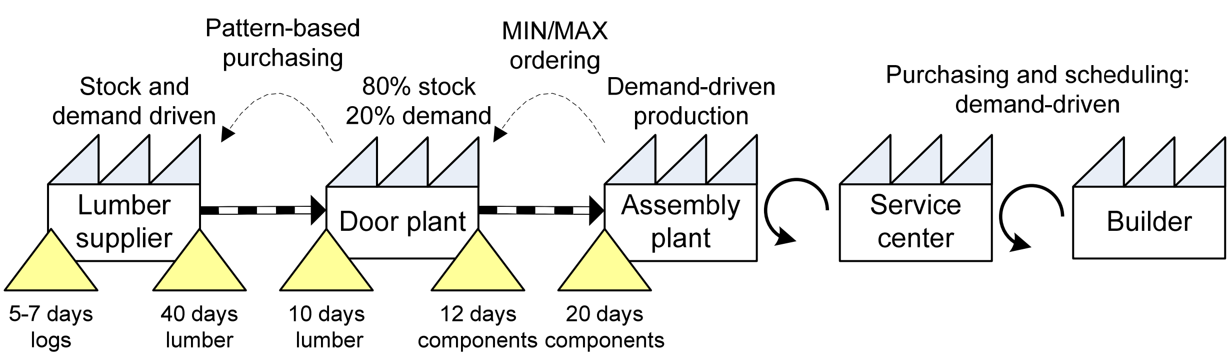


Figure 3-9. Inventory management and scheduling in the cabinets supply chain

3.10.1.1 Decoupling Point

An important characteristic of a supply chain is its “decoupling point”; this is the physical point that separates the investment from the realization stages (Dong, 2001). During the investment stage, production is executed according to forecasted demand and firm orders; and, since forecasts always have a degree of uncertainty, there is usually accumulation of inventories during the investment stage. In the realization stage, production or operations are carried out based on firm customer orders, and inventory levels are usually small or inexistent. In other words, the decoupling point defines the reach of the final customer order into the supply chain (Van-Donk, 2001).

In the supply chain of study, the decoupling point is located at the assembly plant. From lumber suppliers to this point, production occurs both in response to firm orders (made-to-order) and to anticipated demand (made-to-stock), and from the assembly plant operations are executed against firm customer orders.

3.10.1.2 MIN-MAX Inventory Control System

Inventory control at the door and assembly plants is based on a MIN-MAX system. A MIN-MAX inventory system is relatively simple concept: minimum and maximum quantities are set for a specific item; if the quantity on hand drops below the minimum level and order is placed so the quantity reaches the maximum level (see Figure 3-10). The major difference between MIN-MAX models is the point at which orders are placed. There are many algorithms to calculate reorder point, reorder quantity, and to determine which items to order. Major inputs to these models are usually average daily usage, desired service level, buffer size (quantity on-hand plus on production), lead time probability distribution, and an inventory cost model (costs of backordering, holding costs, warehouse costs, ordering costs) (Wang, Chen, & Feng, Agin, 1966; 2005).

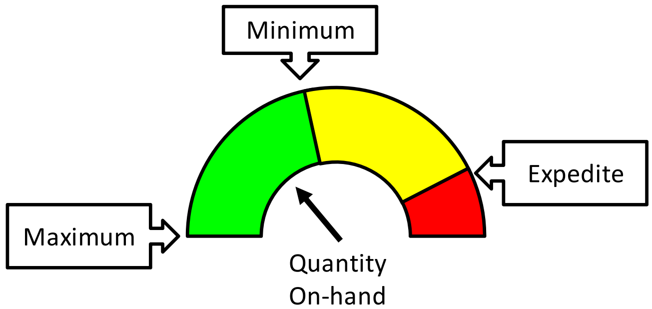


Figure 3-10. Illustration of a MAX-MIN inventory control system

MIN-MAX inventory control systems are a combination of “push” and “pull” models. Traditional “push” models base long- and medium-term production planning on forecasts, as well as scheduling daily operations. Pure “pull” models produce to demand without any buffers, therefore making them vulnerable to changes in demand or lead time. A MIN-MAX system receives replenishment signals from the demand (pull), and calculates inventory and buffers based on forecasts (push) (Pitcher, 2006).

3.11 Value Stream Map

Data about lead time and inventory levels described in this chapter is summarized in Table 3-8. Based on this and other information, a value stream map was drawn for the Company’s supply chain, and it is shown in Figure 3-11.

Table 3-8. Lead time and inventory levels throughout the supply chain

Supply Chain Entity	Lead time (days)		Inventory (days-worth of material)
	Hard maple	Cherry, soft maple, and red oak	
Lumber supplier	12[1]	30	83
Door plant	2	30 (cherry, soft maple) -65 (red.oak)[2]	42[3]
Assembly plant	5	5	20
Service center	5	5	5
Total	24	70-105	150

[1] Assuming 10 days of kiln-drying from green condition and one day of delivery to the door plant
[2] Considers a pre-drying time of 25 days for cherry and soft maple, 60 days for red oak; and 5 days of kiln-drying
[3] 31 days-worth of lumber and in-process wood, and 11 days-worth of finished doors

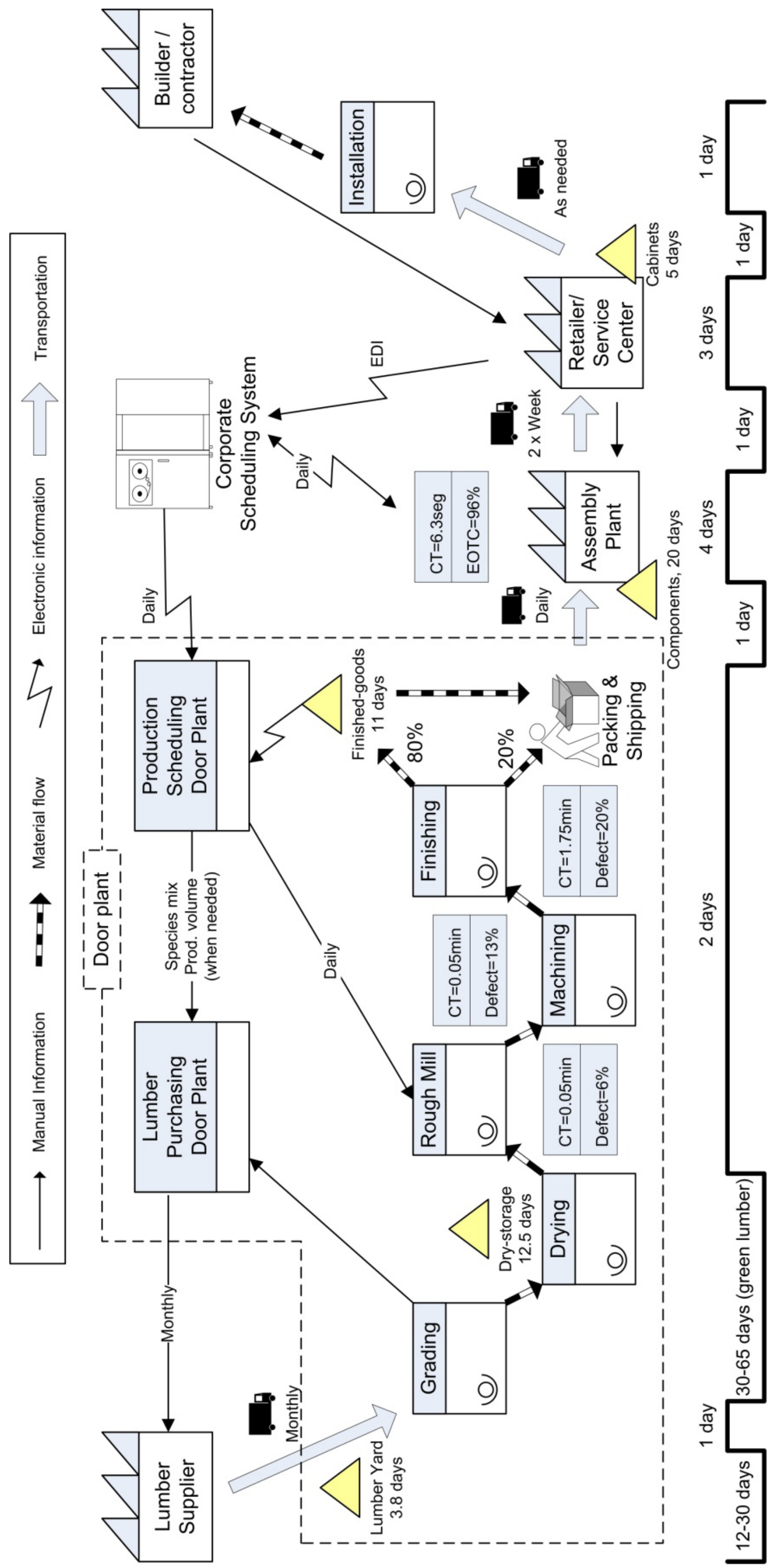


Figure 3-11. Value stream map for the kitchen cabinets company

The total lead time changes greatly when the time for lumber drying is considered. For cherry, red oak, and soft maple (all of them purchased green) the total lead time is between 70 for soft maple and 105 for red oak; and 24 days for hard maple. These calculations assume receiving lumber green (with the exception of hard maple), thus no air-drying time is considered at the lumber supplier facilities, which can take 40 to 100 days, depending on several factors (Denig, Wengert, & Simpson, 2000, p. 41). Not included in the lead time calculations are the approximately 30 days from the time the service center completes the installation to the time the keys are handed over to the homeowner.

The inventory calculation at the door plant includes material in-process, and almost half of it corresponds to lumber in the pre-dryers. The inventory at the assembly plant was calculated considering only doors and drawer fronts. The data in Table 3-8 can also be represented in a Supply Chain Response Matrix (Figure 3-12). The purpose of this tool is to portray "the critical lead time constraints of a supply chain" (Hines & Rich, 1997). In this diagram, the time in each supply chain stage is shown in the horizontal axis and the vertical axis shows the standing inventory at each point (New, 1993).

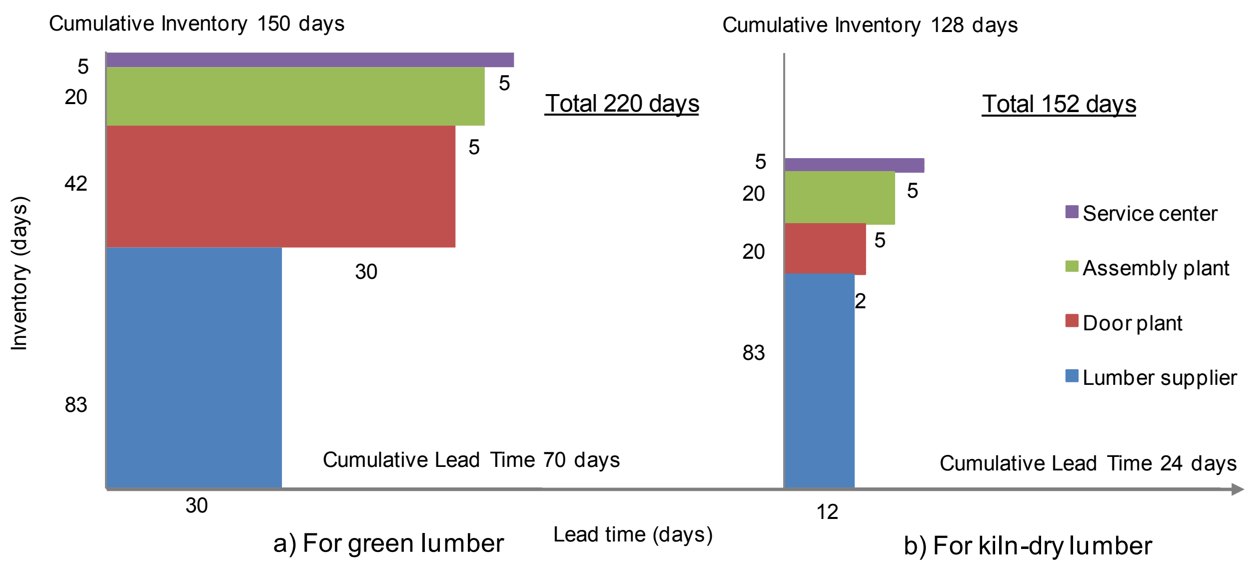


Figure 3-12. Supply chain response matrix (lead times as seen by the customer)

Pre-drying times used in the calculations correspond to the species with the shortest time needed for pre-drying (20 days). An interpretation of the supply chain response matrix in Figure 3-12(a) is that it would take 70 days (the cumulative lead time) to react to a real *increase* in demand (small increases can be met by the standing inventory in the system); and that it would take 177 days to react to a real *decrease* in demand. Thus the total response time is 247 days. A similar analysis can be made with each entity's internal processes.

It is easy to appreciate that the lumber supplier and the door plant carry the largest share of the lead time and inventory, and that any improvements in lead time and inventory management at a supply chain level should start at these two entities. However, it is worth noting that the largest part of the inventory and lead time at the door plant is due to the pre-drying process. Figure 3-12b shows and example of how this changes when lumber is bought kiln-dry from the supplier.

Finally, the actual processing time at each point in the supply chain is likely very small compared to the lead time shown in the horizontal axis of the response matrix; with the rest being work in process. It is the later portion which has to be targeted for reduction by improvement efforts.

Chapter 4. Quality Control and Measurement

In this chapter, the quality measurement practices at all levels of the kitchen cabinet supply chain studied are described. The information presented is the result of interviews and visits conducted from August of 2007 to August of 2008. The order in which the information is presented follows the flow of material in the supply chain explained in Chapter 3; this is, from lumber suppliers to the service center. For each of the entities in the supply chain, the quality control and measurement practices are explained, for both internal and external quality, using the framework illustrated in Figure 4-1(based in part on Choi & Rungtusanatham, 1999; Robinson & Malhotra, 2005). In the context of this study, internal quality refers to quality of the product before it leaves the production facility, which usually involves chiefly control of physical attributes. External quality deals with quality as seen by the next customer, and involves both physical and service attributes, like on-time delivery or customer service.

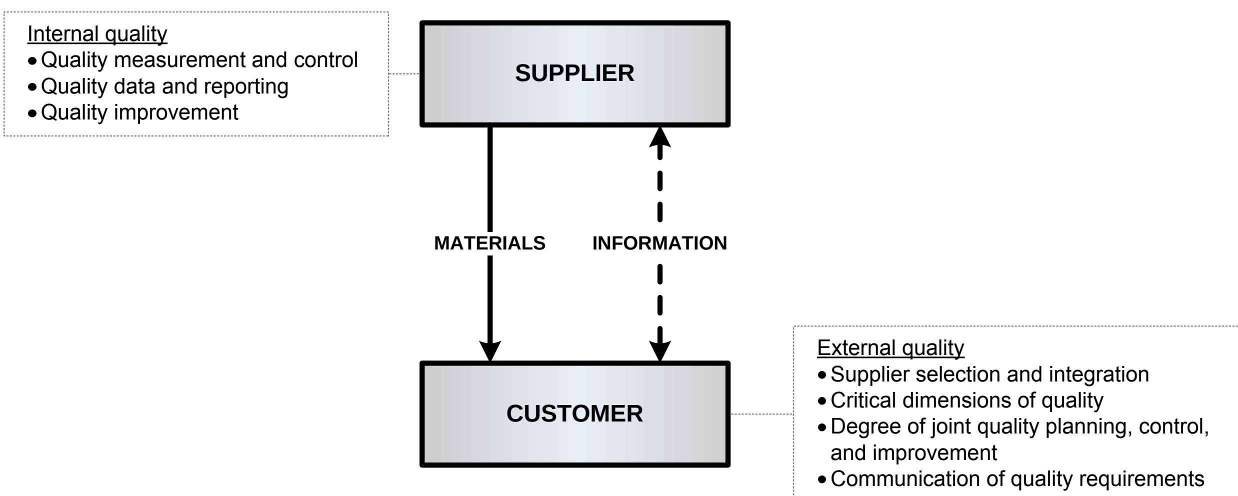


Figure 4-1. Framework for quality measurement

The last section in this chapter includes a discussion about the quality measurement practices with a supply chain management perspective. Specifically, supply chain integration and the differences in practices in relation to the position in the supply chain are analyzed.

4.1 Quality Control and Measurement at the Lumber Suppliers

Five suppliers who provide lumber to the door plant were contacted for the study, and the facilities of four of them were visited for a semi-structured interview with personnel in charge of quality management. Lumber suppliers will be identified just by a number from one to five. Supplier 1 was visited only to get preliminary background information to develop the research instruments that were used to collect data, thus this supplier's information is not presented in this document.

A questionnaire was developed to conduct the interviews in a systematic manner. This questionnaire was based on previous research and was reviewed by two faculty members at Virginia Tech and a person in charge of quality control at a sawmill (see Appendix A). The first part of the questionnaire dealt with demographic information about the lumber suppliers and the second part included specific questions about the quality control and measurement system. Table 4-1 shows a summary of the answers to the first part of the questionnaire. Supplier 5 declined to answer the questionnaire.

Table 4-1. Demographic information of lumber suppliers to the door plant

Characteristic	Supplier 2	Supplier 3	Supplier 4
Type of facility			
Concentration yard		x	x
Sawmill	x	x	
Air-drying	x	x	
Pre-and/or kiln-drying	x	x	x
Annual lumber output (MMBF*)	18	40	18
Number of employees	75	110	70
Drying capacity (MMBF)			
Pre-dryers		1.00	
Kilns	0.22	1.50	1.00
Total	0.22	2.50	1.00
Value-added process			
End-coating	x	x	
End-trimming	x	x	
Pre-surfacing			
Custom-grading		x	x
Custom sorts		x	x
Custom dimensions		x	
Color sorting		x	x
Technology			
Headrig optimizer	x	x	
Edger optimizer			
Trimmer optimizer			
Grade mark reader			
Drop-bin sorter			
Resaw optimizer			
Species supplied to the door plant			
Red oak		x	
Cherry	x		x
Soft maple			
Hard maple	x	x	x

* MMBF = million board feet

4.1.1 Quality Control and Measurement at Lumber Supplier 2

Lumber Supplier 2's facilities include a sawmill, kiln-dryers, and an air-drying yard. This sawmill does not have dedicated personnel for quality control, but the sawmill manager carries out these functions. At the log receiving end, log grade and footage is compared against the list provided by the logging crew and the discrepancies are evaluated once a month. Footage and grade are stamped on each log's end and recorded.

Lumber grading accuracy is monitored using a sample procedure once a month in which lumber graders perform a self-conducted audit. This audit is carried out separating a randomly selected pack of already graded lumber and grading it again to note any discrepancies. However, the results from these audits are not recorded. Thickness variation is controlled by the lumber inspectors as part of the grading process. The sawmill has a circular and a band saw and, according to the manager, the tolerances are 0.10 and 0.03 inches, respectively. During lumber drying, moisture content is monitored both by electric probes and by weight. The only measure that is documented and that is the basis for performance evaluations is overrun.

In regards to the relationship with the door plant, according to the interviewee, rejection of an entire truckload is extremely rare, but there are quality issues in about two to five percent of the cases. Quality issues can be excessive amounts of, for example, mineral streak in red oak, or color in hard or soft maple. These claims are communicated directly and dealt with on a case by case basis.

4.1.2 Quality Control and Measurement at Lumber Supplier 3

Supplier 3 consists of an air-drying yard, a sawmill operation, lumber drying facilities and a concentration yard where lumber is brought from other facilities owned or partnered with the same company. The company offers custom-defined grades, but the cabinet door plant does not buy this product. According to the interviewee, two employees spend most of their time in quality control-related activities: one is a lumber inspector at the end of the green chain and the other inspects the lumber packages ready for shipment. Thickness variation is not monitored with a formal program but constantly as part of the grading process. Grading accuracy is monitored by self-inspection three times a week, but this information is not recorded.

Regarding performance measures, overrun and grade yield are recorded. The company started an improvement initiative two years ago, and it includes keeping track of a performance measure they call “attainment”. Attainment is a comparison between actual performance and an “optimum” level, which corresponds to results obtained under ideal operating conditions (e.g., no downtimes). An 85 percent level is targeted, but no additional quantitative data was made available to the researcher.

In regards to sales to the kitchen cabinet Company, the interviewee said that load rejections are very rare but observations about quality are not uncommon. Quality issues are taken care of by the sales representative at the Company headquarters, and on a case by case basis.

4.1.3 Quality Control and Measurement at Lumber Supplier 4

Supplier 4 is part of a large hardwood lumber manufacturing company that owns facilities in six states of the North- and South-Eastern United States. The facility visited is a concentration yard, which receives green lumber from other facilities within the same company and from external suppliers. The facility includes an air-drying yard, a fan shed and kiln-dryers. This supplier has the most structured quality control system of all lumber suppliers visited, with systematic controls and documentation practices.

The quality manager at Supplier 4 oversees quality control processes at twelve facilities, and has setup a dedicated intranet database for storing quality control-related information. A quality supervisor at each facility is in charge of monitoring quality control-related activities and updating the database continuously.

Table 4-2 lists the major control areas and the most important control items for Supplier 4, as well as the methods and measured used to conduct the controls. Following, there is a brief description of quality control activities and measures at several stages of the lumber manufacturing process.

Table 4-2. Quality control items and measures at Supplier 4

Control area	Control item	Method	Frequency	Major metric
Log scale	Rescale logs Document species Defects Grade accuracy	Sampling 50 logs	Once per week	% from QC % defects % grade difference
Debarker	Diameter reduction Bark remaining Recording of scale	Sampling	Once per week	% volume reduction % of 100% % of missed volume
Minimum opening face	Opening-face flitches	Sampling	3 times per week	% from optimum
Lumber size control	Measure boards for thickness	5 pieces each machine	Every shift	Average thickness Average Std. Dev. Between-board variation Within-board variation Feed speed and width, length
Edger/trimmer	Over-edged strips Under-edged pieces on chain Over-trimmed pieces Under-trimmed pieces	Sampling	Once per week	% volume loss
Pallet cants	Heart centers End defects Side defects	Sampling 3 packs	Once per week	% of no pith Size variation % bad ends and edges Feed speed and width, length
Dip treatment	Chemical concentration Time of submersion pH level	Measure	Once a week	% from recommended
Lumber grading	Grade accuracy Tally accuracy Defect recognition	Sampling	Once a week, per inspector	% difference in dollar value
Lumber drying	Bolster alignment Kiln conditions Use of baffles Maintenance	Checklist	One kiln randomly selected per week	% from optimum
Packages ready for shipment	Squareness Sides and top defects Band placement Proper identification	Checklist	Five packs inspected per week	% from optimum
Ripsaw	Grade recovery Volume recovery Strip test	Sampling	Once per week	% value % volume change % of defect-free strips
Yard packs	Bolster alignment Rooftops Roadways Pack alignment Vegetation Sticker alignment Pile bottom condition	Checklist	3 packs per week	% from optimum

4.1.3.1 Quality control at the Sawmill

At the log yard, log scale accuracy is monitored by sampling 50 logs every week, re-scaling them and recording number of defects, grade and volume. Metrics reported here are percent difference between measured and actual volume, defects, and grade.

Following the sawmill process flow, at the debarker a sample is carefully inspected once a week to check diameter reduction, bark left, and volume. Measures calculated at this point are log volume reduction in percentage, percentage of remaining bark, and percentage of missed volume.

At the headrig, opening-face flitches (unfinished planks) are inspected three times a week and the percentage difference from the optimum is calculated and documented. The optimum in this case is defined by the width of the flitches in relation to the diameter of the log where they came from. Also after the headrig, three packs of pallets cants are inspected every week and characteristics checked are heart centers, end defects, side defects, and size. Measures calculated for pallet cants are percentage of cants with no pith, size variation, and percentage of cants with bad ends and edges.

A control is conducted at the edging and trimming operations once per week to check for over-edging and over-trimming (which produces waste); and under-edging and under-trimming (which may lead to an unnecessarily lower-grade board). For this, full-length strips at the in-feed to the chipper are checked (identifiable by square ends); and the width of the square edge is measured at the narrowest point, to assess how much of the board was left on the edging strip. For the trimming operation, the trim blocks are pulled before entering the chipper; over-trimming is checked by looking at pieces longer than 12 inches, full thickness, with less than one third of wane, and meeting the first lineal foot rule (NHLA) for FAS grade. The measure calculated in this case is percentage of volume lost due to insufficient or excessive edging or trimming.

Thickness variation is measured and monitored at the sawmill. Five boards from each sawmill major machine are measured every shift. Average thickness; standard deviation; and between- and within-board variation are calculated (calculation of these metrics can be found in Brown, 1979).

4.1.3.2 Quality control of Green and Dry Lumber Grading

Grading accuracy is the measure most tightly monitored since lumber grade and volume is the basis to fill purchase orders and their value. Green lumber is graded at reception during the night shift and again after kiln-drying during the day shift. Grading accuracy audits are conducted every week and for each lumber grader. Supervisors at each plant randomly select a package of lumber, re-grade it carefully, and the discrepancies are recorded in several categories, namely (1) value difference, (2) tally (volume) difference, (3) percentage above actual grade, (4) percentage below actual grade, (5) grade mix, and (6) defect percentages on the following categories: wane, splits, stain, machine marks, “miscuts” (excessive variation in thickness), “mispulls” (boards stacked in the wrong grade package).

It is common to have differences between lumber tally and grade reported by the source plant and that determined at the concentration yard. These differences are managed in the following fashion:

- The source mill’s tally is accepted if the value difference is up to three percent
- The value difference is split between the source mill and the concentration yard if the value difference falls between four to six percent
- If there is a six to nine percent-discrepancy in value, the difference is credited to the concentration yard
- The policy is different for external suppliers, and here the guidelines of the National Hardwood Lumber Association (NHLA) is followed: differences of four percent or less in value are considered acceptable (NHLA, 2003, p. 115).

4.1.3.3 Quality control at the Dip Treatment and Recovery Ripsaw

Before undergoing drying, green lumber is treated in an anti-fungal chemical by dipping. This dip-treatment is monitored by measuring the chemical concentration, the time of submersion, and the acidity level (pH). The major metric calculated here is percentage from the recommended level for each of the mentioned process parameters.

Lumber at this facility goes through a rip-sawing operation with the purpose of improving the grade (and thus value) of some boards with defects mostly on the edges (the increase in value from upgrading the board usually offsets the loss in volume caused by the longitudinal cut). Once a week, a number of boards are inspected to check for grade recovery (comparing grade before and after going through the ripsaw), volume recovery (comparing volume in board feet), and presence of defects. The measures calculated at this point are percentage of value increased in the upgrade, percentage of volume change, and percentage of defect-free strips.

4.1.3.4 Quality Control of Lumber Air- and Kiln-Drying

After green lumber is graded, it is arranged in dead-stacked packages if it is sold green or with stickers if it will undergo air- and kiln-drying. The air-drying yard can hold up to two million board feet of lumber and the kilns half that amount. During air-drying, a checklist is followed to control (1) the alignment of packs, bolsters, and stickers; (2) the presence of a rooftop on every pile of lumber; (3) the cleanliness of roadways and yard free of vegetation; and (4) the conditions of pile bottoms. Three packages of lumber per week are inspected and the percentage from the optimum is calculated.

Controls during kiln-drying include bolster alignment, use of baffles, kiln conditions and maintenance. One kiln is randomly selected among the kilns in all the facilities every week and thoroughly inspected with a checklist. The percentage from optimum is calculated for each category. Inspections for the air-drying yard and kiln-drying include similar items as those found in Forest Service publications (Boone, Milota, Danielson, & Huber, 1992; Forest Products Laboratory, 1999a).

4.1.3.5 Quality control of Lumber Ready for Shipment

Once lumber is re-graded, it is stacked into packages of uniform length and grade. Inspection of packages is important because it has been found that customers (especially large customers) do pay attention to the overall appearance of lumber packs (Bush, et al., 1991; Forbes, et al., 1994). Five packages of lumber are inspected per week, and a checklist completed with the following items: (1) squareness; (2) presence of defects on the sides, top and bottom; (3) correct placement of bands; and (4) proper identification (grade, species, piece count, and footage). The percentage from the optimum is calculated for each quality attribute.

4.1.3.6 Reporting and Quality Improvement

An intranet database was created with the sole purpose of storing and processing quality control-related information facilitates documentation and reporting of quality performance. A report of this information is created every month and actions are taken depending on the results. Performance is compared between facilities and over time within the same facility.

Monthly reports are produced for all facilities on the 16 quality control categories listed in Table 4-2, and sent to headquarters and later discussed with the person in charge of operations. Evaluations are posted and can be seen by all personnel in the company. Very importantly, quality performance data is used for compensation purposes. For example, each lumber grader is evaluated on the basis of his/her performance and receives an incentive when the accuracy is at or higher than the target. This practice started five years ago and, among other initiatives, has resulted in an increase in lumber grading accuracy from 82 to 95 percent. Figure 4-2 shows an example of performance report of grading accuracy.

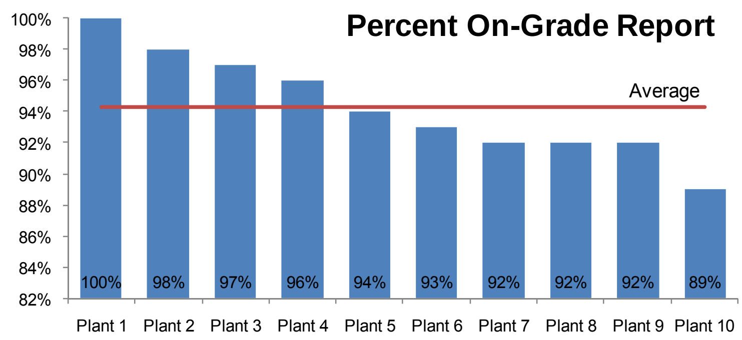


Figure 4-2. Sample of performance report at Supplier 4

In regards to Supplier 4's relationship with the door plant, according to the quality manager the quality requirements are expressed in NHLA lumber grades accompanying the purchase order. Load rejections are rare and quality claims are communicated directly to the sales department of the company, which in turn communicates these to the quality manager.

4.1.4 Quality Control and Measurement at Lumber Supplier 5

Facilities of Supplier 5 include a concentration yard, air- and kiln-drying yard, and a dimension mill. Apart from collecting and drying lumber, it also produces mouldings, plank flooring, and glued panels. The facility receives green lumber from sawmills owned by the same company and external sources. Incoming green lumber is graded, air-dried, kiln-dried, re-graded, and stacked in packages for shipment. There are several controls throughout the process.

At lumber reception, an inspector measures the thickness of incoming green lumber to check thickness consistency, and whether the shipping manifest matches with the purchase order. Every incoming batch of green lumber is assigned a lot number. This number identifies all the information recorded about that particular batch throughout its processing in the concentration yard. For example, grade mix and tally before and after drying, and other characteristics are recorded in the lot's record. Maybe the most important piece of information is the volume of each grade. Ideally, the volume of a certain grade should be constant throughout the process after accounting for shrinkage during kiln-drying. Variations other than the expected shrinkage can be attributed to grading accuracy and drying degrade. Thus, grade mix alone can help to monitor grading accuracy and drying quality.

During and after kiln-drying, the usual stress and moisture content checks are conducted and documented. After kiln-drying lumber is re-graded and this grade is the basis for determining the market value of the product. Lumber inspectors grade normally eight thousand pieces of lumber every day, thus it is important to have in place some mechanism to control variation at this process. At this supplier's facility, dry lumber grading accuracy is controlled by sampling and self-administered audits. In the former, supervisors randomly re-grade packs of lumber and provide feedback to lumber graders using a form. Lumber graders are also responsible for re-grading a number of packages a day and verify color and grade. In addition, a photo eyepiece checks the width of individual boards to verify whether they are wide enough to comply with a lumber grade or a width sort. Once al lumber in a certain lot has been graded and no problems were found, the lot is considered “closed”.

The documents generated for a certain lot are the basis for quality control and help to trace back the causes of the problems when there are customer claims. For example, if a customer complains that a certain truckload of hard maple has excessive amounts of sticker stain, the purchase order can be related to the lot number and then traced back to the air-drying yard to check for how long and under what conditions was the lumber sitting there. An unusually warm winter for example might have contributed to this issue.

After lumber is stacked and strapped in packages ready for shipment, an inspector examines a number of packages every shift, verifying piece count, tally, grading, and overall appearance (no defects should be visible on the sides, top, and bottom of the package). In addition, additional audits are conducted when the packages are loaded on to trucks. However, the results of these audits are not recorded, and feedback is provided immediately to lumber stackers.

4.1.5 Lumber Quality Attributes and Importance

Three of the lumber suppliers interviewed for this study were asked how they perceive that the door plant rates the importance of several product and service attributes. The same question was then asked the door plant. Results are listed in Table 4-3.

Table 4-3. Quality attributes importance questionnaire

Attributes	Importance Rating*			
	Supplier 2	Supplier 3	Supplier 4	Door plant
--- Lumber Characteristics ---				
Accuracy of grading	5	5	5	5
Consistency of grading	5	5	5	5
Consistency of lumber thickness	5	4	4	4
Consistency of lumber overall quality	5	5	5	5
Adequacy and consistency of color	4	5	4	4
Presence of wane	4	3	4	4
Presence of stain	5	5	5	5
Packaging (appearance, stacking)	4	**	5	4
Overall lumber appearance	5	4	5	4
Only for dry lumber:				
Straightness of lumber	5	5	4	5
Presence of surface checks, end splits	4	5	4	5
Accuracy of moisture content	4	5	5	5
Consistency of moisture content	5	4	5	5
--- Supplier Characteristics ---				
Competitive pricing	4	4	4	5
Order mix filled correctly	5	4	5	5
On-schedule delivery	5	5	3	5
Having previous business with supplier	5	4	4	3
Supplier's reputation	4	3	5	3
Personal relationship with supplier	5	4	3	4
Adequacy of your physical facilities	3	3	2	3
Ability to provide kiln-dry lumber	3	5	3	4
Ability to provide end-coated lumber	4	3	2	4
Ability to deliver rapidly on short notice	3	4	4	4
Ability to provide desirable length mix	3	4	3	4
Ability to provide desirable width mix	3	4	3	4
Ability to provide end-trimmed lumber	3	3	3	5
Ability to deliver large orders	4	4	3	3
Ability to deliver mixed loads	2	4	4	1
Ability to provide custom grades	3	4	3	1
Ability to provide a variety of species	3	4	4	3
Ability to arrange credit	2	4	4	3
Ability to arrange shipping	2	4	5	5

* 1 = Not at all important, 2= Not very important, 3= Average importance, 4= Somewhat important, 5= Extremely important
** Depends on the customer

Although the sample is not large enough to find statistically significant differences, some similarities and discrepancies can be identified.

- Overall, both suppliers and the customer rated product attributes higher than service attributes

- All suppliers coincided in that the customer rates grading accuracy and consistency is the most important product attribute, which also matched the customer rating
- Pricing was rated four by all suppliers, which was one point lower that what the customer rated
- End-trimming and end-coating was rated relatively low by suppliers compared with the customer's answer
- The importance of the ability to provide mixed loads and custom grades appear to be over-estimated by the lumber suppliers, since the customer rated these two service attributes with the lowest rating

These results illustrate the point that knowing what the customer considers important in a product and/or service is extremely important in order to design the quality management system in a way that contributes to meet the customer needs. The lumber suppliers in this study, for example, could adjust their performance measurement systems so they reflect the most important attributes to the customer, like accuracy and consistency of grading.

4.2 Quality Control and Measurement at the Components Plant

Quality control checks and inspections are performed at almost every operation in the doors and drawer fronts manufacturing process (see Figure 3-5), from reception of raw materials to finished product. Several tools are used for this purpose. Statistical Process Control (SPC) charts are maintained at several points in the process. Typical Six-Sigma measures of performance are calculated for individual operations and overall processes. Pareto charts are used to identify the most frequent sources of variances and thus decide on which improvement projects have the most potential impact on performance. Checklists are also used to assure systematic checking of critical attributes. These practices are described in detail in this section.

4.2.1 Overview of Quality Control System and Practices

Seven people work on quality control and improvement activities at the door plant: two finishing inspectors (one for each shift), one inspector at the panel plant, two quality auditors, one manager, and one “floater”. Lumber is graded at reception, and then pre-surfaced to assure thickness uniformity. Major controls are conducted at the moulder (for profile), cross-cut saws (for length), rail tenoner (for fit, squareness, tongue length and width, and length), stile and rail pick line (for wood characteristics), assembly (for squareness), sanding (for stock removal and surface finish), and finish line (for finish materials, process, color). There is a hundred percent inspection at the end of the process. When an SPC chart is maintained, operators use them to report when a process goes out of statistical control and proceed to correct the problem by using root-cause analysis.

Every month a quality evaluation is conducted. During these meetings, the major metrics, charts, and work standards are analyzed and compared against the goals. Key categories of non-conformances are examined, like squareness of doors and finish gloss. The goals for major metrics and specifications are set at a corporate level; for example, length tolerance, and the goal for defecs rate per million.

All sampling techniques, inspection criteria, and reaction plans are contained in the Quality Control Plans. This document lists the control items for an operation and other information listed below. A sample quality control plan can be found in Appendix B.

- Product and process identification, work area, and required approvals
- Specification/tolerance for the process. For example, the target length in a crosscut operation and the allowable tolerance above and below that target
- Method of control, specifying the measuring device or visual inspection required
- Data collection form, and person responsible to conduct the control
- Sampling plan, with number of samples and frequency
- Reaction plan, specifying what actions should be taken when the process outputs exceeds specification limits

These control plans are developed jointly by operators and Quality Assurance personnel. Table 4-4 lists the checks and controls at each process.

Table 4-4. List of quality control items for internal processes at the door plant

Process	Control item	
Lumber reception	• Grading accuracy • Company's grade requirements • Limit of 2 Common lumber	• Number of lumber stacks • Moisture content on dry lumber (only maple)
Pre- and kiln-drying	• SPC chart on moisture content range, equilibrium moisture content • Moisture loss control	• Stress tests
Moulder	• Groove width and depth • Strip stock thickness and width • Profile squareness • Profile fit and alignment • Quality of cut	• Amount of joint • Feed rate • SPC chart on moulder groove • SPC chart on thickness
Defect marking station	• Wood, machining and processing defects • Think material • Knots and worm holes	• Color • Bow
Crosscut optimizer	• Machine checks • Length	
Pick line	• Wood, machining, and processing defects • Checks and splits • Crayon marks • Wood color	• Thin material • Knots and worm holes • Bow
Rail tenoner	• Length of rails • Tongue thickness • Squareness • Quality of cut	• Fit • SPC chart on tongue thickness, rail length, and rail squareness
Door assembly	• SPC on door dimensions • Squareness • Profile depth • Chatter • Tear out	• Sanding quality • Handling damage • Hanger holes • Broke bits
Sanding	• Thickness of sanded parts • Machine checks	• SPC chart on thickness
Finishing	• Overall dimensions • Sealer and top coat coverage • Current sheen	• Sealer sanding quality • Color • SPC chart on gloss
Final inspection	• Wood characteristics • Assembly defects • Panel defects • Sanding defects	• Machining defects • Finishing defects • Handling damage

At several points in the process, product and component samples facilitate the quality control process. For example, at the pick line, where operators conduct a thorough inspection of each blank coming out from the crosscut saws, large display panels

(Figure 4-3) are placed displaying samples of wood defects and profiles. Operators are also provided with devices that facilitate the inspection and prevent errors, like bow and thickness gages.

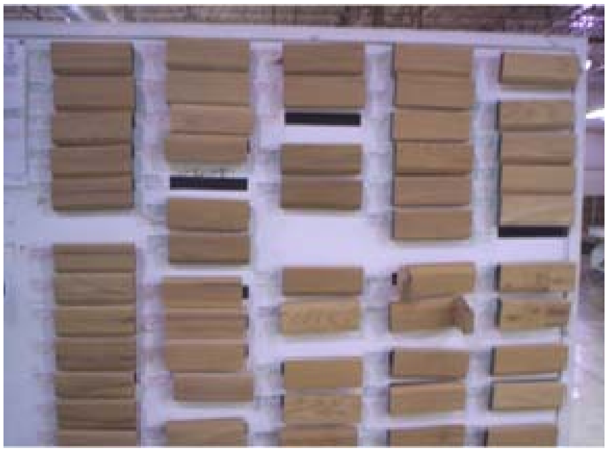


Figure 4-3. Wood defects and profile sample displays at the door plant

The key performance indicators (KPI) are displayed in visibly-located panels with performance information in categories such as safety, customer service (delivery), overall equipment effectiveness, sustainability, and scrap. The metrics displayed are presented on a month-to-date basis and rolling-12 by month; as well as separated by shift.

Regarding training, instruction in quality control is conducted on day to day operations, and on a continuous fashion. Team leaders are responsible for training and quality is a substantial part of their programs.

4.2.2 Quality Control of Incoming Lumber at the Door Plant

As mentioned in section 3.8.2, the incoming lumber is graded and tallied at the door plant. In addition to NHLA grading rules, the Company specifies limits on the percentage of 2-Common lumber, as well as 6 and 8-feet long lumber (see Table 4-5). The decision for including a certain percentage of 2-Common in the lumber mix is made based on a tradeoff between rough-mill yield and lumber cost.

Table 4-5. Requirements for lumber purchases

Lumber	Desired grade mix	6-8-foot lumber	2 Com limit
Oak	5% uppers (max 8%), 90% 1-Common,5% 2-Common No excessive mineral Widths: random. Lengths: random 6 ft and longer	Max. of 4 packs	600 BF per truck
Hard Maple	4% uppers, 96% 1-Common #1 & #2 white color spec Bought kiln-dried due to capacity constraints Widths: random. Lengths: random 6 ft and longer	Max. of 4 packs	1,000 BF per truck (soft maple)
Soft Maple	5% uppers (max), 90% 1-Common, 10% 2-Common #1 & #2 white color spec Widths: random. Lengths: random 6 ft and longer	Max. of 4 packs	1,000 BF per truck (soft maple)
Cherry	5% uppers (max), 85% 1-Common, 15% 2-Common Widths: random. Lengths: random 6 ft and longer	Max. of 4 packs	1,350 BF per truck

Hard maple, which is bought kiln-dry, is inspected for moisture content, 20 measurements for load, and rejected if a certain number of pieces with excessive moisture content are found. Also, hard maple is not graded; instead, it is spot-inspected.

4.2.3 In-Process Audits

Quality control personnel at the door plant conduct in-process audits daily and for each shift, inspecting randomly selected parts and recording rejects and defective items. Operations audited are rip-sawing, moulding, pick line, rail tenoning, drawer front machining, central panels, door assembly, door tenoning, door and drawer front sanding, and shipping. The results of these audits are used to calculate defective parts per million and sigma score, for each operation and department (i.e., rough-mill and finishing departments). The information thus generated is then used to evaluate the relative performance of individual processes and identify opportunities for improvement. Table 4-6 shows a sample record of the results of these inspections.

Table 4-6. Sample for in-process audit record for the moulder operation

Date	Units audited	Units rejected	Defects per million	Sigma score
July 2	24	3	125,000	2.65
July 3	16	0	0	6.60
July 5	16	1	62,500	3.03
July 6	16	3	187,500	2.39
.	.	.	.	.
.	.	.	.	.
July 30	24	3	125,000	2.65
July 31	32	1	31,250	3.36
MTD Average	368	28	76,087	2.93

4.2.4 Controls at the Finishing Line and Color Consistency

The finishing process is probably the one subject to the most stringent quality controls. Most quality issues at the finish line have three sources: substrate variation (wood), variation in the material application (process), and variation in the finishing materials (supplier). Controls at the finishing line are: color (using a spectrophotometer); material certification, which includes several controls; clear coat checks, to look for orange peel (a rough finish surface similar in texture to orange peel), sheen, clarity, and adhesion; finishing hardness checks; chemical resistance checks; film thickness test; adhesion test; and viscosity checks. Every batch of finishing material is inspected. An SPC chart is recorded on gloss readings.

Color consistency is one of the major quality issues in kitchen cabinet manufacturing. This is even more important when cabinet components manufactured and finished at several facilities are assembled in the same kitchen. Color differences in an installed kitchen cabinet can have the following sources: (1) Differences in substrate. Particularly important in clear finishes. Lumber coming from different suppliers, or even from the same supplier, can vary in color due to origin (i.e., the forest), or due to processing characteristics, like temperature used in kiln drying and treatments like steaming or dip-treatment. Grain direction, wood aging, and exposure to light can also affect color. (2) Differences in finishing material. This is a very common source of color differences and the door plant carries out several tests on every batch of finishing materials. There is a representative of the supplier of finishing materials on a full time basis at the door plant to address issues concerning the finishing materials. (3) Finishing process. Changes in finishing processes parameters can have a marked effect on color consistency.

The Quality Manager at this plant is in charge of evaluating the color consistency of the plant's products also between products of different plants. The controls in place to assure color consistency of door and drawer fronts produced are:

- A weekly assessment to evaluate variances in color of items produced at the door plant. This assessment includes inputs from the plant, quality and production managers; the finishing department supervisor; the quality supervisor; the finishing team leader; the quality technician; and a representative of the finishing products suppliers. The results of this weekly evaluation are reported in a qualitative manner, writing down the issues and the corrective action required.
- A monthly inter-plant color analysis, in which participant plants send samples of the different finishes to the door plant. These samples are evaluated for color harmonization with each other and with a corporate master standard. Results are sent to the participating plants, corporate offices, and the finishing materials supplier.
- A monthly analysis of color for individual plants, in which a sample from sent from a components plant is compared with corporate master standards. Results are sent to the participating plant, corporate offices, and to the finishing materials supplier.

4.2.5 Final inspection

Two inspections are conducted once doors come out from the finishing line. The first is a 100 percent inspection carried out by two operators at the end of the finishing hang line, one for each side of the door. Defective doors are either sent for reprocess or discarded if the operators judge that they are not repairable.

The second control is a thorough inspection carried by sampling. Approximately six doors are randomly inspected every day and twelve quality attributes are measured and checked. Table 4-7 lists the attributes and the general acceptance criteria.

Table 4-7. Attributes and tolerances for the final inspection at the door plant

Attribute	Criteria*	Defect description (examples)
Length	± .tolerance [in.]	Out of specification
Width	± . tolerance [in.]	Out of specification
Joints	Max. tolerance [in.]	Out of specification. Open or weak glue joints, misplaced glue, uneven ends
Squareness	Max. tolerance [in./in.]	Out of specification
Warp	Max. tolerance [in.]	Out of specification
Panel	Visual	De-laminations, veneer splits, sand through, rough surface, knife marks, excessive mineral, blue stain, quarter sliced veneer
Identification error	Pass or fail	Wrong ticket
Machining	Visual	Tear-outs, incorrect profile, excessive chatter
Visual	Wood defects	Inspect for shake, checks, splits, poor color, excessive mineral, rot, worm holes, moulder tear-out, moulder burn, flat edge, pulled grain.
Color	Visual to standard	Significant deviation from standard
Smoothness	Visual by feel	
Sealer / top coat coverage	Visual / gage	Insufficient coverage, orange peel, blisters, poor sealer sanding, poor wiping

* Tolerances values are not shown to protect confidentiality

4.2.6 Internal Quality Measures at the Door Plant

An essential part of an effective quality management system is a set of metrics to assess the performance of its processes. Such metrics allow comparing current performance against a target, detect whether a process is in control, and also identify defective products that would otherwise reach the next customer. Quality measures also facilitate the selection of improvement projects, by providing the quality manager a way to assess the relative performance of the internal process. This section describes the quality metrics for internal processes used at the door plant, which include all those measures monitored before the product leaves the facility.

As mentioned before, the Company has adopted Six Sigma as part of its manufacturing philosophy, and thus many of the quality measurement practices used at the Company's facilities are associated with Six Sigma. One of the basic premises of Six Sigma measures is that there is a direct connection between the number of defects and customer satisfaction, thus great attention is placed on measuring how capable is a process of manufacturing defect-free products (Harry, 1998). In the following sections, a description is presented of the quality measures used by the door plant and by other Company's facilities.

4.2.6.1 Defects per Unit and Defects per Opportunity

The basic measure in Six Sigma is defects per unit. A unit can be a physical product, a financial service, a parcel delivery service, or a purchase order form. Given a sample of the output from a certain process, defects per unit (DPU) is the average number of defects found per unit of output, calculated using Equation 1. The input or output from the process can be product related (e.g., a door) or service related (e.g., keying in a purchase order).

$$\text{Defects per Unit (DPU)} = \frac{\text{number of defects found}}{\text{units inspected}} \qquad \text{Equation 1}$$

The disadvantage of the DPU metric is that it does not allow comparisons between processes with different level of complexity. For example, there are more opportunities to have defects in the assembly of a kitchen cabinet than for a cabinet door, thus using DPU to compare the performances of the door and the assembly plants would be inappropriate. To overcome this limitation, the number of opportunities for a defect is used as a denominator in Equation 1, and this new metric is called defects per opportunities (DPO).

$$\text{Defects per Opportunity (DPO)} = \frac{\text{number of defects found}}{\text{opportunities for defects in a unit}} \qquad \text{Equation 2}$$

Equation 2 is modified slightly when a sample containing a certain number of units is inspected. In this case we use Equation 3.

$$\text{Defects per Opportunity (DPO)} = \frac{\text{number of defects found in the sample}}{\text{sample size} \times \text{opportunities per unit}} \qquad \text{Equation 3}$$

The great advantage of DPO is that it allows making comparisons between dissimilar processes, with different outputs or of a different nature. This makes DPO and its variations an excellent tool to use in a supply chain environment, where raw materials can become unrecognizable in the final products, and physical attributes of products (e.g., meeting specifications) can be as important for performance as service attributes (e.g., on-time delivery).

4.2.6.2 Defects per Million Opportunities and Defective Parts per Million

As can be observed in Equation 3, as the product becomes very complex, and if improvement efforts are resulting in a rapidly decreasing defect rate, the DPO metric becomes very small, frequently in the order of a thousandth or even smaller. Such numbers are difficult to work with, and thus a common practice is to multiply the DPU or DPO by one million (Equation 4), resulting in the defects per million opportunities (DPMO) measure, or defective parts per million (DPPM) if there is one opportunity for a defect in a product unit. A process is said to have reached Six Sigma capability when it has a long-term capability of less than 3.4 defects per million opportunities.

$$\text{Defects per Million Opportunities (DPMO)} = \text{DPO} \times 1{,}000{,}000 \qquad \text{Equation 4}$$

4.2.6.3 First-Time Yield (FTY) and Rolled Throughput Yield (RTY)

Given a certain process, at the end of which an inspection is conducted, the units inspected can follow three possible paths: (1) some units meet specifications and continue to the next process, (2) some have defects and are sent back for repair or reprocess, and (3) some units are beyond repair are scraped. This is illustrated in Figure 4-4.

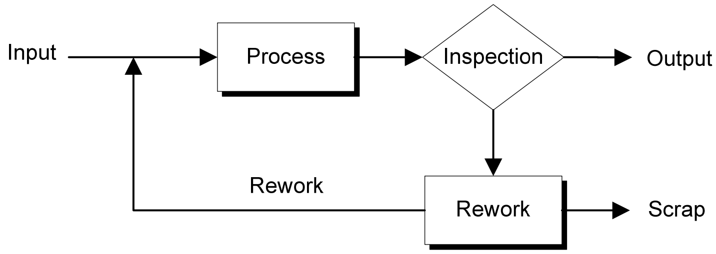


Figure 4-4. Process and inspection diagram

Under a traditional view, yield for this process would be calculated as simply the output divided by the input. It can be expressed either as a fraction or as a percentage.

$$\text{Yield}=\frac{\text{output}}{\text{input}} \qquad \text{Equation 5}$$

Conventional yield, however, does not take into consideration the resources wasted in reprocessing the defective units. It takes materials, labor, and maybe most importantly, time to rework units that do not comply with quality requirements, and these costs are either passed to the customer in terms of higher prices or eat into profits. First-time yield (FTY) includes rework in the calculations (see Equation 6) by subtracting rework from the output.

$$\text{First-Time Yield (FTY)}=\frac{\text{output-rework}}{\text{input}} \qquad \text{Equation 6}$$

First-time yield represents the likelihood of a unit going through the process in Figure 4-4 without being reworked or scraped. In other words, FTY is the percentage of work done right the first time.

When there is a number of operations executed in sequence (Figure 4-5), and the FTY at each process is known, the overall yield for the process is called rolled throughput yield (RTY). The expression used to calculate RTY is shown in Equation 7; simply a multiplication of all the individual yields for all the operations in the process.

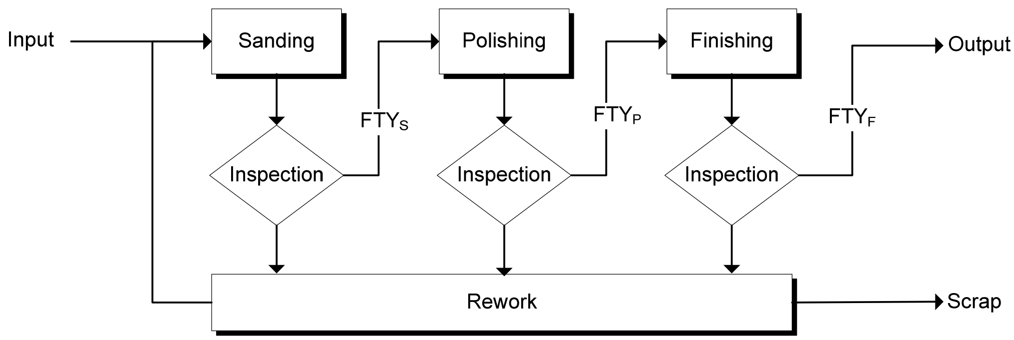


Figure 4-5. Diagram representing sanding and finishing processes at the door plant

$$\text{Rolled Throughput Yield (RTY)} = \prod_{i=1}^{n} FTY_i \qquad \text{Equation 7}$$

4.2.6.4 Sigma Score

Given a certain attribute being controlled that follows a normal distribution, and defined specification limits (Figure 4-6), sigma score (Z) is the number of standard deviations (ρ) that can be fit between the average of the process and the specification limit (SL), in Equation 8). The higher the sigma score, the lower the probability of having defects, because a smaller part of the area under the curve in Figure 4-6 will fall outside the specification limit.

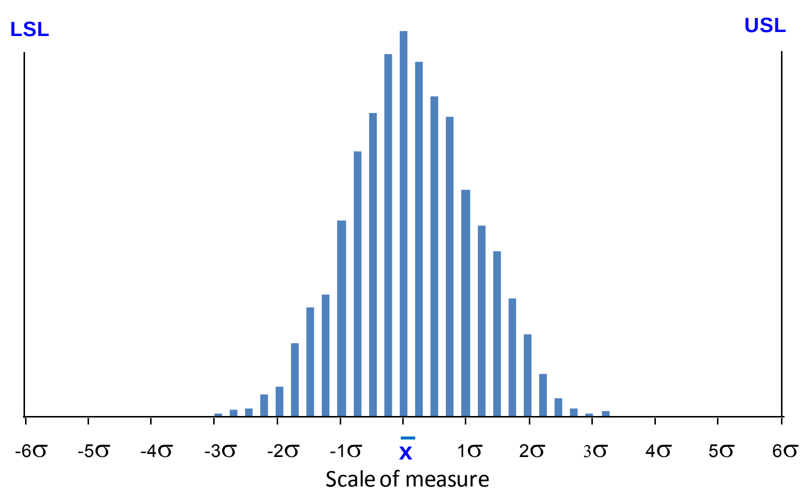


Figure 4-6. Normal distribution and specification limits for a control attribute

$$\text{Sigma score} \quad Z = \frac{|SL - \bar{x}|}{\rho} \qquad \text{Equation 8}$$

Sigma score is widely used among Six Sigma practitioners and is a measure of the capability of a process. However, what is commonly reported is a modified version of the sigma score, as explained below.

The distribution of a process attribute invariably changes with time. For example, the thickness variation in a sawing process increases as the saw looses tension or its teeth become dull. These changes can be of three classes: (1) the mean can move closer or farther from the specification limit, (2) the standard deviation can get wider, or (3) the specification limit can move closer or farther from the process variation, maybe at the request of a customer (Gygi, 2005). To account for these changes, it is normal practice when calculating the sigma score to artificially shift the distribution 1.5 standard deviations towards the specification limits; this way, the area under the shifted curve that falls outside the specification limits will coincide with that of the actual curve (Figure 4-7).

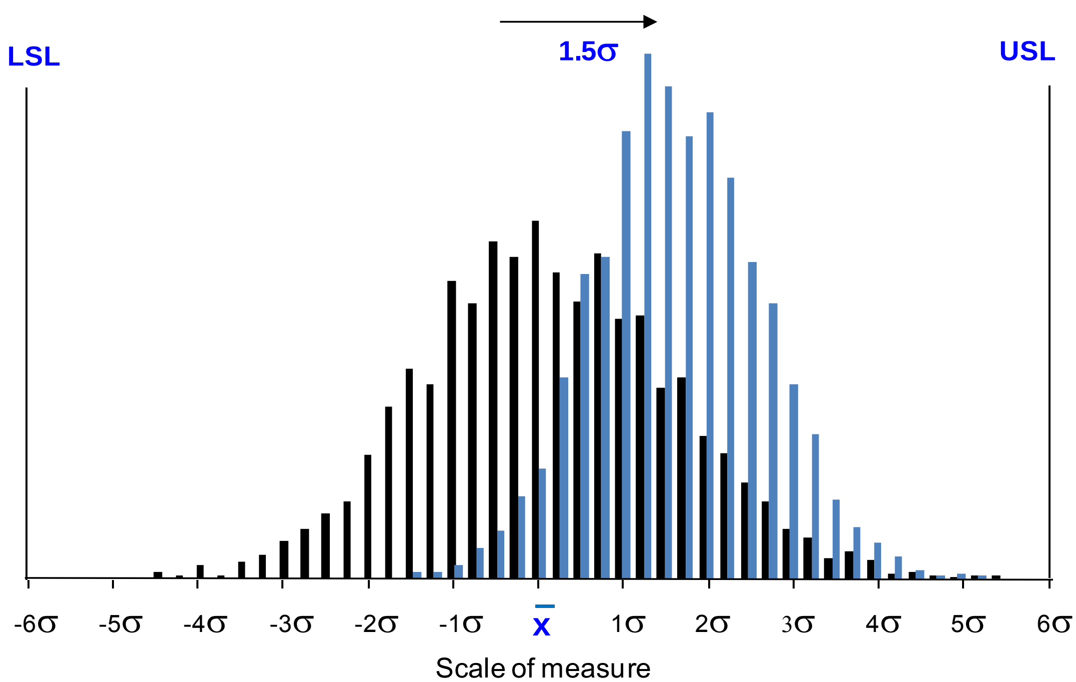


Figure 4-7. Illustration of sigma score drift

In simpler terms, the goal is to have a process that in the long-term can still perform at a 3.4 defects per million. This is mathematically expressed in Equation 9 and it is known as the sigma drift. Thus, a Six Sigma level of performance actually means that even if the process shifts 1.5 standard deviations to one side, it stills produces only 3.4 defects per million opportunities. Table 4-8 lists the values for long-term defects per million opportunities (DPMO) and the equivalent short-term sigma score (Z).

$$Z_{\text{Short-term}} = Z_{\text{Long-term}} + 1.5 \qquad \text{Equation 9}$$

Table 4-8. Relationship between sigma score and defects per million opportunities

Short-term Z score	Long-term DPMO
1.0	691,462
1.5	500,000
2.0	308,538
2.5	158,655
3.0	66,807
3.5	22,750
4.0	6,210
4.5	1,350
5.0	233
5.5	32
6.0	3.4

4.2.7 External Quality Measures at the Door Plant

The door plant monitors the shipping performance to its internal customers: the assembly plants. The measure used is On-Time Delivery and represents the percentage of orders that are sent on-time. This measure is monitored and updated daily and has a target value of 100 percent.

4.2.8 Quality Improvement at the Components Plant

Quality strategy and practices for Company's facilities are determined at corporate level. The corporate manufacturing philosophy combines three systems: Six-Sigma, Lean Manufacturing, and Kaizen events; these methodologies can be identified at all levels of the supply chain within the Company. Therefore, the information presented in this section applies not only to the door plant but to the assembly plant and the service center.

Since the Company started implementing Six-Sigma in 2002, it worked with a renowned institute to certify its employees as Six Sigma Black, Green, and Orange Belts. These certifications reflect the degree to which a professional is trained in Six-Sigma philosophy and principles. Black Belts undergo 128 hours of training and must execute two projects in a year. Green Belts train 64 hours and execute one project a year. An Orange Belt certification requires 48 hours of training and they conduct one project a year. The complexity and scope of the projects varies by the level of training. Six-Sigma projects follow the improvement model known as DMAIC (Define, Measure, Analyze, Improve, and Control). Figure 4-8 illustrates the DMAIC model (Pyzdek, 2003, p. 238).

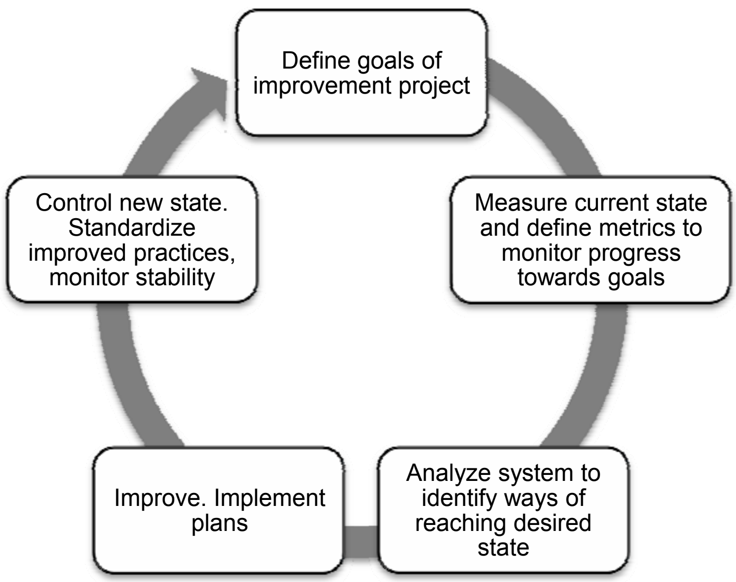


Figure 4-8. General view of the DMAIC model

Another improvement methodology routinely used by the Company is Kaizen events. A Kaizen event is a short-term improvement project, typically lasting one week, with very specific goals and achievement metrics; and in which a cross-functional team meets continuously to analyze and solve a problem (Farris, 2006, pp. 16-18).

The time frames for improvement projects, according to corporate guidelines, are four months for DMAIC projects and one week for Kaizen events; although both can take longer. A third type of improvement event is known at the door plant as a “Shop Floor Problem Solving” event, and is designed to be completed within one week.

There are also company-wide efforts to improve quality management. The Company's quality control managers meet once a year to discuss quality issues, and there are monthly evaluations at each plant.

4.3 Quality Control and Measurement at the Assembly Plant

Measures used at the assembly plant are similar to those used at the door plant. In-process measures will not be described with the same detail, but the focus will be on the measures calculated at the final inspection (internal quality) and those recorded after products are shipped (external quality).

4.3.1 In-Process Quality Control and Measurement

As in the door plant, the assembly plant maintains "glass house" displays in each one of the 10 production areas, with major performance metrics in areas such as safety, defect rate, scrap, and sustainability. Additionally, supervisors conduct audits to all processes every day, known as "walk-through" audits. Before taking components to the assembly cells, part pickers inspect parts. Some examples of quality controls follow:

- Inspection of doors at the end of sanding operation.
- Part pickers inspect doors at the time of pulling them from the distribution center.
- Cabinets are tested for static loading. They must sustain a predetermined load during a period.

Not all of these controls are recorded. For example, parts pickers inspect doors when pulling them from the distribution center, and reject some, but no measure is recorded at this point.

4.3.2 Final Inspection at the Assembly Cells

The assembly plant operates several assembly cells, to which "parts pickers" deliver components and accessories taken from the distribution center thirty minutes ahead of the start of the assembly. One cabinet is assembled every 53 seconds. At the end of the assembly cells, and before cabinets are placed inside their boxes, a quality inspector conducts a careful examination of products. Defects observed by the inspectors can fall in one (or more) of the categories listed in Table 4-9.

Table 4-9. Control items for final inspection at the assembly cells

Defect category	Defect Subcategory
1. Blown staples	Drawers
	E/P frame
	Top or bottom
2. Excess glue	White glue
	Hot melt glue
3. Flush wall surface	Frame to end-panel
	Back/hang-rail to end
4. Flush base surface	Pine rail to end
	Frame to end-panel
5. Drawer front alignment	
6. Cabinet mislabeling	Wrong door or drawer front
	Wrong color
	Wrong style
7. Cabinet squareness	
8. Missing inclusions	Paperwork
	MGD pack
	Blind panel
9. Visual	Chips
	Dents
	Scratches
10. Functional	Doors
	Shelves not seated
	Drawers or trays
	Door bumpers or hex dots

Although there is no formal quality control procedure for parts coming from the components plants, they are inspected as they are handled by operators and parts pickers, separating defective items in a red cart. Pickers can, in a day, reject as much as is rejected in the assembly cells and the rejects from these two sources are not separated. Rejects by parts pickers, however, carries the risk of incurring in higher costs by rejecting parts that could be repaired at the cell.

“Visual” defects and “Excess Glue” are by far the most common defects. The later invariably happen in the assembly cells. Visual defects consist in chip-outs, dents and scratches, an undetermined percentage of which is caused before items arrive to the assembly plant, during transportation.

4.3.3 External Measures at the Assembly Plant

The assembly plants can supply the Company's products either to external customers (retailers and builders) or internal customers (service centers), thus external quality measures become more important at this level in the supply chain. Two major metrics measure performance at the assembly plant: On-Time Complete and Eyes-of-the-Customer.

4.3.3.1 On-Time Complete (OTC)

On-time complete (OTC) represents the percentage of customers' orders that were shipped in their entirety and on, or before the due date. Basically is a measure of logistics performance to this point in the supply chain (Lambert, 2006). The target for OTC is 99 percent, and is set at corporate level. The reasons for not to achieving a target performance are recorded in two big categories: by cause and by product type (Table 4-10).

Table 4-10. Sources of variances for on-time-complete calculation

By cause	By product
Supply plant	Door
Inventory error	Front
Scrap	Frame
Assembly issues	End-panel
Glaze	Back
Excessive demand	Other
Miscellaneous	Accessory

The OTC metric, however, does not take into consideration if the orders were delivered without quality issues, or even if the correct items sent to the customers. Although it is important for a customer to receive his/her order on the promised date, it is equally important that the product does not have any flaws. To account for these issues, the eyes-of-the customer (EOTC) metric is calculated.

4.3.3.2 Eyes-of-the-Customer (EOTC)

The eyes-of-the customer (EOTC) metric is calculated with a 20-day lag from the moment the order is shipped. At the end of this period, claims from customers are considered defects and OTC is adjusted accordingly. These claims can fall in one of eleven categories, listed and explained in Table 4-11. EOTC measures the percentage of orders delivered with no errors in the categories determined as most important for customer satisfaction, and is normally lower than OTC; in this sense, EOTC is similar to the "perfect order" metric, and is more directly associated with customer satisfaction (Novack & Thomas, 2004). The goal for EOTC is 92 percent, and is set at the corporate level.

Table 4-11. Non-conformances recorded to calculate eyes-of-the-customer (EOTC)

Type or issue	Description
Backorder	It happens when the assembly plant does not have a component required to assemble the cabinet or accessory, and consequently an order cannot be sent complete.
Shortage	It happens when according to the assembly plant's records an item was loaded on the truck but the customer did not receive it
Damage	Damages to the product discovered after shipment, caused by transportation or handling
Mislabel	Product was incorrectly labeled and thus not usable for the order
Keying/order entry error	An order is sent to customer care but there is wrongly entered into the system
Customer care processing error	An order out of standards is sent to the assembly plant electronically but it is not corrected by the customer care personnel
Capacity	When the production capacity of the assembly plant falls short and the order's due date has to be delayed one or two days
Non-conforming product	Cabinet or cabinet parts have materials or assembly defects
Service center	Issues caused by the service center that delayed installation
Unresolved	Issues that could be resolved during the 20 days that the order is kept open to calculate the EOTC metric

4.4 Quality Control and Measurement at the Retailer

Once an order of cabinets arrives at the store from the assembly plant, only a visual inspection on the boxes is carried out, and items that have obvious handling damage are retained. Boxes are opened at the construction site and inspected there. If quality issues are found, delivery personnel report directly to the project coordinator, who takes the appropriate action. Items that need replacement due to a quality issue are especially costly for the store, since it incurs a charge every time a component is reordered. The reorder form contains a letter code that denotes the type of defect, "M" means damaged from factory, and "F" means field damage, which occurs after the factory. The assembly plant expedites reordered items and these arrive in four days or less. Common defects in descending order of frequency handling damage, color mismatches, mislabeling, cabinet construction, backordered items, and late shipments.

The only metric that is tracked is defect rate. According to a project coordinator interviewed, about ten percent of orders had some sort of defect, but not always requiring a reorder. Regarding importance of quality attributes, the office manager rated price, lead time, customer service, cabinet construction, aesthetics and little or no handling damage as extremely important for the store and its customers. However, building companies tend to focus more on lead time and price, while retail customers look more closely at the aesthetics, construction, and functionality of the product.

4.5 Quality Control and Measurement at the Service Center

The service center is part of the kitchen cabinet Company, therefore it follows the strategy and guidelines regarding quality control and improvement set at a corporate level. The service center maintains a “glass house” similar to the one found at the door and assembly plants (section 4.2), but since this supply chain entity provides a service instead of manufacturing a product, this is reflected in the key performance indicators that are observed. As is the case for the door and assembly plants, the major metrics are kept in a public, visible place, accessible to all the personnel.

4.5.1 Internal Quality Control and Measurement

Internal quality metrics at the service center measure the efficiency with which it performs the installation services. Using the least amount of resources and with as little defects as possible are major targets for these metrics.

4.5.1.1 No-charge-items

Items that for any reason had to be reordered but that cannot be charged to the client constitute a loss for the company. The number of such items are recorded and reported as a percentage of total number of items. The goal for this metric is one percent.

4.5.1.2 “Bone pile” count

Every time an item has some quality issue, it is marked as defective, and separated to a dedicated area within the warehouse, known as “bone pile”. The branch manager keeps track of these items and tries to keep the piece count to a maximum of thirty. Some items in this section were only mislabeled, in which case they are used in future orders.

4.5.1.3 Trips per house

The number of trips that are necessary to install a kitchen is recorded as a measure of efficiency, since each trip requires resources and time that could be spent in another order. There is a time lag of about thirty days since when the kitchen is installed to the closing of the house (when keys are handed over to the owner); during this period the service center has to make repairs or changes to ensure full satisfaction of the builder. Sometimes, these trips include repairs to damage caused by other activities taking place in the construction during this period. When the owner is handed over the keys of the house, he/she conducts a thorough inspection and notes all those items that are not to his/her satisfaction, and this can also originate the need for additional trips to the house. The goal for this is metric is to complete the installation in one trip, but usually it takes two to three trips to complete a kitchen.

4.5.1.4 Installation quality control

The service center provides installation service for all of its cabinet sales; this allows them to have more control in identifying and correcting quality issues before inspection by the builder superintendent or the homeowner. Two inspections are conducted before the installation can be considered complete. The first is a self inspection carried out by the installer, giving him the opportunity to correct any deficiencies that might have escaped his/her attention during the installation process. The second inspection is carried out by a supervisor, and takes place typically up to 48 hours after installation is completed. Both inspections are conducted using a checklist, which items are listed in Table 4-12.

Table 4-12. Installation inspection checklist

Installer self-inspection checklist	Supervisor inspection checklist
------------------- Cabinets -------------------	
☐ Cabinets Plumb and Level	☐ Cabinets plumb and level
☐ Cabinets Properly Secured	☐ Cabinets properly secured
☐ Door/drawers aligned	☐ Doors/drawers aligned
☐ Plumbing cutouts neat/tight	☐ Plumbing/electrical cutouts neat/tight
☐ Toe kick fitted, trimmed and puttied	☐ Toe kick fitted trim (OCM)
☐ Range opening to specs	☐ Range opening
☐ Dishwasher opening to specs	☐ Hood box built/secure
☐ Hood box built and secured	☐ Filler >1" returned on refrigerator cab
☐ Trim nails (brads) set/putty	☐ Trim nails (brads) set/filled
☐ Bumpers on all doors/drawers	☐ Bumpers on doors and aligned
☐ Holes in cabinets plugged	☐ Holes in cabinets plugged
☐ Shelf clips/supports in correctly	☐ Shelf clips/support in correctly
☐ Hardware on and correct	☐ Hardware on and correct
------------------- Countertops -------------------	
☐ Clean	☐ Tops clean
☐ Sink/cook top cutouts to specs	☐ Sink cutout correct
	☐ Cook top cutout correct
	☐ Edge band undamaged
	☐ Splashes caulked properly
	☐ Tops covered with cardboard
	☐ Seam fill in miters
------------------- Clean-up -------------------	
☐ Cabinets clean (sawdust/glue/cutouts)	☐ Cabinets clean (sawdust, dirt, glue)
☐ Floor swept/all scraps removed	☐ Floor swept, all scraps removed
☐ Debris removed to refuse area	☐ Boxes broken down, in trash bin
☐ Extra cabinets/access called in	☐ Extra cabinets/accessories called in

4.5.2 External quality measurement

4.5.2.1 On-time-complete (OTC)

On-time complete (OTC) is the percentage of orders that are completed on time and meeting the criteria listed in Table 4-12. This measure is similar to the one of the same name used at the assembly plant (see Section 4.3.3.1). The way it is recorded and calculated is that for each work order (installation of cabinets in a house), the different issues (known as variances) that may arise before the installation is complete are recorded in an electronic spreadsheet and at the end of each week and month the ratio between orders completed and total orders is computed. The records are constructed in a way that it is possible to identify the customer and house where the variances occur; the name of the installer; and the week when the variance occurred.

The issues, or variances, that prevent an order to be considered complete can fall in one of twelve categories. A list of the categories and a brief description are shown in Table 4-13.

Table 4-13. Variances recorded to calculate On-time-complete (OTC)

Type or variance	Description
Field Service Representative (FSR) error	Typically a measurement error that results in a cabinet of the wrong size. Also includes wrong color, wrong option, etc., caused by the FSR
Custom parts	Errors related to any product installed other than cabinets: including countertops, marble, custom parts supplied by an outside vendor, etc.
Damage	Any damage in a cabinet or cabinet part that is not repairable. Since most damages are concealed, it can included damage before and after items have been received at the service center
Plant error	Errors attributable to the assembly plant, like a wrong part in box, defects in the materials or assembly. Also include data errors, but these are rare
Order error	Consists of a keying error for cabinets and/or cabinet parts
Warehouse error	Typically a failure to deliver the correct item to the house, also includes damage caused by handling in the warehouse
Installer error	Any defect caused during the installation process
Plant backorder	Back orders not received by the day of installation
Sales error	Any error related to layout or drawings done by sales representative
Stolen	Any product stolen from warehouse or job site that cannot be replaced in time for installation
Builder error	Errors related to framing, plumbing or information processes attributable to the construction company, that prevent completion of installation

From Table 4-13, out of the twelve categories only “plant errors” and “plant backorders” can be clearly originated at the assembly plant. Errors caused by the field service representatives, order keying, warehouse, installers, and sales representatives can be attributed to processes executed by the service center. Custom parts errors, stolen goods, and builder errors are originated externally.

Custom parts refer to externally-acquired parts, typically countertops and cabinet hardware. The most common causes for “custom part” are receiving a damaged part or a part with the wrong dimensions. The latter happens because in most cases measurements are taken without the walls being completed and allowances are added up to the initial dimensions to account for wall components.

The OTC measure, however, only takes into account completion until inspection by a supervisor from the service center. About thirty days pass between the initial completion of the installation and the inspection carried out by the homeowner when receiving the house, and during this time and at the time of the inspection, some issues may arise that requires repairing or changing components in the kitchen cabinets. The service center takes care of these problems, usually at its cost. However, the time-to-fix, no-charge items, and trips-per-house measures do take these occurrences into account.

4.5.2.2 Customer satisfaction

Customer satisfaction at the service center level is measured by a telephone survey, conducted by a third party hired by the Company. The construction superintendents of each construction site are contacted and asked the questions listed in Table 4-14. Answers are given in a scale from zero to one hundred percent, the latter represents complete satisfaction. There is also place for comments by the customer in this survey.

Table 4-14. Customer satisfaction survey

Question	Measures satisfaction with
1. Deliveries are complete and on time	Service Center
2. Product and service concerns are corrected in a timely fashion	Service Center
3. Delivery dates are confirmed prior to delivery	Field Service Rep.
4. Field Service Representative is available and helpful in satisfying needs	Field Service Rep.
5. Customer service calls are returned in a timely manner	Customer Service Rep.
6. The Customer Service Representative helps resolve issues	Customer Service Rep.
7. The Company is doing a good job at your project	Service Center
8. Would you recommend the Company’s products and services?	The Company

The responses to questions one to seven in Table 4-14 are averaged and reported as the overall satisfaction with the Service Center at personnel meetings for feedback. The Service Center’s goal for customer satisfaction is 90 percent.

4.5.2.3 Time-to-Fix

After the installation of kitchen and bath cabinets is complete, some quality issues may occur, which could be caused by (1) damage by other activities taking place at the construction site, (2) quality problems attributable to the Company, found by the construction superintendent, and (3) quality problems identified by the homeowner at the moment of inspection. No matter what the source of the problem, the service center personnel have to correct the problem as soon as possible. These concerns are reported to the appropriate personnel at the service center through the customer service center, and entered in a tracking system, that keeps track of the time passed from the customer's initial call to when corrective action is taken. This is called "time-to-fix" and constitutes another measure of external quality. Corrections usually entail the ordering of a replacement component or accessory, which involves a lead time that is not in the control of the service center. Components made by the Company are expedited through a program put in place for these cases, and lead times of expedited orders are usually of less than five days. The goal for this metric is ten days. At the moment of the study, however, the average time-to-fix was of five days.

4.5.3 Quality Control and Improvement

During the installation, the construction superintendent walks every house and takes note of any issue that he/she might find. The superintendent then reports the problems to the service center and a data is set for corrections. All these issues are reported through customer service in a Service Automation Manager (ASM) system.

As noted before, at the time of closing, the homeowner inspects the house thoroughly and notes any issue that he/she is not satisfied with. The correction of the issues is negotiated with the construction superintendent and a date is agreed upon to complete all the remaining work.

The service center personnel meet once a week to discuss the different issues concerning operations at the branch. Concerns related to product or service quality are treated at these meetings, a root-cause analysis conducted, and the relevant metrics are reported to each employee. Reports are also released every month. When the assembly plant needs to be notified on the issues, these are reported directly.

4.5.4 Quality Attributes

The purchasing decisions by the construction company regarding kitchen and bath cabinets involve several functional levels, and each one is somehow involved in quality control of the product being purchased (see section 3.9.1). However, the importance each decision level places on certain attributes of the product and service provided by cabinet Company is not uniform. To explore this, the importance of five product and service attributes was evaluated at the three decision levels in the construction company with the help of the Service center manager. Results are shown in Table 4-15.

Table 4-15. Quality attributes importance for the construction company

1 = Not important at all, 2 = Not very important, 3 = Average importance
4 = Somewhat important, 5 = Extremely important

Attribute	Purchasing manager	Construccion manager	Superintendent
Competitive price	☐1 ☐2 ☐3 ☐4 ☑5	☐1 ☐2 ☐3 ☑4 ☐5	☐1 ☑2 ☐3 ☐4 ☐5
Lead time	☐1 ☑2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☑4 ☐5	☐1 ☐2 ☐3 ☐4 ☑5
Customer service	☐1 ☐2 ☐3 ☑4 ☐5	☐1 ☐2 ☑3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☑5
Construction	☐1 ☐2 ☑3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☑5	☐1 ☐2 ☐3 ☐4 ☑5
Aesthetics	☐1 ☑2 ☐3 ☐4 ☐5	☐1 ☐2 ☑3 ☐4 ☐5	☐1 ☐2 ☑3 ☐4 ☐5

As Table 4-15 shows, the importance of price decreases from the purchasing manager to the construction superintendent, while the importance placed on lead time goes in the opposite direction. Although the differences are not as marked for customer service, cabinet construction and aesthetics, some discrepancies can be identified. The physical quality attributes of the product (cabinet construction) and customer service rated very high for the construction superintendent, not surprising since this person is closely involved with the installation process, and receives direct feedback from the final customers. Somewhat unexpectedly, however, aesthetics was not rated high for any of the decision levels at the construction company, perhaps due to the fact that this issue was already considered in the pre-selection process much earlier in the purchasing process.

4.6 Customer Satisfaction Survey

The Company hires a third party to conduct a periodic customer satisfaction survey among all its customers. Four functions are evaluated in these surveys, and each function has several attributes, as listed in Table 4-16:

Table 4-16. Customer satisfaction survey, functions and attributes

Function	Attribute
Customer Care	Knowledgeable
	Responsive to needs
	Orders processed accurately
	Resolution on first contact
Product Quality	Good value
	High quality construction and workmanship
	Smooth and blemish-free product finish
	Uniform and consistent color
	High quality materials
Logistics and transportation	Orders on time
	Orders received in good condition
	Complete and accurate documentation
	Delivery change notification
	Loaded in sequence and separated from other orders
Sales Support	Responsive to needs
	Knowledgeable about product
	Keeps customer informed
	Understands my business needs
	Good resource for market information
	Provides design information

The performance and importance of each attribute is rated on a one-to-five scale, being five the highest performance. A rating of four is considered satisfactory and the difference between performance and importance (gap) is used to identify critical areas that need improvement. Table 4-16 lists attributes in order of importance. Other data that is obtained from the surveys are: satisfaction data by region and market, customers at risk, and areas that need improvement.

4.7 Quality Reporting at the Corporate Level

The Company reports performance measurements for all of its operations in a Corporate Dashboard, which contains measurements in several categories: from human resources to customer services. Performance measures are presented on a daily, month-to-date, and year-to-date basis. The Operations category includes the key quality indicators, which are (1) defect rate per million, (2) scrap, and (3) cost of quality. Cost of quality includes appraisal, prevention, and internal and external failure costs. Regarding defect rate per million (DPPM or NCPPM), each plant reports a monthly cumulative average. For example, in the case of the door plant, the cumulative average is calculated by averaging the overall performance for door and drawer fronts.

4.8 Communication of Quality Issues in the Supply Chain

In this section the main channels for communication of quality issues are described for all entities of the supply chain of study. During the interviews at each plant, quality assurance personnel were asked how they communicate quality requirements to their suppliers, how feedback on their performance is provided, and how quality problems are reported to them. Results are shown below

The door plant communicates requirements for lumber quality chiefly in the purchase order, specifying grade mix and other special requirements (see Table 4-5). The supplier gets the grade bill, which is the result of the grading carried out during the reception of the lumber at the door plant. When quality issues arise, loads are either rejected or the issues communicated directly to the account manager at the lumber supplier, chiefly by phone but also by email. The supplier does not participate in the development of the lumber grade mix or the development of a custom grade.

Regarding issues in the door plant’s output quality, these are mostly communicated directly (phone and email). There is no reach beyond the door plant’s immediate customer and supplier. The assembly plant receives feedback from customers through the customer care department, which issues weekly reports about quality issues that came up. When customers are internal, meaning the service centers owned by the Company, feedback is communicated directly.

Quality issues at the service center level are communicated through the customer service. The service center communicates quality issues to its external suppliers (those providing components other than cabinets) in the same way. According to the interviewee at the service center, the quality alert is rarely used.

Chapter 5. Quality Performance in the Supply Chain

In this chapter, data on quality performance throughout the supply chain of study is presented and analyzed. The order followed is the same as the flow of materials, starting at the lumber supplier and ending at the service center. The period of analysis is one year and data is presented in a monthly basis and sometimes weekly basis. The numerical information here presented was changed to protect the confidentiality of the companies' data; these changes, however, do not affect the relationships found during the statistical analysis.

5.1 Quality Performance at the Lumber Supplier

Data for quality performance presented in this section corresponds to Supplier 4, except where noted. As mentioned in section 3.8.2, there is a time lag between purchase and usage of three of the four species purchased by the door plant, with red oak having the longest time, about 70 days for pre- and kiln-drying. For this reason, performance data for the lumber supplier is presented from November to December of the next year, since green lumber purchased in November of one year will most likely be processed in January of the next year.

5.1.1 Grading Accuracy

Grading accuracy is perhaps the most important measure of internal quality performance at the lumber supplier, since the grading process determines lumber value and its accuracy and consistency is regarded among the most important quality attributes by the customer (Table 4-3). Grading accuracy has two major components:

- *On-grade percentage*. Percentage of lumber which stated grade corresponds with the grade as determined by weekly audits; and the difference between the target and measured values. The target value for this measure is 96 percent

- *Tally difference* is the percent difference between volume as determined by the grading process and that one determined by weekly audits. The target difference is zero.

In Figure 5-1, on grade percentage and tally difference are portrayed for the period of study. A steady decline in accuracy is apparent from November to August, from 91.3 to 89.2 percent; and then an increase through December. In average, grading accuracy was about 5 points below the target value of 96 percent. Tally accuracy was 0.5 percent above the goal of zero difference.

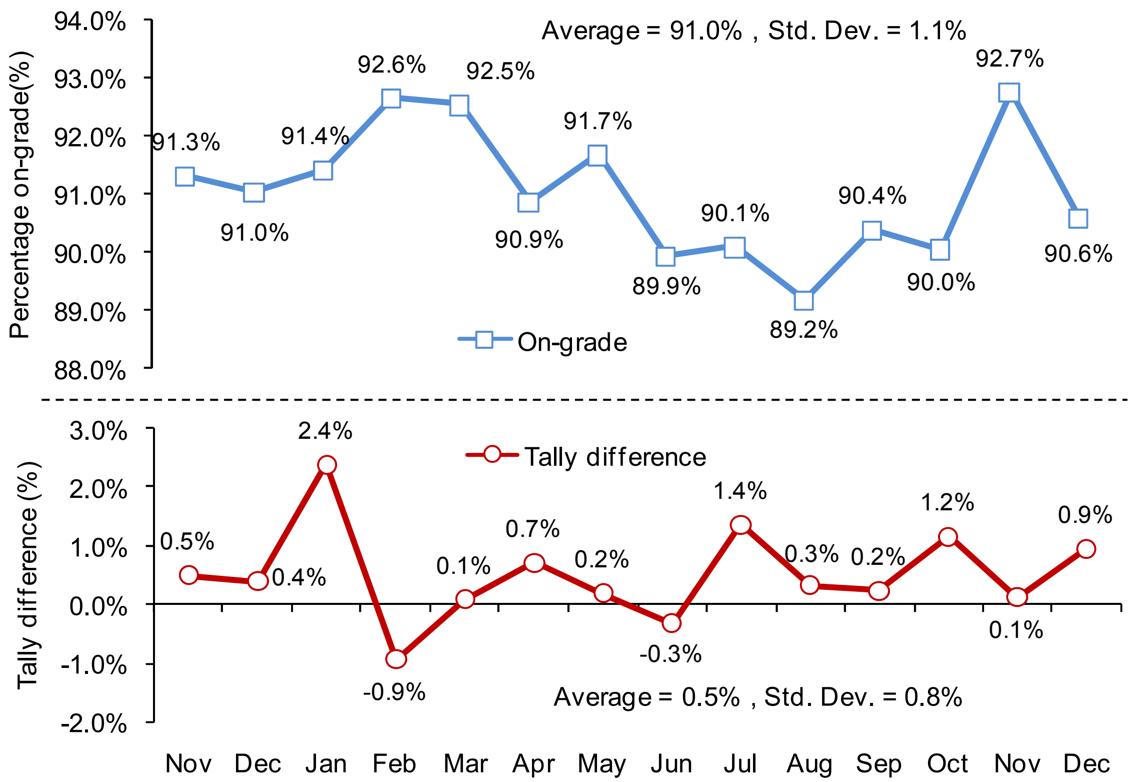


Figure 5-1. Overall grading and tally accuracy at Lumber Supplier 4

The company started to monitor grading accuracy and use it as a basis for compensation five years ago, and according to the interviewee significant improvements have been achieved. To analyze these changes, Figure 5-2 shows a comparison of accuracy and other measures for the last three years.

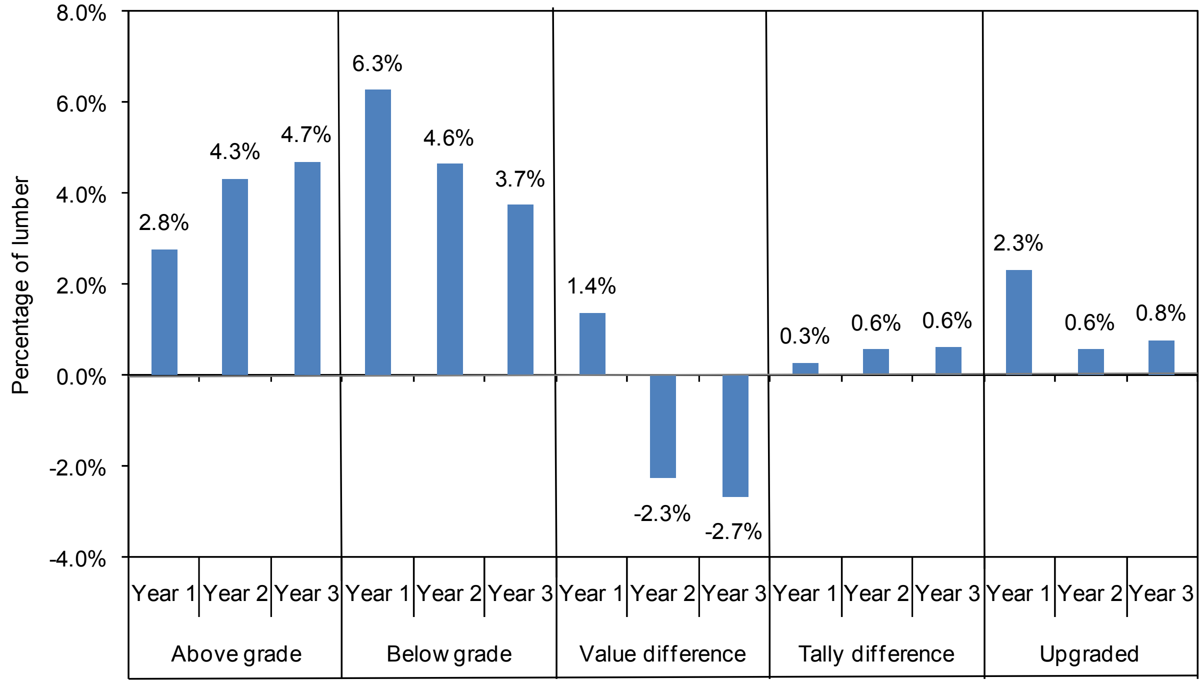


Figure 5-2. Major grading accuracy indicators for three years at Lumber Supplier 4

It can be observed in Figure 5-2 that the percentage of lumber graded above its actual grade (the later determined by the quality control personnel) grew as the percentage of under-graded lumber decreased. It would be expected that the growth in over-estimated grade translate in increasingly negative lumber value differences (the value difference is negative when the actual value is higher), and in fact this is confirmed by the figures, going from 1.4 percent overvalued lumber in Year 1 to a 2.7 undervalued lumber in Year 3. Tally difference doubled from Year 1 to Year 2, but stayed at the same level in Year 3. The percentage of upgraded lumber adds to the value of the lumber output. However, there is a decrease in the percentage of upgraded lumber from Year 1 to Year 3. Data in Figure 5-2 supports the quality manager assertion that accuracy has improved in the last years, since the net growth of above and below grade percentage is negative.

Grading accuracy can also be analyzed in view of the species processed, to examine if there are significant differences in accuracy depending on the species being graded. It could be expected that lumber graders have a tendency to be more accurate in those species that are most frequently processed. Only the species purchased by the door plant were analyzed for this study. Figure 5-3 shows the grade mix processed by Supplier 4 only for the species purchased by the door plant.

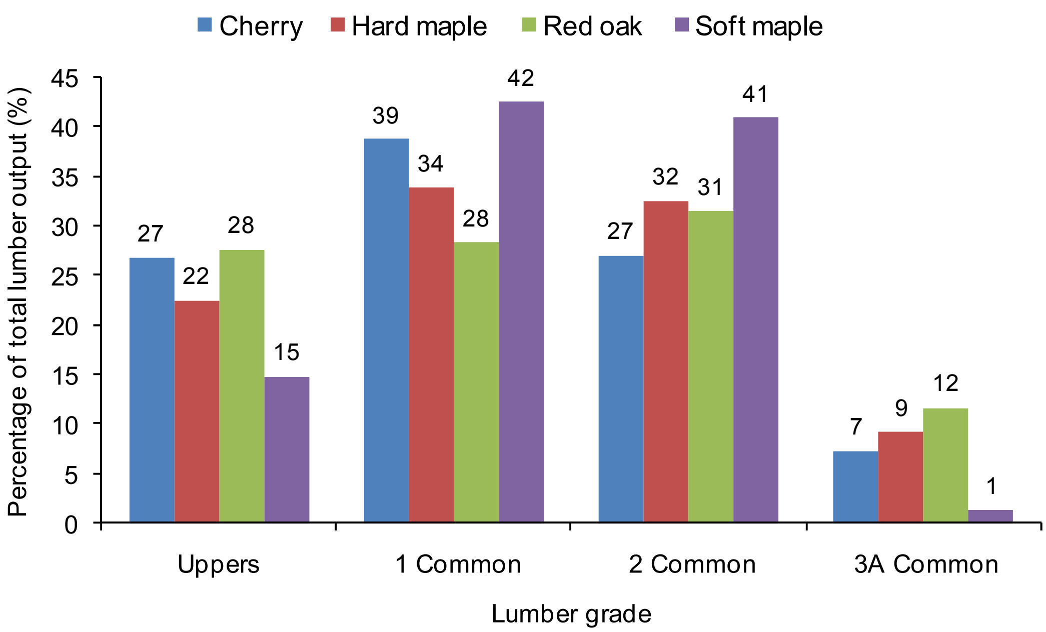


Figure 5-3. Lumber grade mix for Lumber Supplier 4

Table 5-1lists the average on-grade percentage for the same species and a multiple comparisons analysis results at 0.05. Two homogeneous subgroups were found: soft maple, cherry, and hard maple; and cherry, hard maple and red oak. Red oak grading accuracy is the highest and that of soft maple the lowest.

Table 5-1. Grading accuracy by species

	Soft Maple	Cherry	Hard Maple	Red Oak
Mean - homogeneous subsets (Tukey HSD method)	85.5%	88.0%	90.6%	
		88.0%	90.6%	95.6%
Std. Dev.	9.6%	8.2%	7.9%	2.8%

During the audits, the type of defects detected is also recorded. Defects that reduce lumber grade are listed in Figure 5-4, along with the percentage detected during the audits. Presence of wane is by far the most common defect.

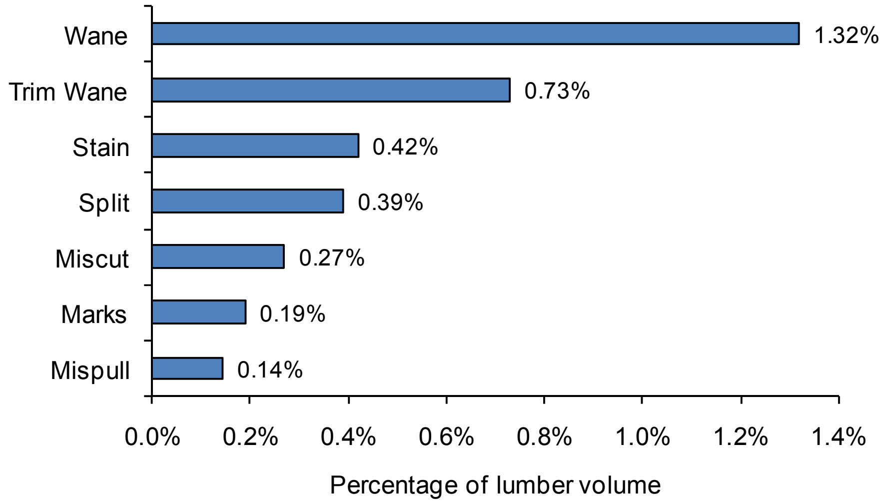


Figure 5-4. Grading accuracy by wood defects as percentage of lumber volume

5.1.2 Grade Mix of Lumber Purchased by the Door Plant

The door plant purchases lumber according to a required grade mix for every species, shown in Table 4-5. With the exception of hard maple, all lumber is graded at reception and payments determined accordingly. Figure 5-5 shows the average lumber grade mix purchased in the period of analysis for each species, from all suppliers (error bars at one standard deviation above and below average).

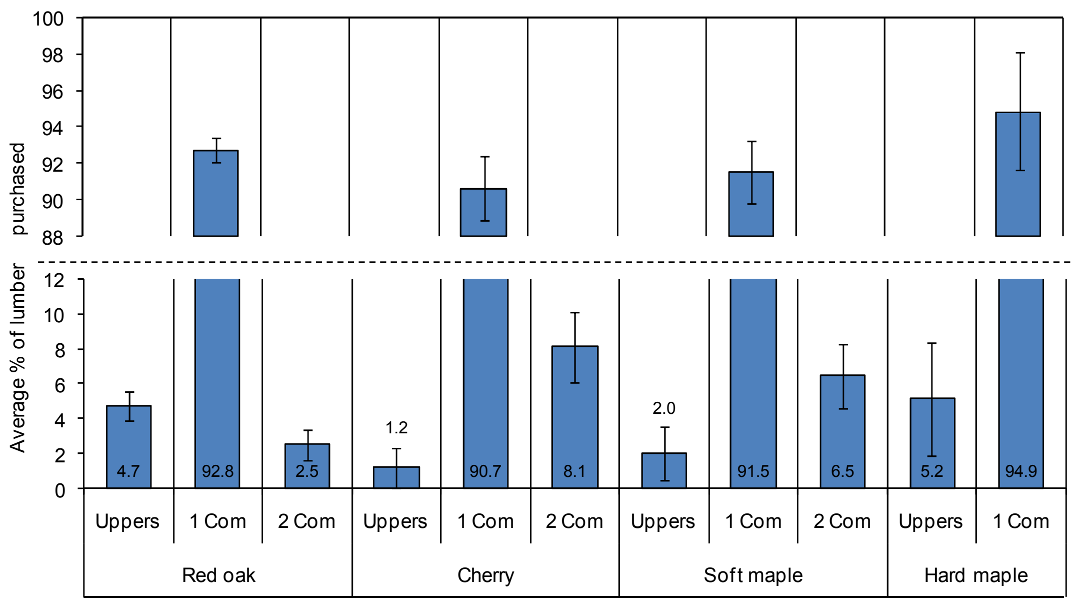


Figure 5-5. Average lumber mix purchased by the door plant during the year of analysis

It can be seen in Figure 5-5 that, in average, the lumber received at the door plant meets the 1-Common and 2-Common grade mix requirements (these are listed in Table 4-5), with the exception of hard maple, which was 1.1 percent below the minimum specified for 1-Common lumber (96 percent). It should be noted however, that the specification for the “uppers” grade in hard maple was higher before and a decision was taken to reduced the amount of the mentioned grade to 4 percent early in the year of analysis, thus this change was by design thus the 1.1 percent difference cannot be attributed to suppliers. A closer look at the grade mix of each species is presented in Figure 5-6, and the shift in hard maple grade requirements is clearly evident.

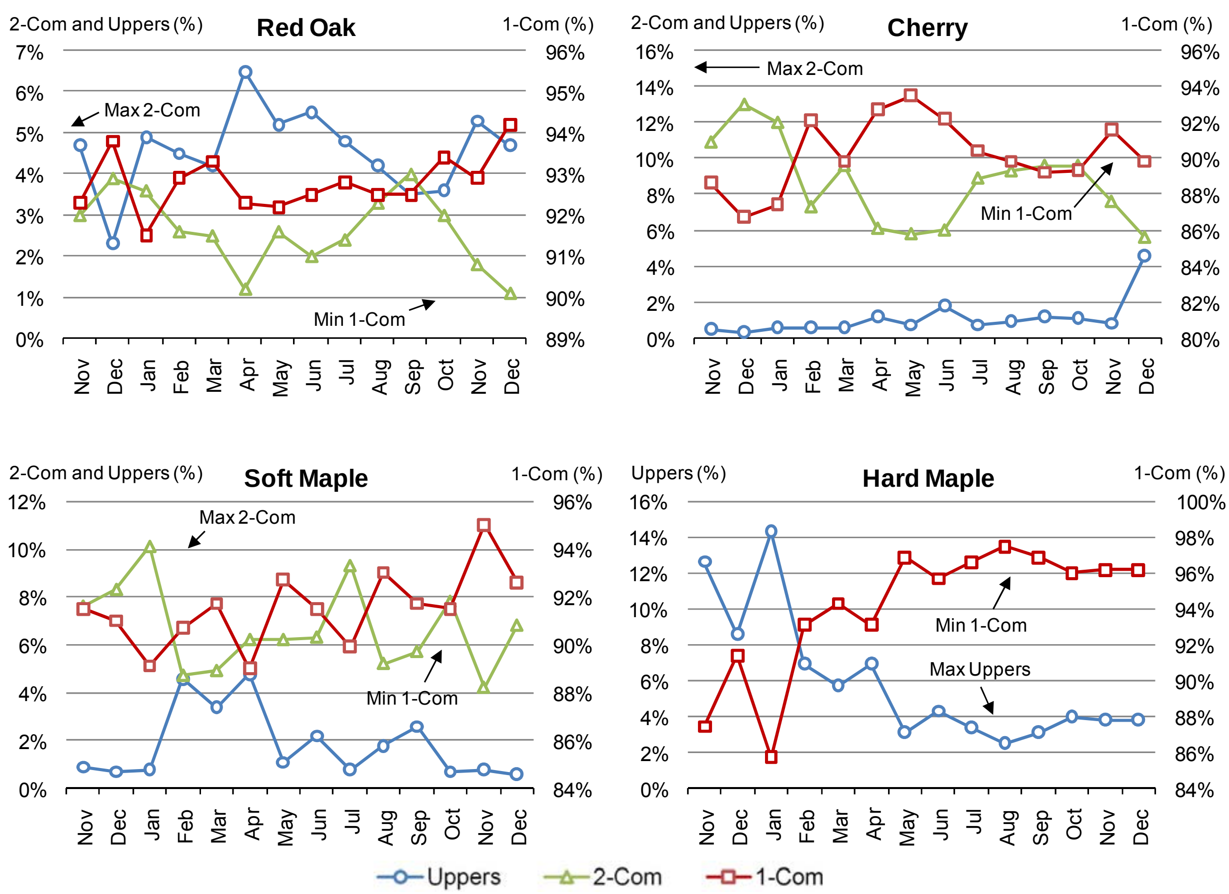


Figure 5-6. Monthly lumber grade mix purchased by the door

5.1.3 Grade Mix from Supplier 4

In the previous section the grade mix presented corresponded with the combined lumber purchases from all the suppliers of the door plant. The following graphs depict the grade mix for purchase orders delivered by Supplier 4 in a year.

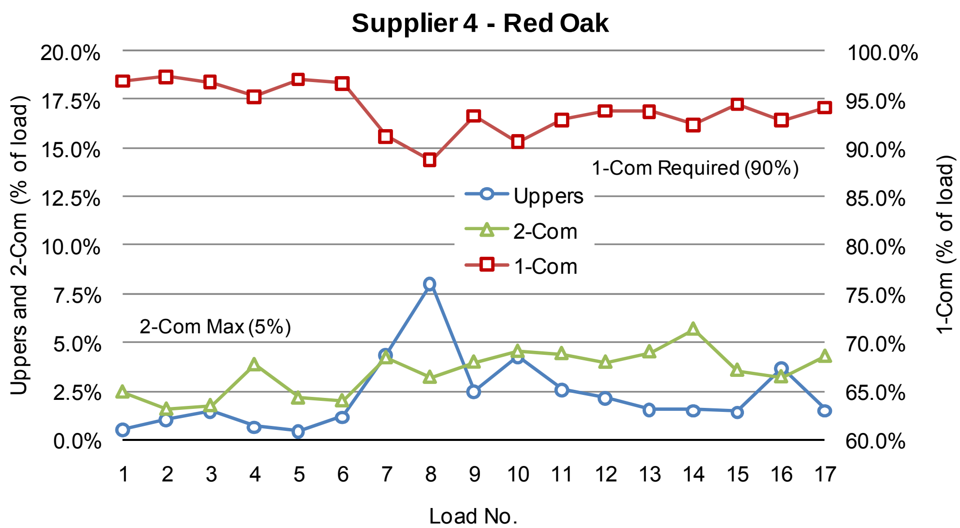


Figure 5-7. Red oak lumber grade mix from Supplier 4

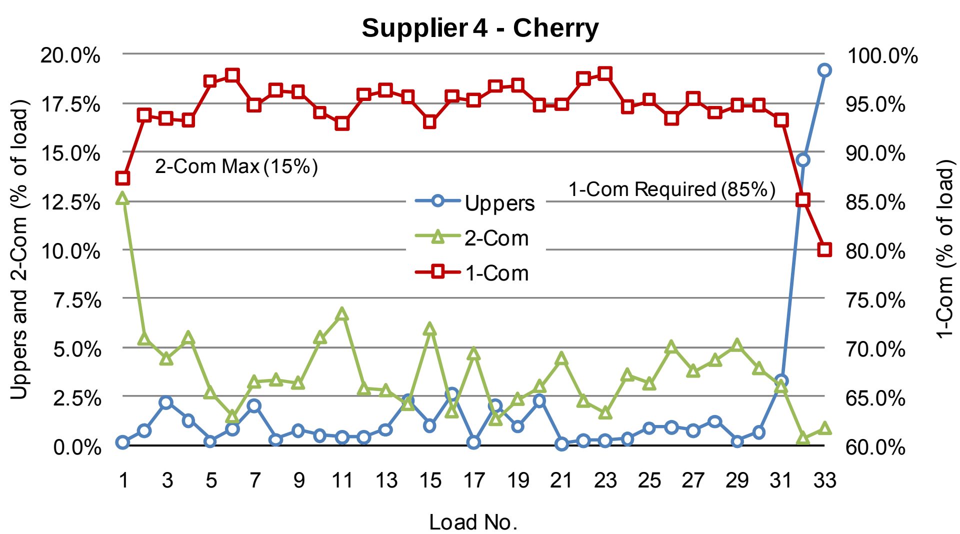


Figure 5-8. Cherry lumber grade mix from Supplier 4

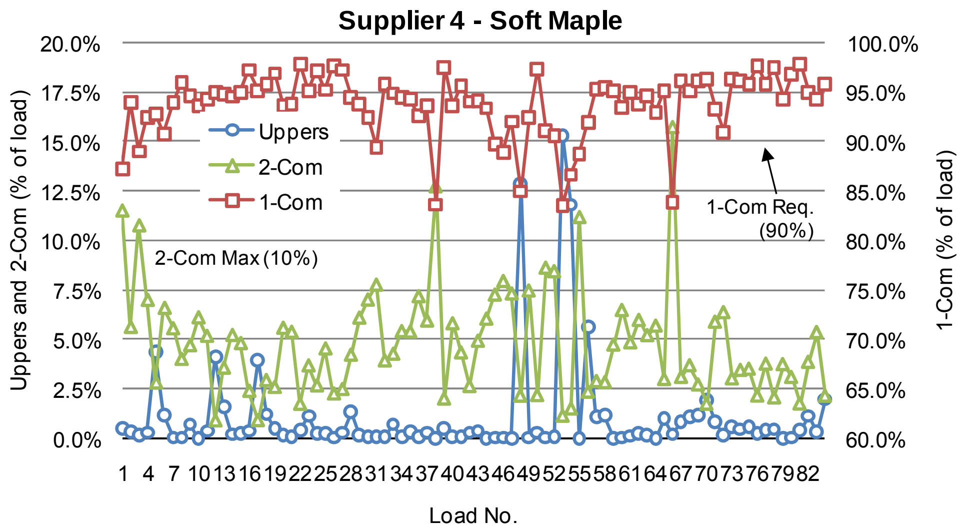


Figure 5-9. Soft maple lumber grade mix from Supplier 4

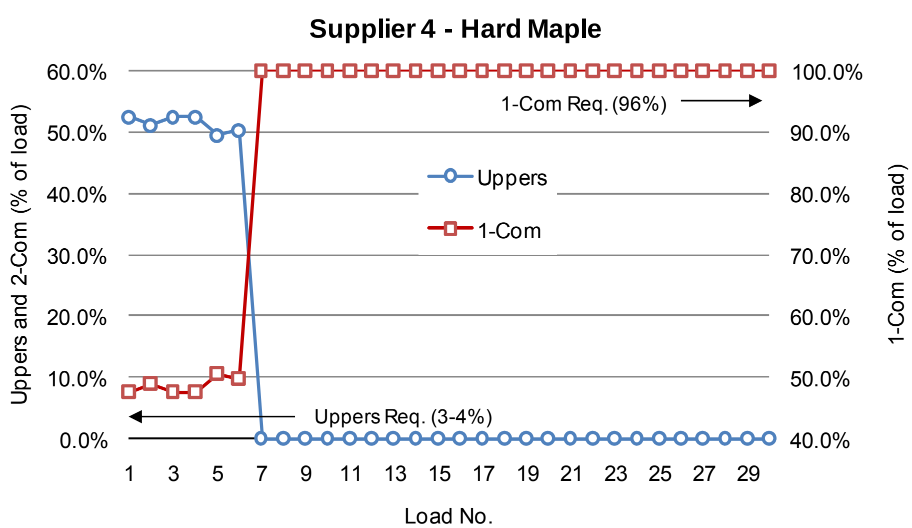


Figure 5-10. Hard maple lumber grade mix from Supplier 4

5.1.4 Supplier Evaluation

At the time of the study, the door plant did not have a formal evaluation or certification program for lumber suppliers. Some factors to consider when designing a supplier evaluation program based on the lumber's volume and grade information are:

- The buyer pays according to its determination of the grade and not on what it is declared in the shipment manifest

- When a truckload seems far from meeting the specified grade mix, the door plant rejects the load in its entirety. This is judged by the lumber inspector, based on what he/she considers to be a significant sample.
- When the amount of a lower grade in a load exceeds the specification in a small amount (a judgment made by the lumber grader after grading a representative part of the load), the shipment is accepted but the amount in excess is simply not counted as part of the load and is recorded as "outs"
- Timely delivery of lumber in most cases is not an issue; only hard maple, which is purchased kiln-dried can potentially disrupt production since the planning horizon for purchases of this species is very short

Thus, in a sense, all lumber loads that are received meet the requirements set by the door plant. However, a close look of the grade mix data can reveal some useful information for evaluation purposes. Figure 5-11 shows the percentage of 2-Common cherry lumber delivered by Suppliers 3 and 4 during the period of study.

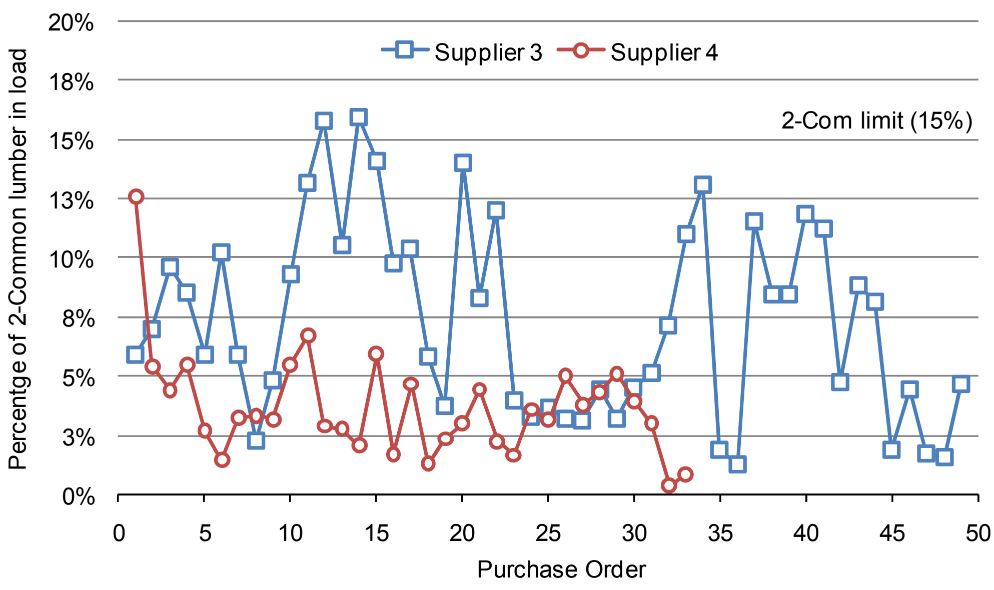


Figure 5-11. Historic percentage of 2-Common lumber from Suppliers 3 and 4

It can be observed in Figure 5-11 that although both suppliers in average performed well below the specified limit for 2-Common lumber, Supplier 3 sent excessive amounts in two instances, and that its deliveries are more variable and in average higher in 2-

Common lumber content than Supplier 4. The same information but in a histogram format is presented in Figure 5-12.

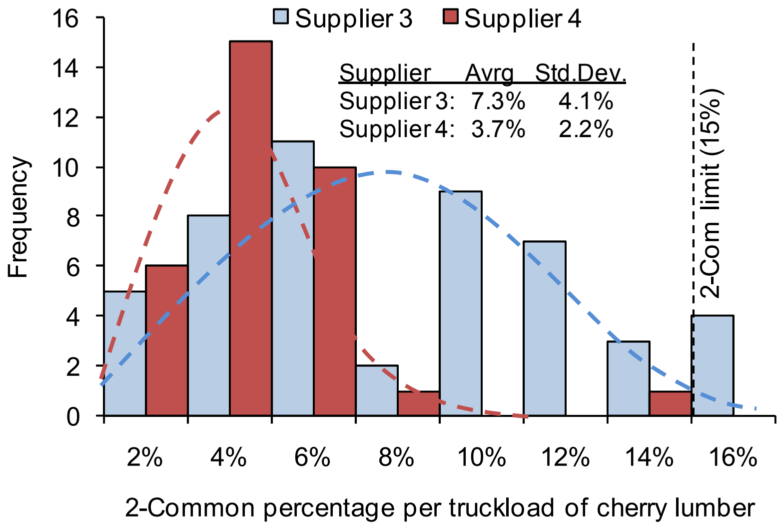


Figure 5-12. Frequency of 2-Common cherry lumber deliveries to the door plant

According to Figure 5-12, both lumber suppliers 3 and 4 comply with the specification for 2-Common cherry lumber (maximum 15 percent), but since lumber is graded at the door plant, the grade mix does not constitute appropriate information to evaluate the capability of individual suppliers. Furthermore, when the amount of, for example, 2-Common lumber considerably exceeds the specifications, the door plant simply rejects the entire truckload, and the information from that shipment is lost. According to the principles of statistical process control, variability is a better indicator of capability of a process than simply meeting a specification limit (Raisinghani, et al., 2005; Young & Winistorfer, 1999). Six-sigma philosophy departs from the traditional definition of quality as “complying with the specifications” to “perform on target and with as little variation as possible” (Gygi, 2005, p. 127).

A potential approach on how the grade mix data could be used to evaluate suppliers’ performance is explained in the remaining of this section. The two data sets shown in Figure 5-12 follow normal distributions; according to a Kolmogorov-Smirnov test of normality (p-value was 0.418 and 0.742 for Supplier 3 and Supplier 4, respectively). With this knowledge, it is possible to estimate the probability of each supplier of missing the 2-Common cherry lumber requirement. Using the normal distribution table of probabilities the following values are obtained:

$$P(x \leq 15\%) = 1 - CDF_{7.3\%,4.1\%}(15\%) = 2.97\%$$ Supplier 3

$$P(x \leq 15\%) = 1 - CDF_{3.7\%,2.2\%}(15\%) = 0.00\%$$ Supplier 4

Another way to evaluate suppliers is to calculate their process capability indexes. The capability index is commonly used in six-sigma improvement programs, and measures how capable a process is to meet a certain specification (Breyfogle, 1999, p. 186); or in other words, it compares the voice of the customer (the specification limits) to the voice of the process (its variability). The larger the capability index, the smaller the probability of the process going out of specifications. According to Chandra (2001, p. 92), the capability index C_P for a process with only upper specification limit (this is the case for 2-Common lumber), is calculated by Equation 5.1:

$$C_P = \frac{USL - \bar{x}}{3\sigma}$$ Equation 5.1

Where USL is the upper specification limit, for 2-Common cherry lumber is 15 percent; and (and σ are the mean and standard deviation of the process, respectively. Replacing the data in Figure 5-12:

$$C_{P3} = \frac{15\% - 7.3\%}{3 \times 4.1\%} = 0.6$$ Supplier 3

$$C_{P4} = \frac{15\% - 3.7\%}{3 \times 2.2\%} = 1.7$$ Supplier 4

In general, it is accepted that if the capability index is greater than 1.33 the process is capable in the short term (Gygi, 2005, p. 146). A six-sigma level process has a capability index of 2.00.

The information presented above is not intended to draw conclusions on a particular supplier, but as an example of how the door plant could use the information readily available to assess supplier performance and give them valuable feedback on process variability, which in turn could help to build better relationships. It is also important to consider specific species when calculating these measures, since the same supplier could perform better at delivering some species than others. Lastly, suppliers that provide hard maple to the door plant could be also evaluated on delivery performance, using a measure such as on-time delivery (see 4.3.3.1).

5.2 Quality Performance at the Door Plant

Data on the performance data for the door plant is presented in this section, starting with internal quality measures, which include (1) results from the in-process audits, (2) first-time-yield data on finishing operations, and lastly (3) results for the final inspection. On external measures, the door plant keeps track of on-time delivery of components to the assembly plants, and results for this metric are presented in the last part of this section.

5.2.1 In-Process Audit Results

Figure 5-13 shows the average defective parts per million (DPPM) for the door-manufacturing process for year of analysis. In general, rough-mill operations (from rip-sawing to rail tenoner operation) had relatively low DPPM compared with finishing operations (from door assembly to door sanding). Among rough-mill operations, the rail and stile inspection has the highest DPPM. At this point, blanks coming out from the cross cutting optimizers are inspected for wood and processing defects, thus this is really an indicator of the detection rate up to this point. Central panels are also inspected at arrival from another plant, but since this is an external supplier, results of this inspection were not included in the analysis.

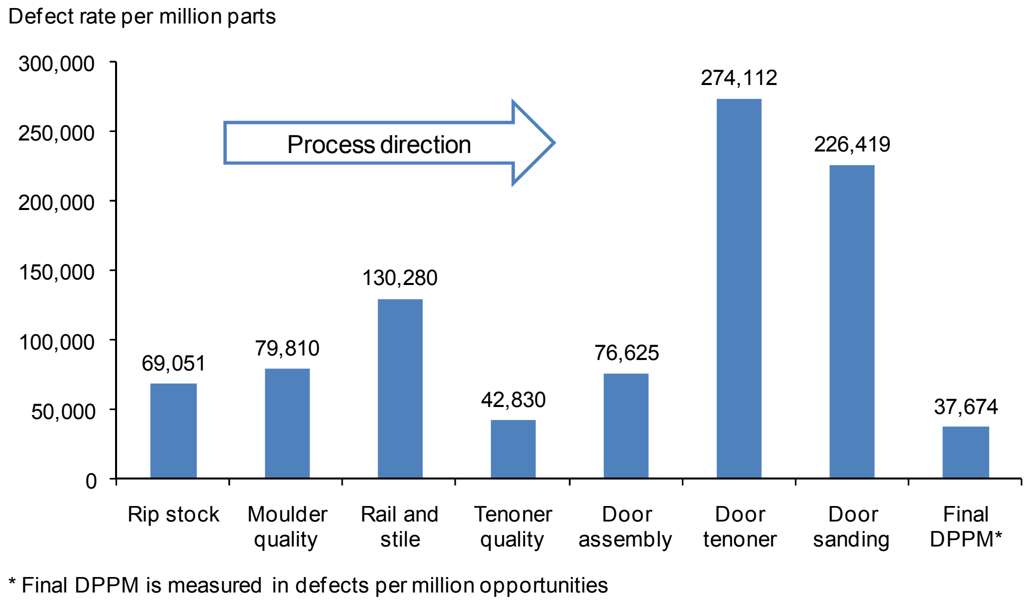


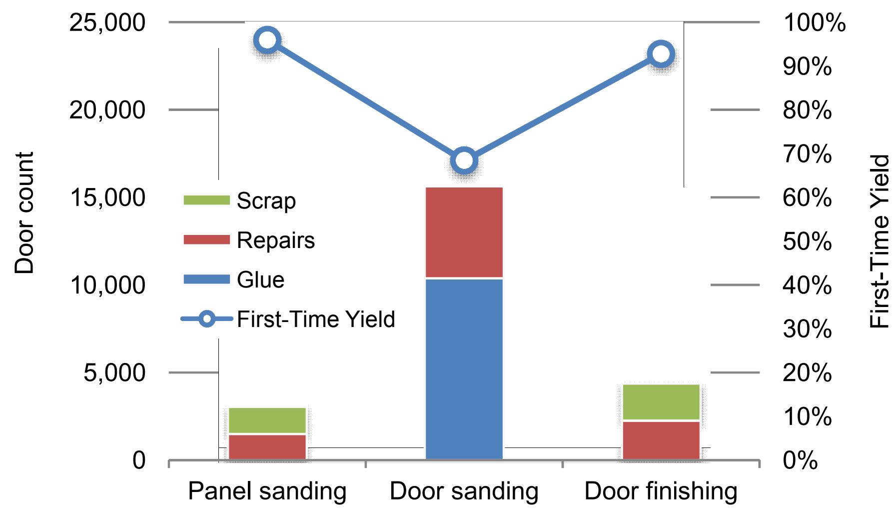
Figure 5-13. Average defect rate for the door plant's processes

5.2.2 First Time Yield (FTY) and Rolled Throughput Yield (RTY)

The finishing department at the door plant comprises a sequence of three operations. In order of execution:

1. Central panel sanding, in two consecutive wide belt abrasive-sanding machines (one for each side of the panel). Panels are inspected and scrapped or repaired as needed.
2. Door sanding, in two consecutive wide belt abrasive-sanding machines (one for each side of the door), with a 100 percent inspection by operators at the exit of each machine. Operators remove excessive glue, repair and touch up as necessary.
3. Finishing in a hang spray line, where successive layers of toner, stain, sealer, and topcoat are applied.

All the rework and discarding done at the inspection stations is recorded and reported using the First-Time Yield measure (see 4.2.6.3). Figure 5-14 shows the results for the first-time yield and rolled throughput yield measures at the finishing department for one month.



Total doors processed *	74,676	73,320	60,400
First-Time Yield	96%	68%	93%
Rolled Throughput Yield		61%	
Z-score		1.5	

Production data changed to protect confidentiality

Figure 5-14. First-time yield and throughput yield at the finishing department

As the previous figure shows, most of the defects are detected and repaired during the door sanding operation; the overall defect rate at the finishing line is about one-fifth of that of the door sanding station; but the number of scrapped doors is three times higher at the finishing process since at this point defective doors are less likely to be repairable. It may appear surprising that, although two of the three operations have yields above 90 percent, the overall yield is only 61 percent, meaning that about 4 out of 10 parts going through this sequence of operations are either reworked or discarded. This is because rolled throughput falls rapidly with the complexity of the process, reflected in the number of operations required to manufacture a product or component. This is illustrated in the Figure 5-15, where the rolled throughput was plotted against the number of operations and for four yield levels. It was assumed that all the operations in the process have the same yield. For example, a process that consists of two operations, both with a first-time yield of 95 percent, the rolled throughput yield is 95x95 = 90 percent, but if the same process has 10 operations, the rolled throughput becomes 95^{10}=60 percent. Thus, very high yield levels should be achieved in each operation in a complex process in order to attain a good overall performance.

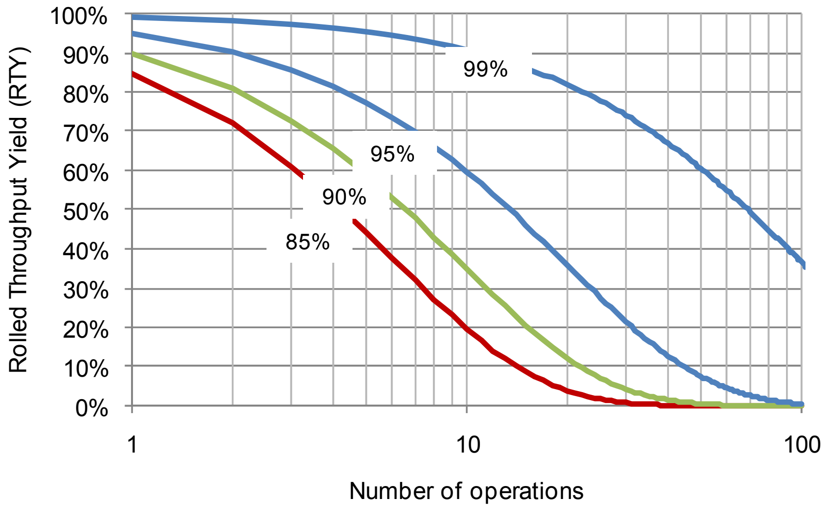


Figure 5-15. Rolled throughput yield vs. process complexity at four levels of individual yields

5.2.3 Defect Rate Per Million at the Final Inspection

Figure 5-16 shows the results of the audits of finished products for the year of analysis, expressed in defects per million opportunities on a weekly and monthly basis. Figure 5-17 is a Pareto chart showing the frequency of each defect category and its cumulative percentage.

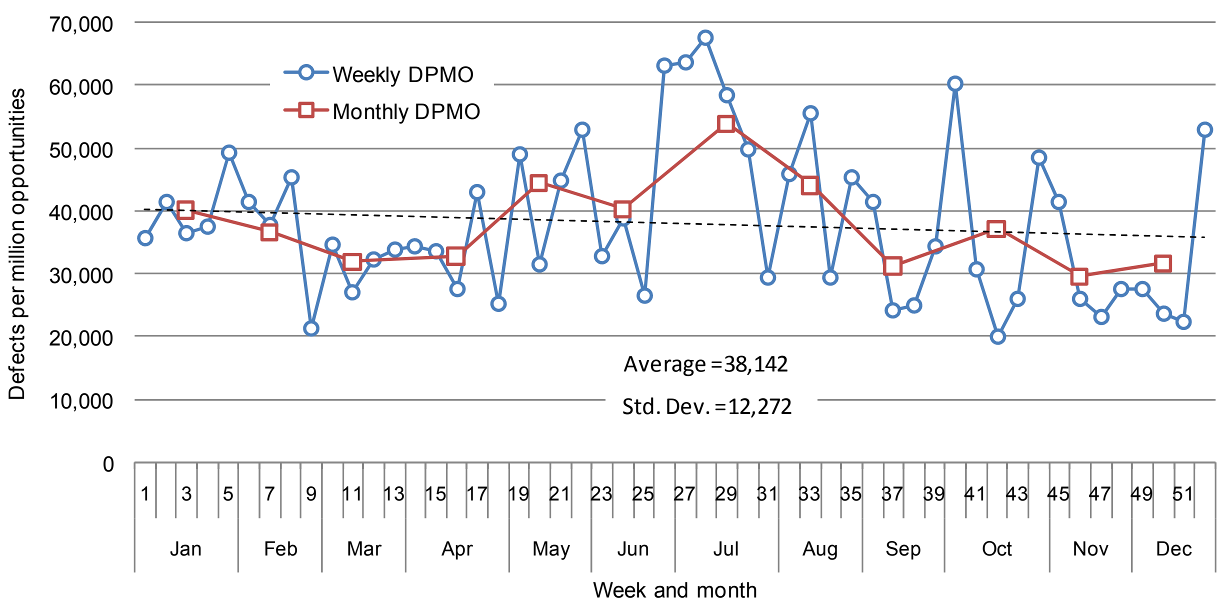


Figure 5-16. Defects per million opportunities at the door plant

The weekly defect rate averages 38,142 with a high variability, as revealed by the standard deviation. There is also a decreasing trend of the average, from approximately 40,000 defective parts per million to 35,000 (see trend line). On a monthly basis, there is a sharp increase in defect rate during July, of about 60 percent above the average.

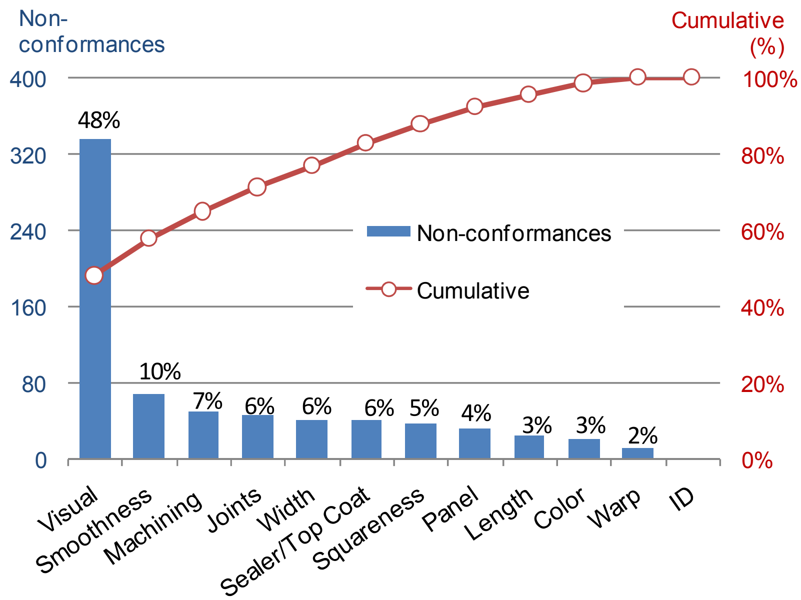


Figure 5-17. Pareto chart of defects at the door plant's final inspection

It is apparent from Figure 5-17 that "visual" defects are the most common, with close to one-half of the total defect ocurrences in the year of analysis. These defects consist of wood characteristics like knots and mineral streak, not detected previously during the manufacturing process. Since different species have different types and frequency of defects, an analysis by species can help to determine if some species are more likely to contain certain defects. With this purpose, the average number of defects per door was calculated for the species processed at the door plant in Figure 5-18, separated by total defects and only for "visual" defects.

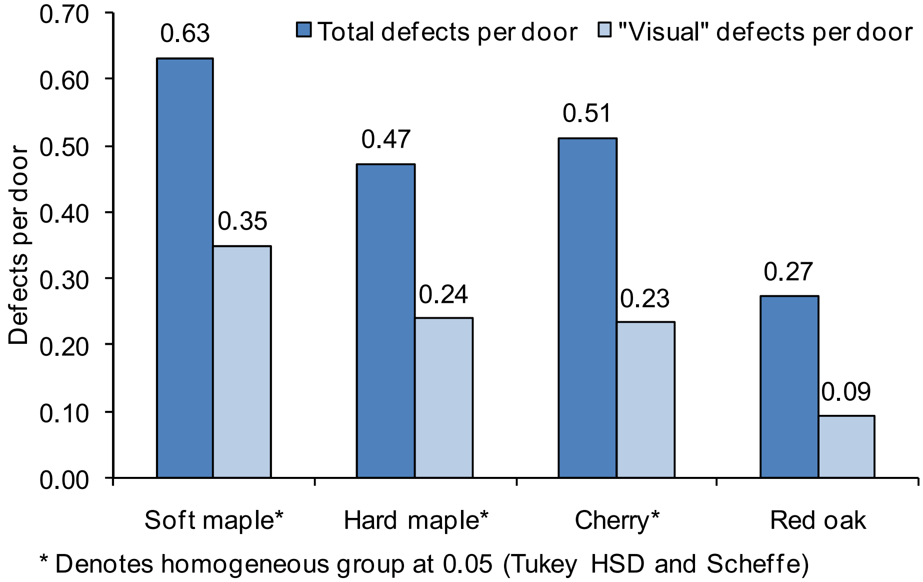


Figure 5-18. Average number of defects per door at the door plant's final inspection

Soft maple has the highest number of defects per door; however, a multiple comparison of means revealed significant differences only between red oak and the other three species. If the species are put in descending order by number of total defects per door, cherry doors are second after soft maple; but if sorted by visual defects, they occupy the third place after hard maple, suggesting that cherry doors should have a relatively high frequency of defects in some other category. This is explored in Figure 5-19, which shows the number of defects per door, for all defect categories and species.

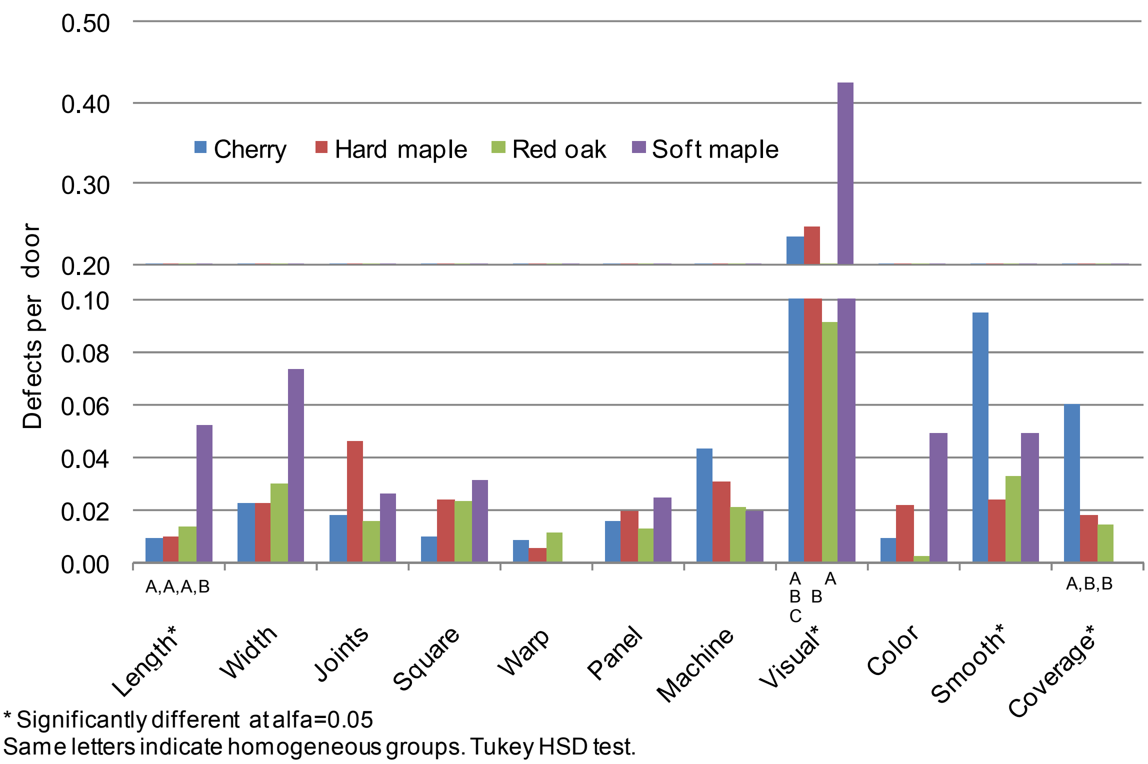


Figure 5-19. Defects per door by species, door plant's final inspection

Soft maple has the highest number of defects per door in six categories; however, significant differences were found only in "length", "visual", "smooth", and "coverage" defects (see Table 4-7). A post-hoc analysis revealed that soft maple had the largest length and visual defects per door, and that cherry had more coverage defects that the other three species. Part of this can be traced back to the type of finishing process that the door plant uses, which applies electrostatic finish to the wood. Electrostatic finishing processes in general apply a uniform coat and produce less volatile organic compounds (VOC) than conventional spraying. However, since it needs an electrically charged work piece, it is sensible to some properties of the substrate, like moisture content (Hiziroglu, 2007). According the interviewee at the door plant, cherry appears to behave differently than other species with this type of finishing technology.

5.2.4 On-Time Delivery to the Assembly Plant

Figure 5-20 shows the weekly on-time delivery performance for the year of analysis (the target value is 100 percent). Production volume has been also plotted in Figure 5-20, to investigate a possible relationship between these two variables. The highest variability occurs during the months from April to August that, when compared with production, suggests a negative correlation between production volume and delivery performance. This and other relationships will be explored in depth in the last section of this chapter.

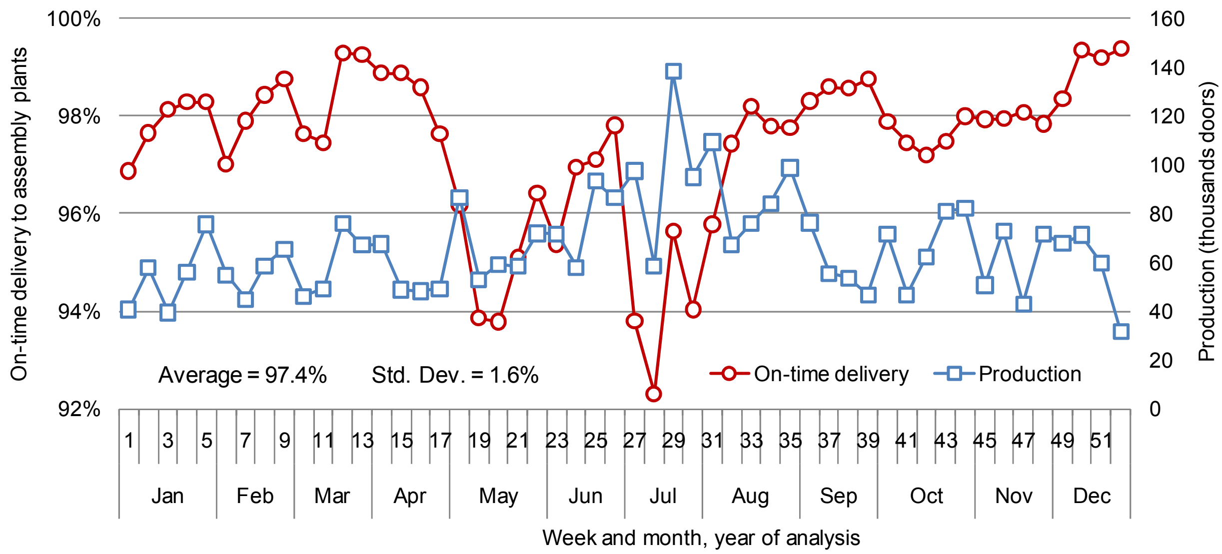


Figure 5-20. On-time delivery from door to assembly plant

The on-time shipping calculation includes all types of orders: stock, made to order, and pick-and-pull. Major causes for not delivering on-time are: very short lead time orders, scrap or quality issues with scheduled quantities not at 90 percent, processing down time, product minimum levels not matching requirements or orders and lot sizes not matching between pallets.

5.2.5 Impact of Current Practices on the Door Plant's Performance

Some of the results the door plant has achieved from current practices of quality control and measurement are are listed below:

- Over $1.3 million in savings from Kaizen (see 4.2.8) events in two years
- $1.6 million savings from DMAIC scrap-reduction projects in four years
- 78 percent reduction in defect rate in eight years through lean manufacturing initiatives. This includes drawer fronts and central panels.

Figure 5-21 shows a comparison of in-process defect rate and defect rate at the final inspection for the same month on a three year period. The final defect rate is measured in defect rate per million opportunities and corresponds to the average of the year. It can be seen that the final defect rate has decreased in 60 percent in three years, or an annualized rate of improvement of 35.6 percent.

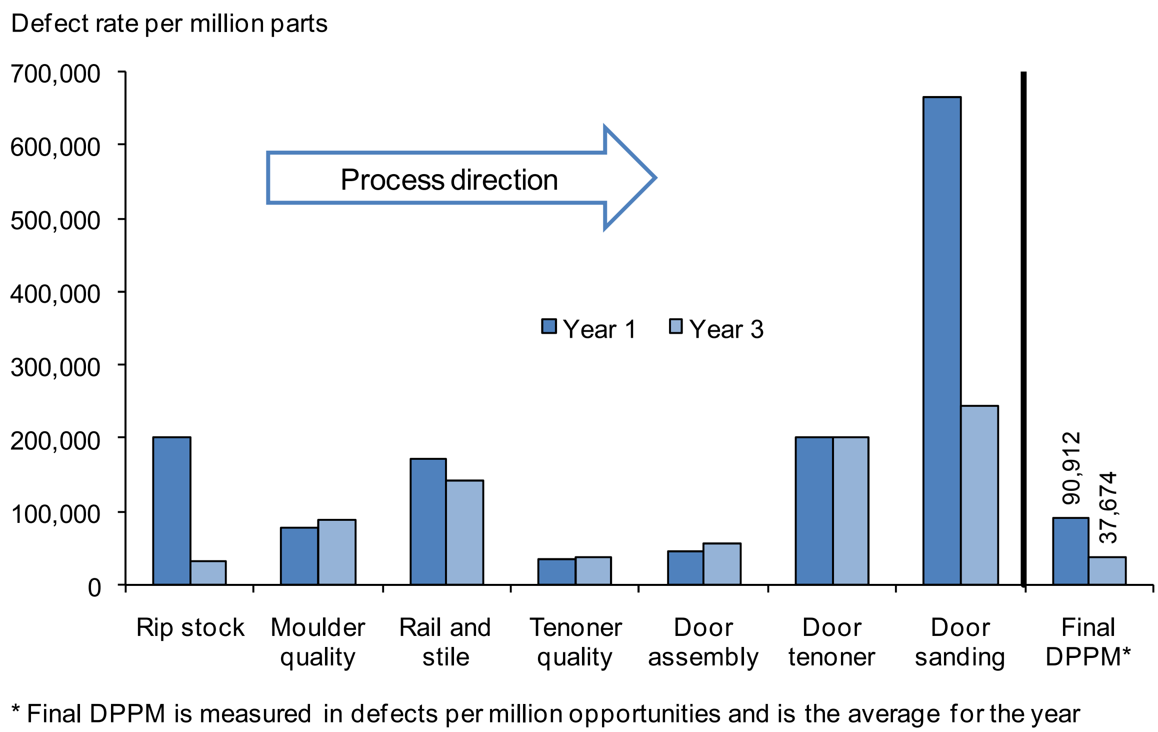


Figure 5-21. Impact of improvement on in-process and final defect rate

5.3 Quality Performance at the Assembly Plant

5.3.1 Defects per Million at the Final Inspection

Figure 5-22 depicts non-conformances per million at the final inspection of the assembly plant for the year of analysis, as well as the planned values. Figure 5-23 is a Pareto chart of the defect categories.

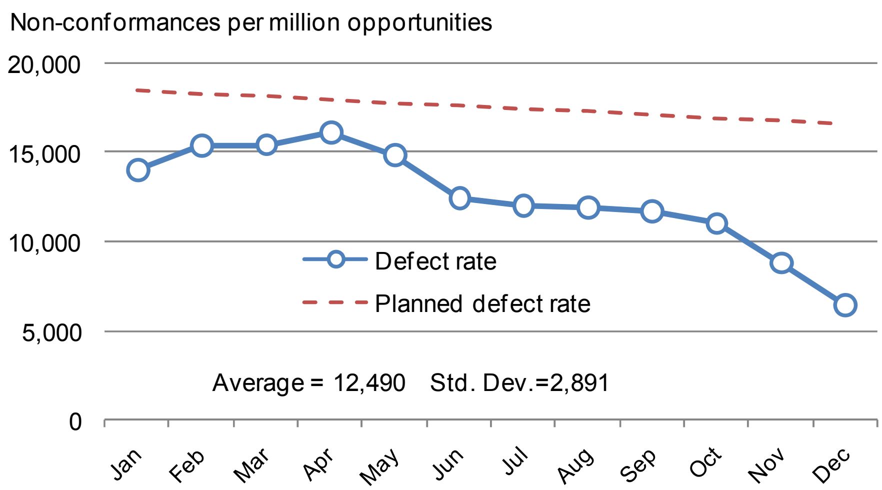


Figure 5-22. Non-conforming parts per million at the assembly plant's final inspection

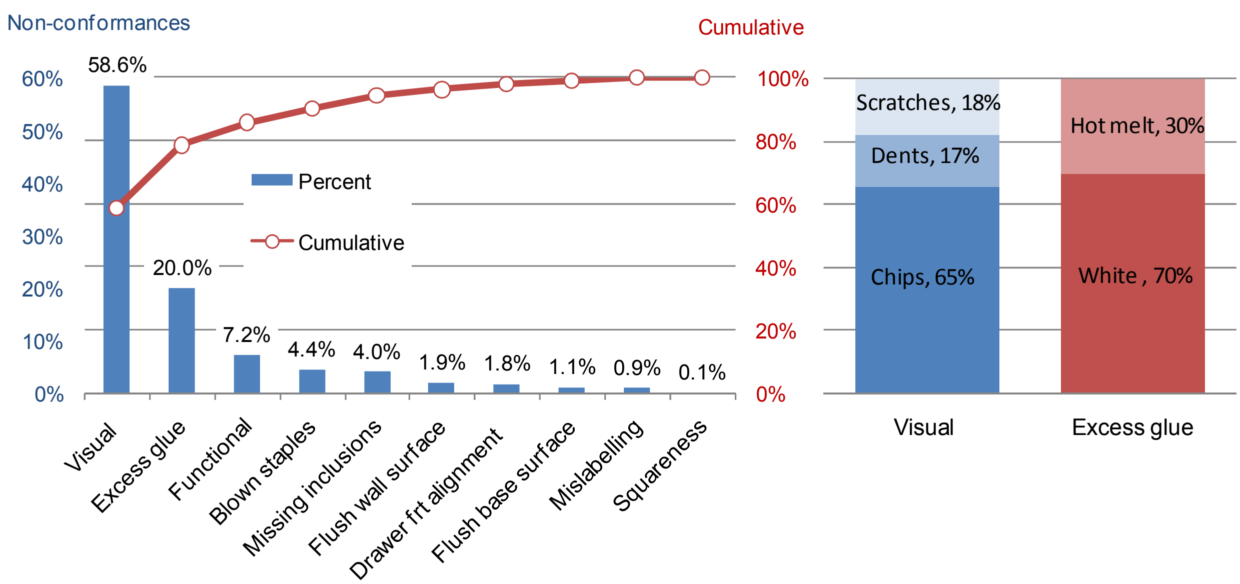


Figure 5-23. Pareto chart of defects at the assembly plant's final inspection, year of analysis

The non-conformances per million opportunities decreased steadily during the period of analysis, a 54 percent fall in twelve months. Some seasonality can be observed, with two humps in April and September-October. The dashed lines in Figure 5-22 represent the target values.

Regarding the frequency of defects, "visual" defects were by far the most frequent, with close to 60 percent of total occurrences, followed by excess glue with twenty percent. Visual defects are caused by handling of components, and are comprised by dents, chip-outs, and scratches. It is estimated that about twelve percent of visual defects are caused during transportation from the source plants, and that another twelve percent get repaired at the assembly cells. Chip-outs are the most common, accounting for about two thirds of total visual defects.

5.3.2 On-Time Complete (OTC) and Eyes-of-the-Customer (EOTC)

The percentage of orders sent on, or before the due date, or on-time complete (OTC), for the period of January to December is shown in Figure 5-24. The plant has performed at an average of 98.9 percent, above the stated target of 98.5 percent. The measure corrected for defects occurring after shipment, EOTC, averaged 94.6 percent for the year, more than two percentage points above the 92 percent-goal.

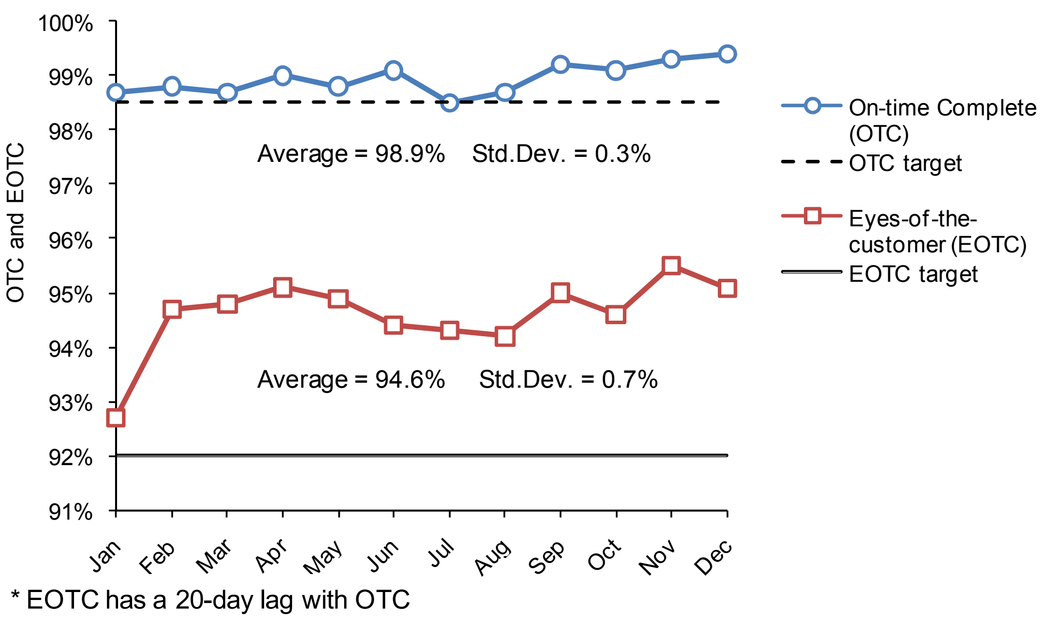


Figure 5-24. On-time complete and eyes-of-the-customer, assembly plant

The service center keeps track of the issues that prevent orders to be shipped on-time and complete (OTC), and separates these issues by cause and product. A Pareto chart of such data is presented in Figure 5-25. Inventory errors were the main cause for OTC defects, followed by issues originated component plants. Cabinet doors were by far the most common cause for OTC defects. Considering the average value for OTC and production volume for the year of analysis, the assembly plant does not send 1.1 percent of its orders on-time or complete, or about 150 orders per month.

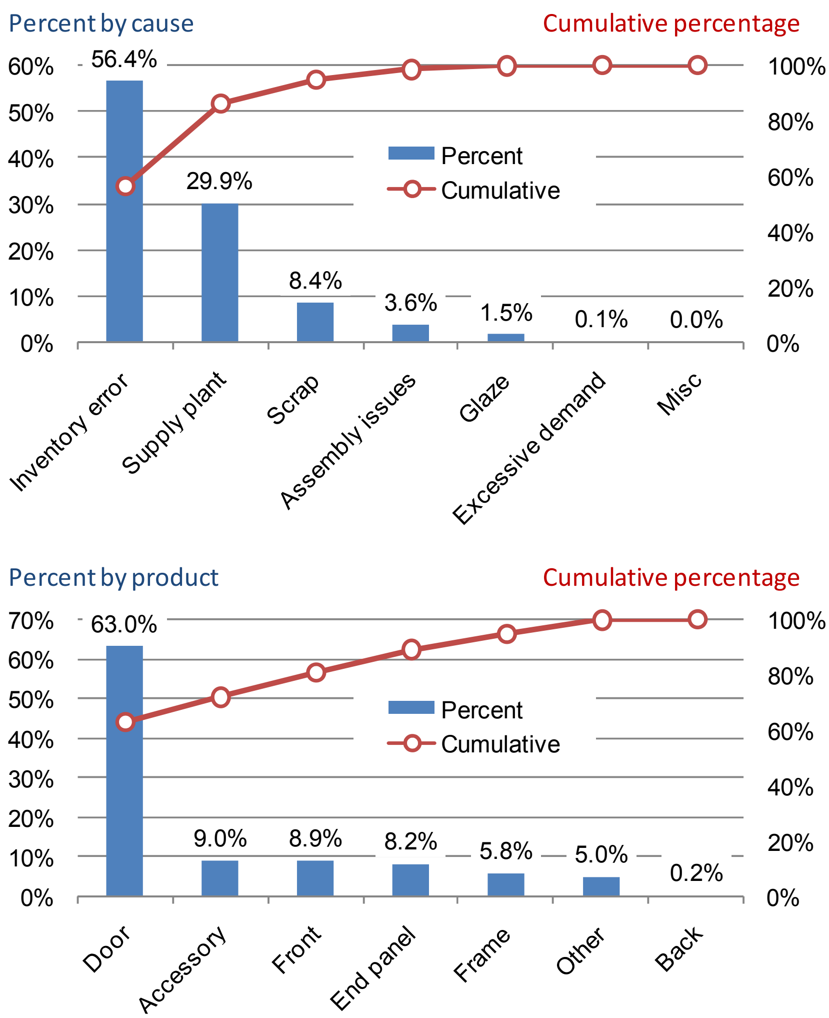


Figure 5-25. Pareto chart for on-time complete issues by cause and product, year of analysis

Once orders are sent from the assembly plant, they are kept "open" for 20 days, and any issues that may come up during this period is considered a defect and taken into account to calculate the eyes-of-the-customer metric, or ETOC. Figure 5-26 is a Pareto chart of defects that occur after products are shipped from the assembly plants. The most common type of defect is related to non-conformances in the product, with 27 percent of total occurrences. Product defects are those not detected during the final inspection at the assembly lines but detected by the customer, who places a claim or rejects the product. Product defects have roughly the same distribution as that shown in

Figure 5-23, being chips, dents and scratches the most common occurrences. Second in frequency are those defects caused by transportation or handling damage after products leave the assembly plant.

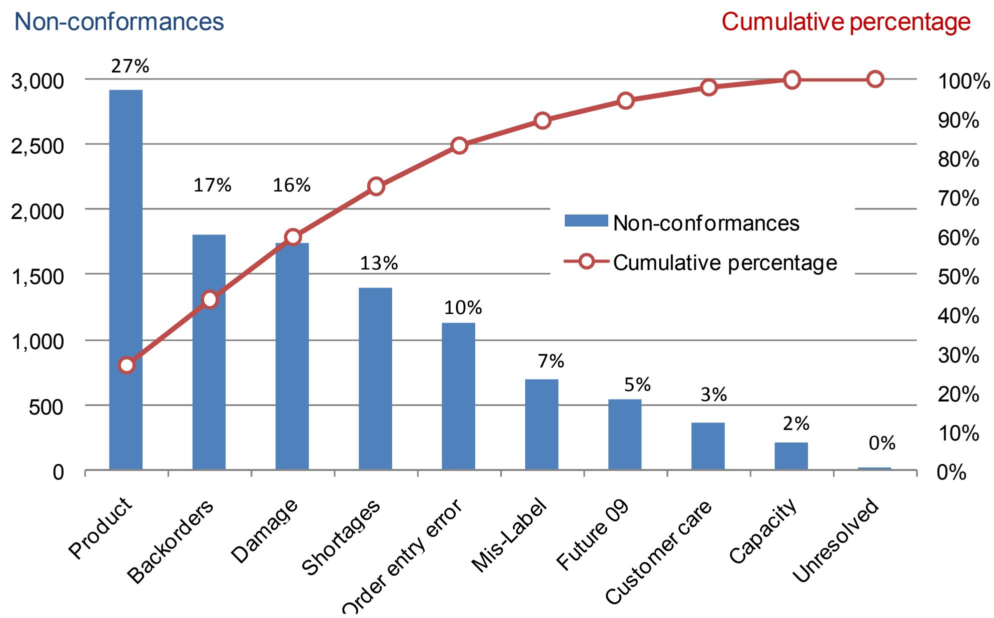


Figure 5-26. Pareto chart for after-shipment quality issues at assembly plant, year of analysis

5.3.3 Impact of Current Practices on the Assembly Plant's Performance

The impact of the current quality management practices on the assembly plant's performance can be appreciated in the scrap and on-time complete figures. Scrap is measured in dollar per product unit ($/unit), and decreased at an annual rate of 11.8 percent. On-time complete improved at an annualized rate of 1.2 percent.

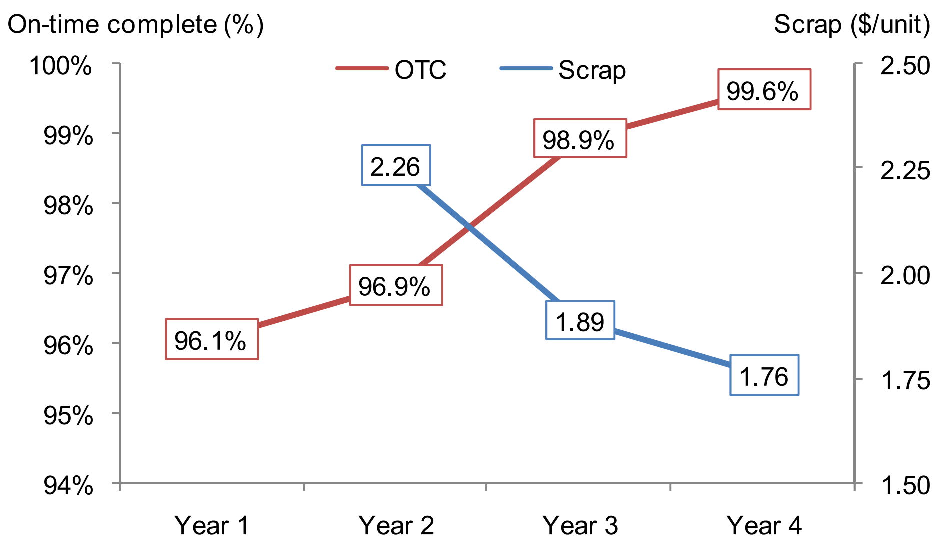


Figure 5-27. Impact of improvement on scrap and on-time shipping

It is evident from Figure 5-27 that the time performance of the assembly plant is entering the phase of diminishing returns. This is consistent with what Harry (2000) stated, that usually 80 percent of the progress towards a six-sigma performance is made in approximately 20 percent of the time over which the final goal is planned to be achieved.

5.4 Quality Performance at the Service Center

The service center keeps track of five performance measures, but perhaps the most important ones are on-time complete and the results of the customer satisfaction survey. The former measures the percentage of orders that are completed without any product or service issue and the second measures directly how does the customer, the construction company that is, feels about the company and the service center; thus, the on-time complete (OTC) at the service center is comparable to the eyes-of-the-customer (EOTC) at the assembly plant. Values of both metrics are presented in this section for the year of analysis.

5.4.1 *On-Time Complete*

As Figure 5-28 shows, the service center performed at an average of 88.4 percent, 1.6 percentage points below the target. A seasonal effect is apparent in the monthly data, although the highest and lowest levels (May and September) do not coincide with those of the door and assembly plant, as could be expected if these cycles would be associated with high demand, and considering the relatively short lead time from order to installation (ten days).

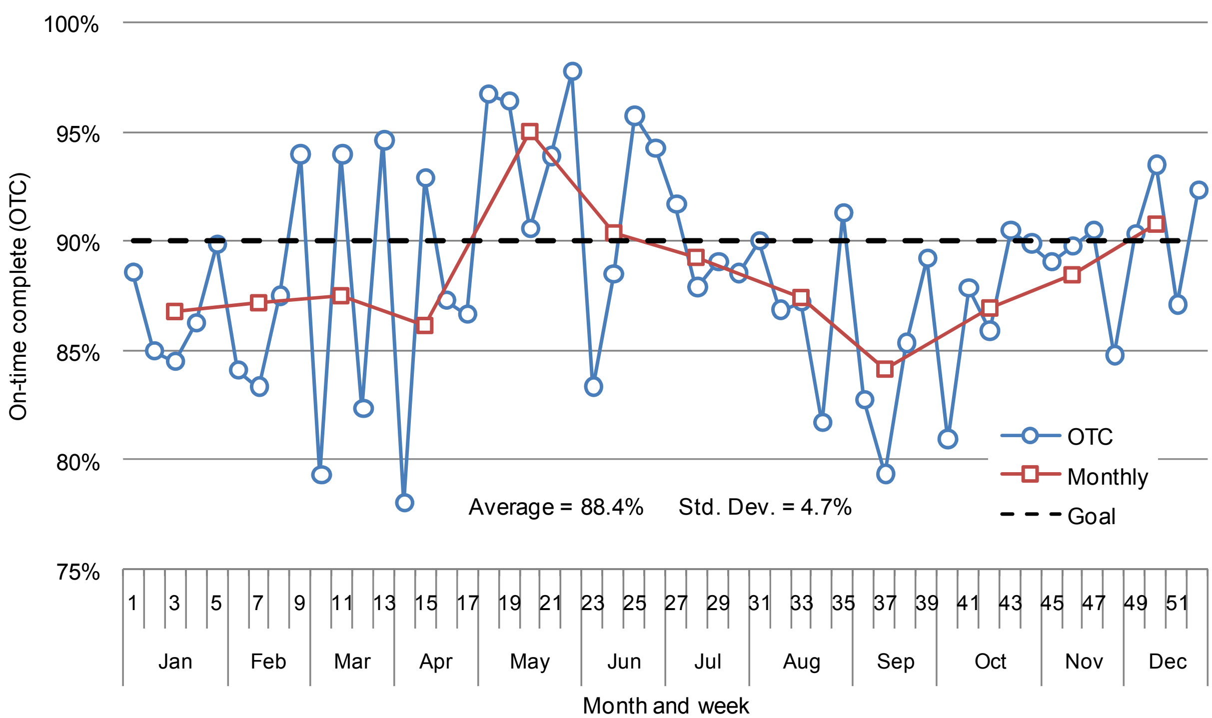


Figure 5-28. On-time complete at the Service Center, year of analysis

A Pareto chart of the causes for variances at the service center level is shown in Figure 5-29. Field representative and custom parts errors make up almost 60 percent of all variances. The former are caused by measuring errors by the service center's representatives and the later due to external suppliers sending the incorrect components and accessories, mostly countertops. The only items that can be unmistakably attributed to the assembly or component plants are “plant errors”, and “plant backorders”, accounting to 11 percent of total variances. According to the interviewee at the service center, when customers claim a product defect, most likely the defect would be related to color or grain variability, both highly associated to the customers' perceptions and tastes.

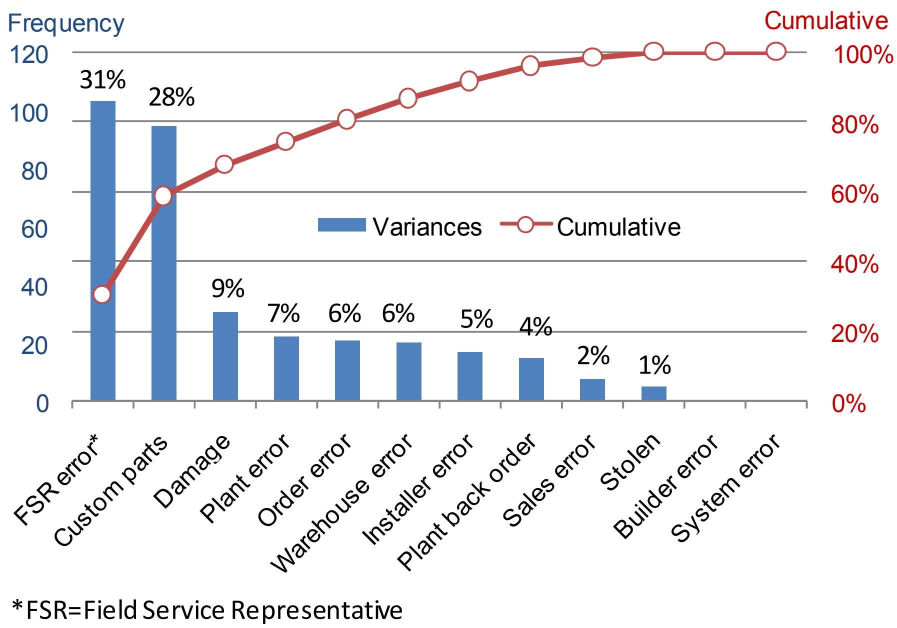


Figure 5-29. Pareto chart of variances at the service center for year of analysis

5.4.2 Quality Issues after Initial Installation

As stated in Section 4.5.2.1, the On-Time Complete measure does not capture those issues that arise after a Field Representative at the service center inspects the installation work at one construction site. Below the most common causes for final customer complaints are discussed.

Color variation is the most frequent cause for final customer complaints. It is important to distinguish if variations happen within doors or between doors. Within-door variation means that some components in the same door have significantly different color. Between-doors color variations mean that there are significant differences in color between doors in the same installed kitchen cabinet. According to the interviewee at the service center, within-door color variations are most common, typically a rail having different color than the central panel. The species with the most color variation issues is cherry. Regarding wood defects, mineral streak is most common in the maples, grain variation in red oak, and pinhole knots in cherry.

5.4.3 Customer Satisfaction Survey

Table 5-2 lists the results of the customer satisfaction survey for one month, conducted by a third party hired by the cabinet Company. A 90 percent goal is targeted for the satisfaction level with both the service center and the Company's products.

Table 5-2. Service center customer satisfaction survey for one month

Question	Average*	Std. Dev.
1. Deliveries are complete and on-time	96.4	7.7
2. Product and service concerns are corrected in a timely fashion	96.9	7.3
3. Delivery dates are confirmed prior to delivery	96.0	10.1
4. The Field Service Representative is available and is helpful in satisfying needs	98.7	5.0
5. Customer service calls are returned in a timely manner	98.2	5.8
6. The Customer Service Representative helps resolve issues	98.1	5.9
7. The company is doing a good job at your project	97.3	6.9
Overall satisfaction with Service Center	97.4	5.1
Would you recommend the company's product and services	100.0	0.0

* Satisfaction level from 1 to 100

** Bars' size reflect relative magnitudes, not absolute values

The first three questions, which are related to time performance of delivery and defect correction, had relatively low values and high variability. Questions 4 to 6 are related to customer care and in these questions the service center was rated consistently high. The overall performance for both the Company and the service center is well above the stated goal of 90 percent. However, it is important to note that this is just a sample for one month (45 surveys) and does not reflect trends over a long period.

5.4.4 Impact of Current Practices on the Service Center's Performance

According to the interviewee at the service center, the On-time complete measure has improved from a yearly average of 72.4 to 88.5 seven years. This represents a 22.3 percent improvement, or an annualized rate of improvement of 3.4 percent.

5.5 Customer Satisfaction Survey

A customer satisfaction survey is conducted periodically by a third party hired by the Company. In the survey, four main functional areas are evaluated with several attributes in each function. In Figure 5-30, results from a past survey were represented in a combined measure of performance and importance (rating), with the purpose of reflecting not only the level of satisfaction of the customer with the company's performance, but also the importance that customers assign to each attribute. Both satisfaction and importance are answered on a 1 to 5 scale.

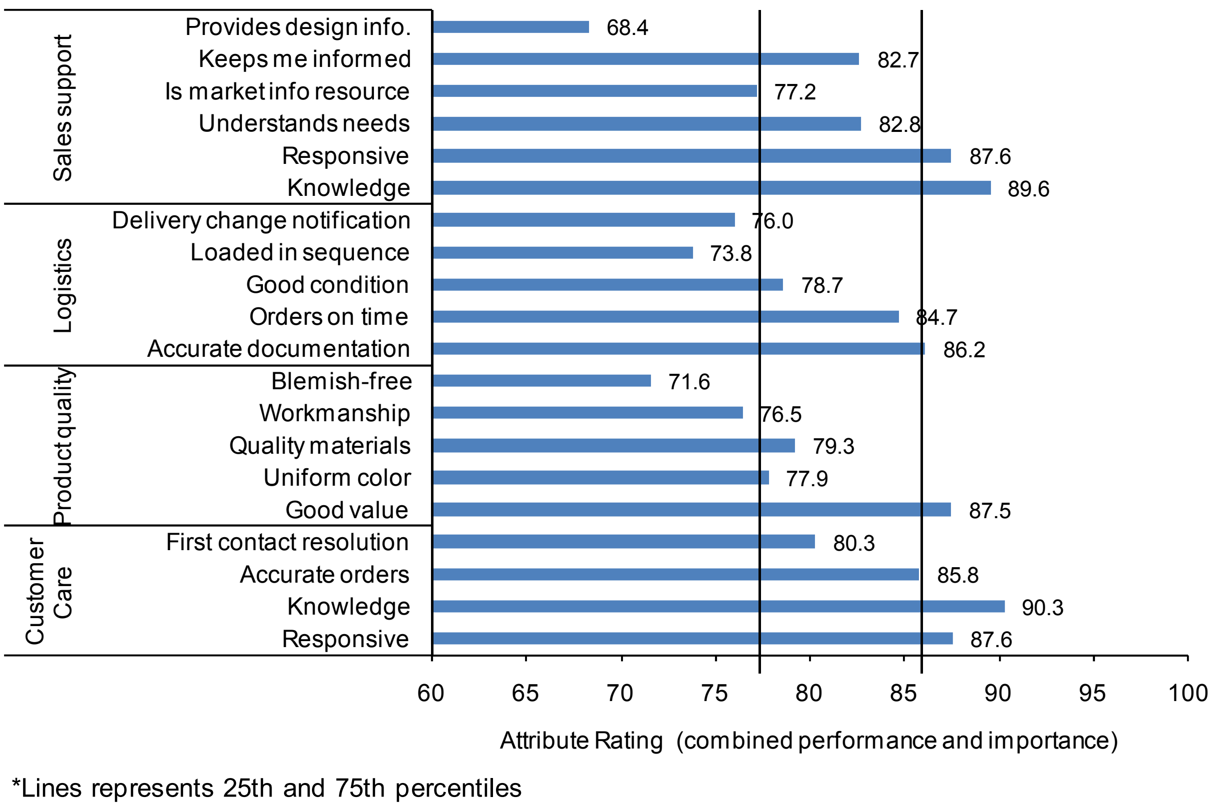


Figure 5-30. Relative difference between attribute importance and performance

A potential criteria to assign priorities to improvement needs, is to look those attributes which performance fell very close of below the 25th percentile. Under such criteria, product quality and logistics were the areas with most need of improvement, since these two functions had the lowest average ratings (78.6 and 79.9, respectively). Regarding individual quality attributes, the following can be regarded as good candidates for improvement initiatives are:

Product quality	• Blemish-free finish • Construction quality and workmanship • Quality of materials • Uniform color
Logistics and transportation	• Loading • Delivery change notification • Good condition
Sales support	• Providing design information • Sales as market information resource

5.6 Supply Chain Quality Performance Relationships

In this section, a discussion of the relationship between quality performance and other variables at different levels in the supply chain is presented. The main purpose of this analysis is to investigate which factors have more influence on the performance level throughout the supply chain. The data used was presented in the previous sections of this chapter. The statistical tools used for the analysis were correlation and regression analysis; ANOVA tables; and post-hoc analysis.

5.6.1 Relationship between Defect Rate and Production Volume

A first inspection to the quality performance data at the different supply-chain entities collected during this study appeared to show a positive correlation between the level of activity and the defect rate. At a constant capacity, raising demand can lead to increased workload pressure on the production system. This is illustrated by the causal-loop diagram in Figure 5-31, where it can be observed that, as production backlog increases, the pressure of workload increases, and quality decreases, which in turn increases the amount of rework, thus increasing the backlog.

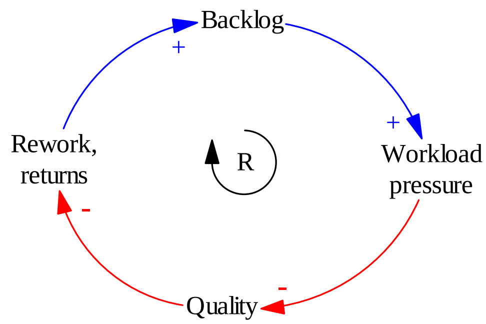


Figure 5-31. Demand and workload pressure

Furthermore, it is fairly well documented that workload pressure can lead to more errors and as a result lower quality performance. Akkermans (2007), for example, lists the following insights in relation to workload pressure and performance (Akkermans, 2007):

- *Increasing workload leads to more errors*. This issue can be related to the Yerkes-Dodson law of psychology, which states that as the level of arousal (workload pressure) increases, the response (performance) first increases up to an "optimal level of response and learning" (Teigen, 1994), but beyond this optimal point performance starts to fall.
- *Higher schedule pressure leads to more errors*. Oliva and Sterman studied the erosion of service quality and concluded that this erosion occurs in part because a tendency of workers to lower service standard when work pressure is high. A typical response in customer service, for example, is to reduce the time spent on each customer order in order to meet throughput goals (Oliva & Sterman, 2001).
- *Workload pressure reduces detection rates*. There are two main reasons for this happening: The first is that as workload pressure increases, workers fail to notice errors at the same rate as they would do under normal circumstances. This can be explained by the Yerkes-Dodson law. The second reason is that pressure to meet schedules may cause people to purposefully conceal problems from managers and team members (Ford & Sterman, 2003).
- *Error prevention is less rewarding than error solving.* People have a propensity to prioritize short run benefits to long-term ones; and allocate more resources to "fire fighting" (Repenning, 2001). Moreover, it has been demonstrated that doing things in

such fashion is naturally very difficult to overcome, and it is possible to get stuck in a "fire sighting" mode.

- *Errors and workloads cascade down in multi-stage processes*. This is an important issue in the context of the present study. Problems at early stages of a supply chain, lead to problems that are more costly to solve that would otherwise have been if solved at earlier stages (Repenning, 2001).

For all the above mentioned reasons, it is reasonable to expect a higher occurrence of defects when workload pressure is high. A partial look at two reinforcing loops in Akkermans' model (Akkermans, 2007), shown in Figure 5-32, provides an easy to understand explanation of why and how this happens. As schedule pressure increases, personnel tend to make more errors and also fail to detect some defects, which lead to a lower quality performance. As quality lowers, the usable acceptable output also decreases, which further increases schedule pressure. Lower quality also means that more rework is necessary, which increases the workload; and as the workload increases, quality further decreases. Two balancing loops (not shown) counter these reinforcing loops: a usual response to higher workload is that managers increase capacity (by for example, working overtime). Increased capacity reduces the schedule pressure. In a second balancing loop, as personnel solve problems (rework), their expertise increases, leading to an increase in quality performance.

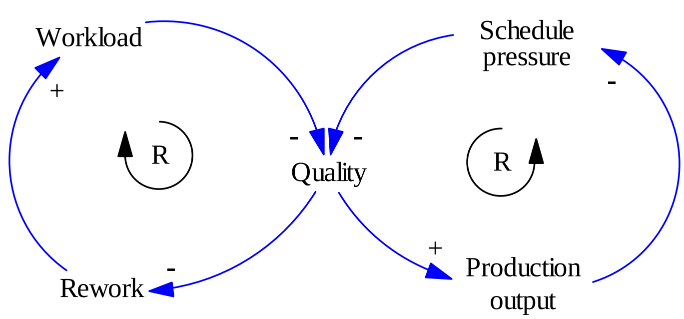


Figure 5-32. Partial look of main feedback loops model of production ramp-ups

In order to analyze the influence of workload quantity, overall quality performance and production volumes were analyzed at each step of the supply chain. Figure 5-33, Figure 5-34, and Figure 5-35 show the main quality indicators and the production volumes at the door plant, the assembly plant, and the service center, respectively. Additionally, Figure 5-36 shows the relationship between the production volume at the door plant and the backorder rate recorded at the assembly plant, showing a high correlation. Simple linear regression analysis results are also shown, a p-value lower than 0.05 means that the linear regression between the two variables is significant. Table 5-3 shows a summary of the analysis, broken down by defect category at each stage of the supply chain.

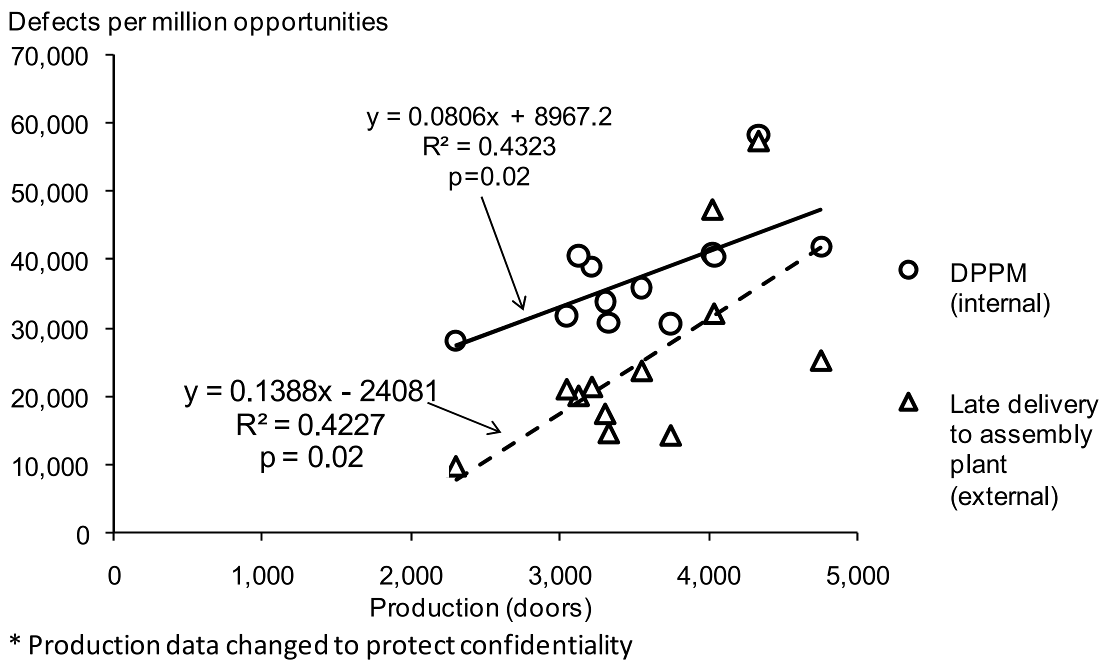


Figure 5-33. Relationship between final defect rate and production volume at the door plant

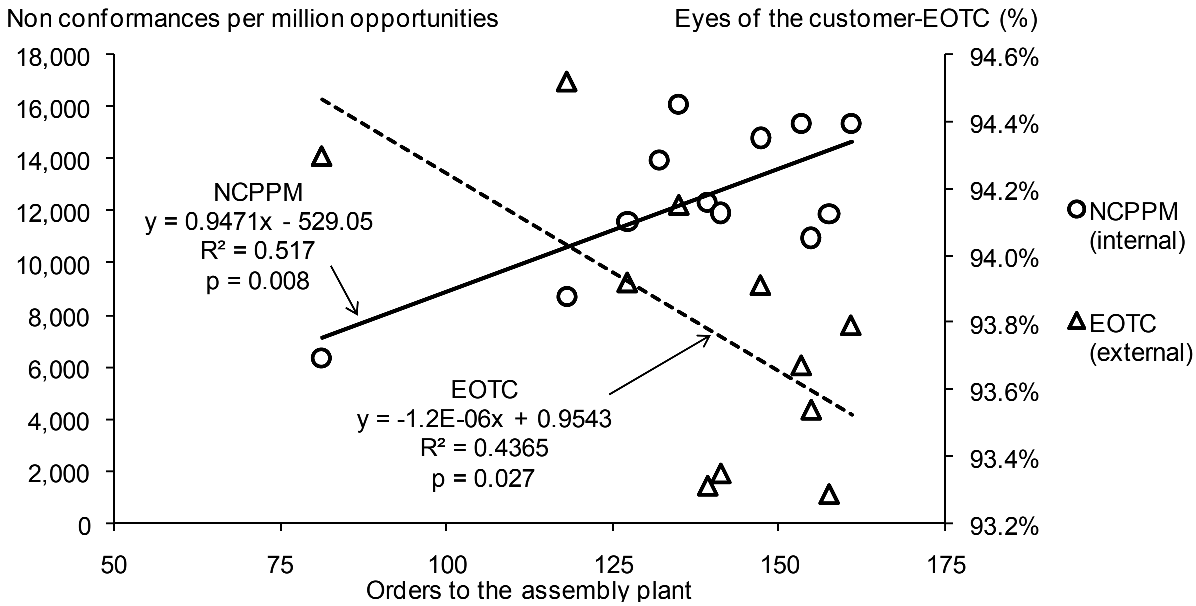


Figure 5-34. Relationship between external and internal defect rates and production volume at the assembly plant

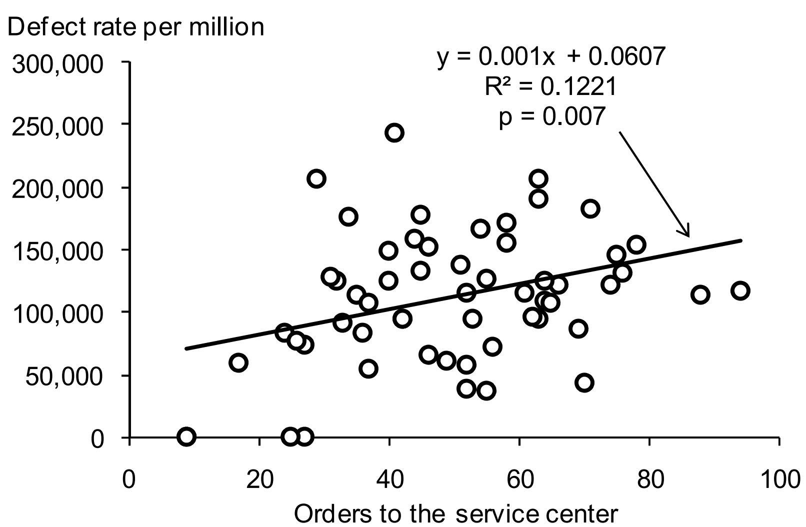


Figure 5-35. Relationship between defect rate and orders at the service center

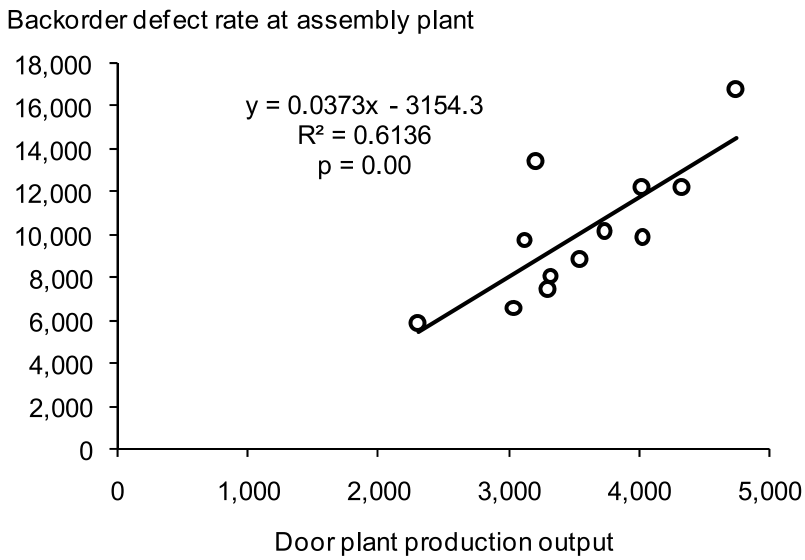


Figure 5-36. Relationship between assembly plant's backorder rate and door production

From Figure 5-33, Figure 5-34, Figure 5-35, Figure 5-36, and Table 5-3, it can be observed that, throughout the supply chain, production volume has a significant impact on defect rate. The root causes for this were discussed at the beginning of this section (5.6.1) and can be summarized as (1) increased workload leading to more errors, (2) lowering of standards when schedule pressure is high, (3) detection rates reduced as a result of workload pressure, and (4) a tendency to "firefighting" instead of preventing. The correlation between defect rate and production can be analyzed in light of the defect categories that are inspected at each stage of the supply chain. Table 5-3 lists the major defect types at each point in the supply chain, the cumulative percentage, and regression analysis results for each category.

Table 5-3. Summary of effect of production volume on defect rate

Door plant										
In-process (internal)			Final inspection (internal)				Lead time performance (external)			
Defect type	F	r[1]	Defect type	F	r	%[2]	Defect type	F	r	%
Door sanding	✖	0.58	Visual		0.33	48	Late delivery to assembly plant[3]	✖	0.52	100
Pick line		0.42	Smoothness	✖	0.61	58				
Door assembly		0.05	Machining		0.51	65				
Door tenoner		0.34	Joints		0.40	71				
Moulder		0.01	Width		0.17	77				
Rail tenoner		0.42	Sealer/top coat		0.01	83				
Rip stock		0.23	Squareness		0.28	88				
			Panel		0.51	92				
Panel sanding		0.24	Length		0.18	95				
Door finishing		0.05	Color		0.04	98				
			Warp		0.10	100				
			Total (DPPM)	✖	0.66		Late delivery	✖	0.52	100

Assembly plant							
Final inspection (internal)				After shipment (external)			
Defect type	F	r	%	Defect type	F	r	%
Visual	✖	0.71	59	Non-conform. prod.		0.44	27
Excess glue		0.08	79	Backorders	✖	0.67	44
Functional		0.41	86	Damage		0.58	60
Blown staples		0.35	90	Shortages		0.50	73
Missing inclusions		0.00	94	Order entry		0.13	83
Flush wall surface		-0.31	96	Mislabeling		0.05	90
Drwr.front alignmt.		0.03	98	Future 09		0.23	95
Flush base surface		-0.06	99	Customer care		0.22	98
Mislabeling		0.09	100	Capacity		0.04	100
Squareness		-0.06	100	Unresolved		0.04	100
Total (NCPPM)	✖	0.72		Total (EOTC)	✖	0.66	

Service center			
Overall performance (external)			
Defect type	F	r	%
FSR error		0.02	31
Custom parts err.	✖	0.28	59
Damage		0.10	68
Plant error		0.00	75
Order error	✖	0.26	81
Warehouse error		0.03	87
Installer error		0.24	92
Plant back order		0.17	97
Sales error		0.18	99
Stolen		0.09	100
Total (OTC)	✖	0.35	

✖ Slope different than zero at 0.05. From linear regression ANOVA test (Reject H_0: slope $\beta_1 = 0$)

[1] Correlation coefficient between defect rate and production volume

[2] Cumulative percentage of defects

[3] Using an exponential model

Among the door-manufacturing processes audited, only the defect rate at the door sanding operation was significantly influenced by production volume, suggesting that there is enough capacity in most operations to sustain current production volumes without significant increases in defect rates. Results at the door plant's final inspection, however, show a significant regression between defect rate (DPPM) and door production volume, and "smoothness" was the only individual attribute with a significant linear regression, thus suggesting that the finishing operations are the most affected by production volume, (smoothness defects are mostly caused by poorly executed finishing operations). Also at the door plant, on-time delivery to the assembly plants is significantly influenced by production at 0.05.

At the assembly plant level, variations of the main internal quality indicator, non-conformant parts per million, can be in great part explained by production volume, and not surprisingly, visual-type defects had, among all issues inspected at the end of the assembly cells, a strong linear relationship with production quantity. This can be understood considering the nature of visual defects, which consist of dents, chip-outs, and scratches, which can increase significantly when the speed of production also increases. Among the components of the main external quality indicator (eyes-of-the-customer, or EOTC), only backorders had a significant result for the regression ANOVA, as did the parent metric. At the service center level, the main performance measure, on-time complete, is affected significantly by the level of activity, represented by number of orders. Also, the rate of backorders at the assembly plant and the production volume at the door plant show a remarkably high correlation (Figure 5-36), consistent with what is shown in Figure 5-25, that close to two thirds of the OTD variations are caused by doors.

Further analysis of the nature of the defects being evaluated can help to increase the understanding of the relationship between defect rate and production. For example, the most common defects detected at the door plant's final inspection are "visual" defects, which consist in unacceptable wood characteristics. Visual defects accounted for almost half of total defects but have a relatively low correlation (0.29) with production volume, which could be expected considering that wood defects would be most probably be correlated with the quality of the lumber than with production volume. Similarly, of the two most important sources of errors at the service center, "field service representative" and "custom parts", only the latter has a significant association with the number of orders received. Field service representative variances consist mostly of measurement errors when surveying the construction site, which are not very likely influenced by the level of activity at the service center. At the assembly plant level, the defect category with the highest correlation coefficient is “backorders” (0.60), which occurs when a part required to complete an order is not available at the time of shipment and has to be back-ordered. Backorders result in part from the nature of the inventory planning (e.g., a large order is placed for an item with low usage, for which very little inventory is kept), and also as a result of surges in demand that might slow down the supply chain’s reaction time.

In summary, it was observed that the correlation between defect rate and production volume is consistently significant throughout the supply chain. Production volume significantly influences only the defect rate of the final product at the door plant and the sanding operation. The Company targets 85 percent capacity utilization and this might give the supply chain flexibility to accommodate changes in demand. At the assembly plant level, for example, capacity issues make up only two percent of the total variances facing its immediate customers. Backorders, also related to production volume, are 17 percent of total external defects at the assembly plant and five percent at the service center level.

The Company works under lean manufacturing principles, and such a system promotes volume flexibility mainly by (1) producing in very small batches and to demand (ideally, a product unit at a time), which prevents tying up capacity and materials in products that might not be needed; (2) using U-shaped cellular setups that can easily increase throughput by adding cross-trained operators; (3) designing the production system in a way that prevents defects to occur, thus increasing availability and efficiency; (4) using rapid machine setup, which can dramatically decrease lead time, especially when producing small batches (Kocakülâh, Brown, & Thomson, 2008).

5.6.2 Defect rate and Quality of Inputs

In this section, the correlation between the quality of external inputs and the quality of the final product at each entity in the supply chain is analyzed. The approach followed was to analyze historical quality performance data of the relevant inputs and outputs.

5.6.2.1 Door Plant

Of the eleven defect categories inspected at the end of the door manufacturing process, listed in Table 5-3, the ones that can be more clearly related to quality of an external supplier are central panel defects and visual defects. Visual defects consist mostly of wood defects (e.g., excessive mineral streak or knots) not detected at the pick line inspection (the pick line is the last process at the rough mill, section 3.8.2). A suitable indicator of the presence of wood defects entering the process is the percentage of 2-Common-lumber being processed at the door plant, as lower grades contain more defects per board foot than higher grades. To illustrate this, Figure 5-37 shows the results of a study conducted on red oak, in which 2,000 red oak boards were examined for defects (Harding, Steele, & Nordin, 1993). For example, 2-Common red oak-lumber has 75 percent more knots and 63 percent more bark pockets than the immediate higher grade lumber, 1-Common. As is the case for most kitchen cabinet manufacturers, 2-Common is the lowest grade allowed in their lumber purchases (Smith, Pohle, Araman, & Cumbo, 2004), and is included in the grade mix in order to balance raw material costs (2-Common lumber is about 20 to 50 percent cheaper than 1-Common lumber) and rough-mill yield, as there is about 10 percent yield difference between 1- and 2-Common red oak lumber (Gatchell & Thomas, 1997).

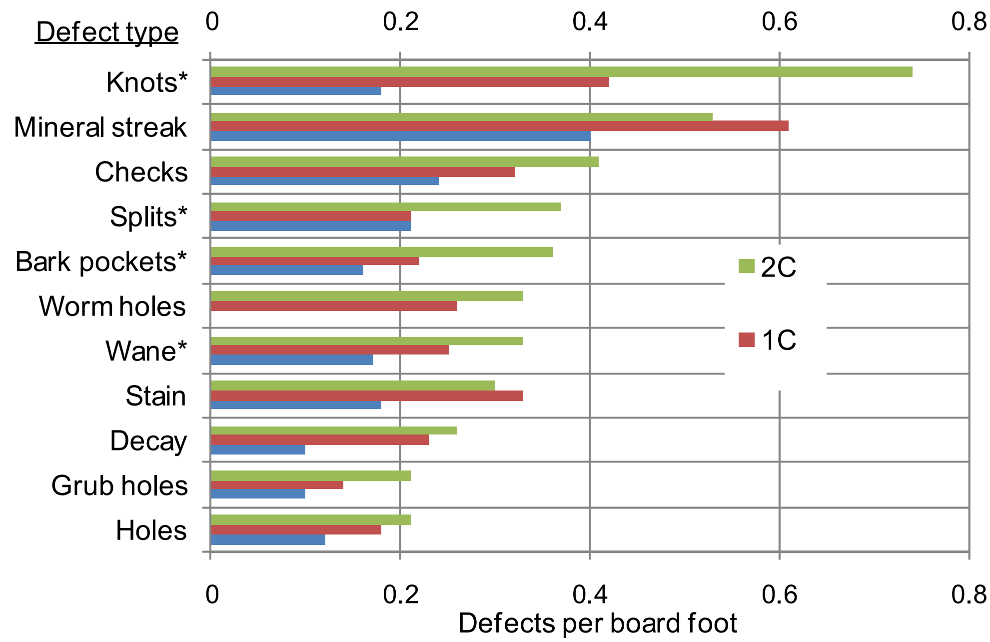
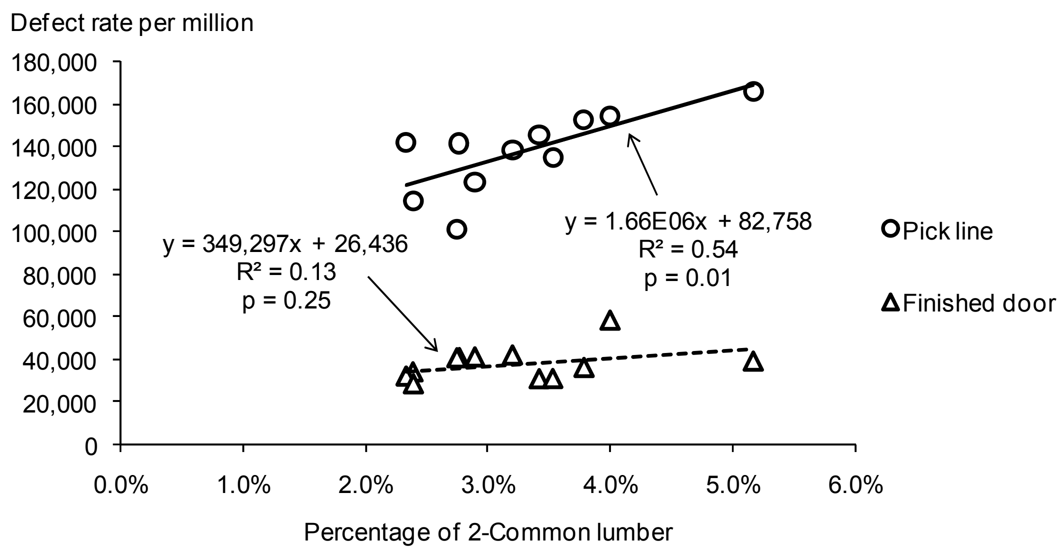


Figure 5-37. Number of defects per board foot for three lumber grades

The pick-line is an intermediate operation in the door manufacturing process, where stile and rail blanks coming out from a crosscut saw are sorted out and inspected for wood and processing defects (see Figure 3-5). Most wood defects should be filtered out at this inspection. Figure 5-38 shows the defect rate at the pick line and at the final inspection, and the amount of 2-Common lumber in percentage used. The defect rate at the pick line is determined by sampling a set of rails and stiles that have been already inspected; thus, this is also a measure of the detection rate at this point. If the inspection after the rough mill performs at a high detection rate, it would be expected that the amount of 2-Common lumber account for very little of the variation in the finished product quality. Furthermore, there are several other inspections after the rough mill (at the door tenoner, the sanding, polishing, and immediately after the finishing process), and each filters out wood defects. In fact, as Figure 5-38 shows, a low correlation between the percentage of 2-Common lumber and defect rate at the final inspection, and a slope not significantly different from zero at 0.05. This is different for the defect rate at the pick line, however, where the regression is significant at 0.05, meaning that the amount of 2-Common lumber coming into the rough mill significantly influences the defect rate at the pick line. The regression equation suggests that, at a constant detection rate, for every percentage point of 2-Common lumber added to the grade mix, there will be about 16,600 more defects per million, which at the rate of production during the year of analysis translate in 23,500 undetected defective pieces stiles and rails with some sort of defect per month.



* Pick line defect rate measured in defects per million parts and defecet rate at final inspection measured in defects per million opportunitiesDefect rate

Figure 5-38. Relationship between defect rate and percent of 2-Common lumber at the door plant

The positive linear correlation between the defect rate and the percentage of 2-Common lumber entering the system can be better understood if a constant detection rate is assumed, since larger amounts of 2-Common lumber would contain more defects per board foot, and defects that go undetected would grow proportionally.

Some interaction between the detection rate, the production volume and the amount of 2-Common lumber is also possible. Given a cutting bill, more cuts are required to process lower lumber grades in a rough mill. In one simulation study, for example, for a moderately difficult cutting bill and a straight line rip-saw setup, 61 percent more cuts were required to process 2-Common lumber compared to the time required for 1-Common lumber (Steele, 1999). Thus, high workload pressure and larger amounts of 2-Common lumber could act together and result in lower detection rates, with workers slipping through more errors than usual, as described by the reinforcing feedback loop shown in Figure 5-32.

The other major external input to the door plant process is the central panel. Figure 5-39 shows defect rate of central panels and doors. The defect rate of central panels is determined by an in-process audit, conducted randomly immediately after panels are received. Common panel defects are de-lamination, knife marks, and visible glue lines.

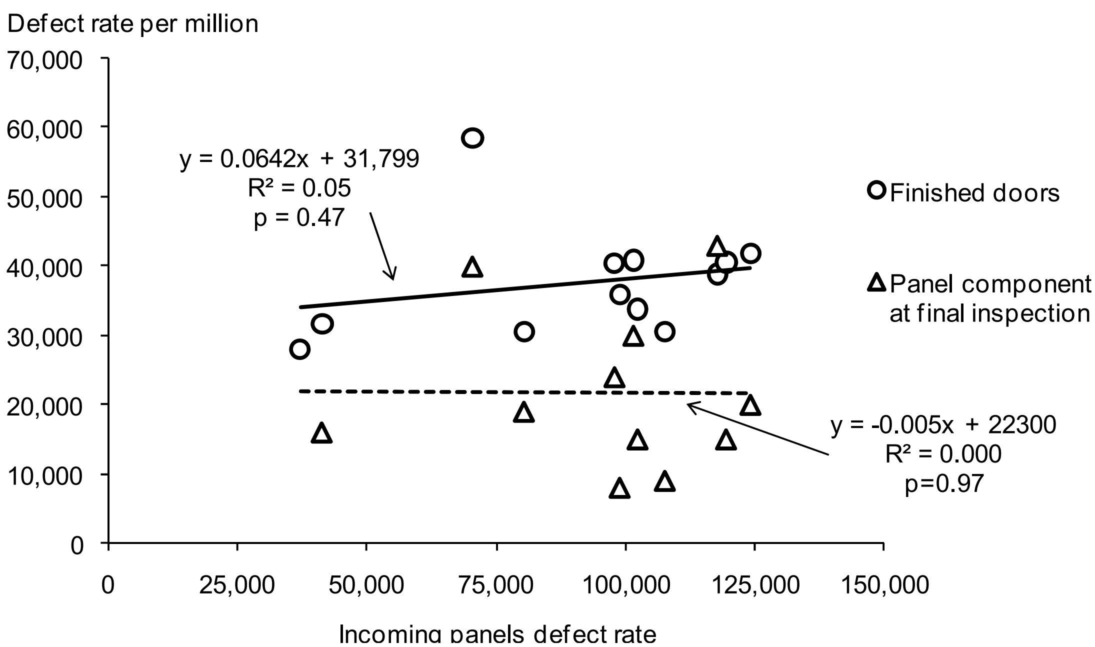


Figure 5-39. Relationship between defect rate and central panels defect rate at the door plant

Figure 5-39 shows that the linear relationship between panel defect rate and defect rate at the final inspection is not as strong as with lumber quality. Panel defects make up only 4.4 percent of total defects at the last door inspection and the plant where the panels are manufactured belongs to the same Company and uses similar quality control practices. Similarly, no significant regression exists between the panel defects component of door quality and defect rate of incoming panels.

A third defect category that can be related to external suppliers is the quality of the sealer and top coat at the finishing stage. The defects at this point can be partly attributed to variations in the coating materials. The door plant performs several laboratory tests on every batch of finishing materials received from its suppliers. The influence of the quality of these suppliers' deliveries on the final product quality however, is not easy to separate from processing variability, and there is also an effect of the substrate (wood) on the quality of the finishing. Doors made of cherry, for example, have a significantly higher number of smoothness- and sealer/top coverage-type defects (see 5.2.3).

5.6.2.2 Assembly Plant

The assembly plant does not have a quality control procedure for the components arriving from other plants and store them directly, thus the defect rate at the final inspection from the door plant was used. Two sets of quality performance data were available: the defect occurrence at the final inspection, used to calculate the non-conformant parts per million (NCPPM, see 5.3.1); and the defect occurrence after products are shipped, used for the eyes-of-the-customer (EOTC, see 5.3.2) metric calculation. No data on intermediate processes at the assembly plant was available. The following chart compares the defect rate of doors coming from the focal facility and the defect rate at the final inspection in the assembly plant.

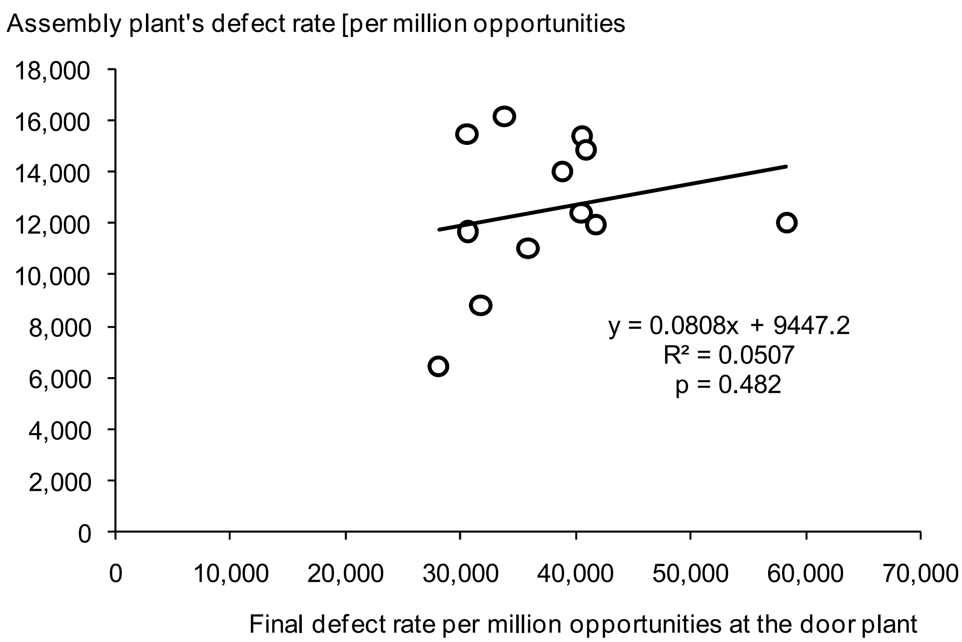


Figure 5-40. Relationship between internal defect rates at the assembly plant and the door plant

Linear correlation between doors (inputs) and cabinets (outputs) defect rate is almost non-existent, and the regression analysis ANOVA was non-significant at alfa=0.05. One potential reason for this is that, as can be observed in Table 5-3, of the ten defect categories inspected at the end of the assembly process, none can be directly related to quality of components, and a good part of defective components are filtered out by parts pickers before getting to the assembly cell. Also, the assembly plant receives components from five plants, as well as accessories from external suppliers, making doors from the focal facility a relatively small percentage of the incoming materials, thus obscuring its impact on the cabinet final quality.

It is also possible to examine the relationship between the internal and external defect rate at the assembly plant. This means analyzing if a significant relationship exists between the defect rate as determined at the final inspection (non-conformant parts per million, or NCPPM) and after products are shipped (eyes-of-the-customer, or EOTC). The eyes-of-the customer measures all the issues that come up after items are shipped and its most important component non-conformant product (see Table 5-3). Figure 5-41 shows these two measures of performance.

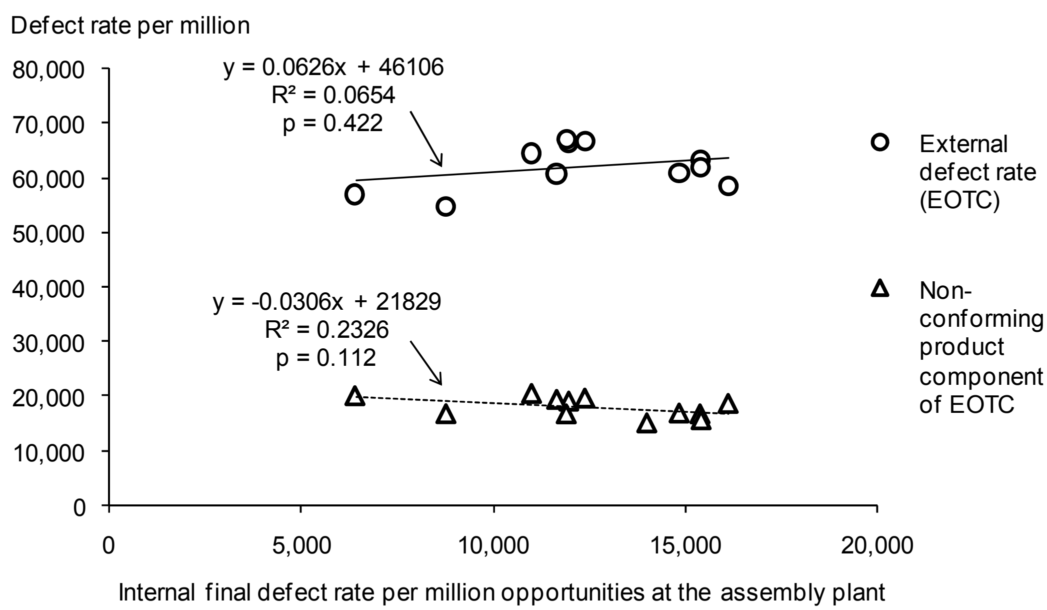


Figure 5-41. Relationship between external and internal defect rates at the assembly plant

There is a low correlation between internal defect rate at the assembly plant (NCPPM) and the external defect rate (EOTC). Although product issues have the largest share of defects found after shipment of products (27 percent). A potential explanation is that the "product" component represents only 27 percent of the total defects found after product shipment; the remaining 63 percent is attributed to mostly service and inventory management issues, like backorders, keying errors, and mislabeling (Figure 5-26). Even when considering only the "non-conforming product" component of the regression is not significant at 0.05. According to one interviewee at the assembly plant, the most common product defects found after shipment are dents, chips, and scratches.

5.6.2.3 Service Center

The service center does inspect incoming cabinets from the assembly plant, but rather when the items are taken out of their boxes at the construction site for installation. At this point, however, a defective cabinet or component prevents the completion of the installation job and has to be rush-ordered to the assembly plant. These occurrences are recorded to calculate on-time-complete (OTC), the major performance metric at the service center. The next figure shows the performance of the assembly plant and the service center in terms of defects per million. Additionally, the plant error component of the OTC metric was plotted.

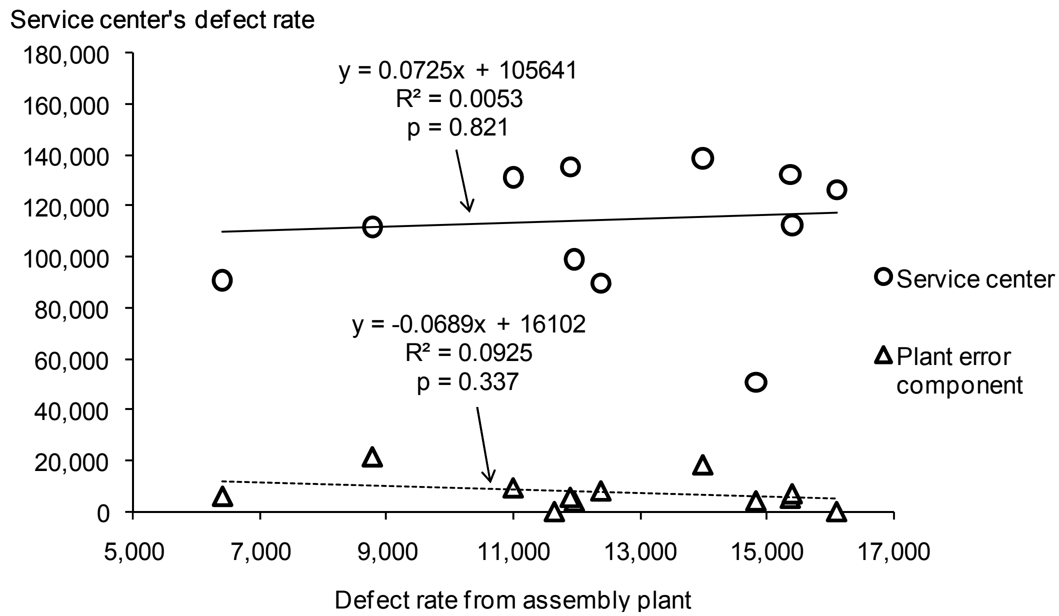


Figure 5-42. Relationship between defect rates at the service center and at the assembly plant

From Table 4-13, which lists and describes the quality categories evaluated when computing the OTC metric at the service center, only one defect type ("plant errors") can be related to the physical product sent from the assembly, and this type of error accounted only for 6.5 percent of total defects in the year of analysis (Figure 5-29). Thus, it is not surprising that the correlation between the defect rate at the assembly plant and the final performance of the service center is low and the slope between these two variables is non-significantly different from zero at a 0.05 level.

Nine percent of defects at the service center are caused by damage, which is usually concealed and difficult to establish where exactly it occurred. Figure 5-43 shows that almost a third the damage rate at the service center can be explained by the visual defects rate recorded at the assembly plant's final inspection. As mentioned before, visual defects consist in chip-outs, dents and scratches.

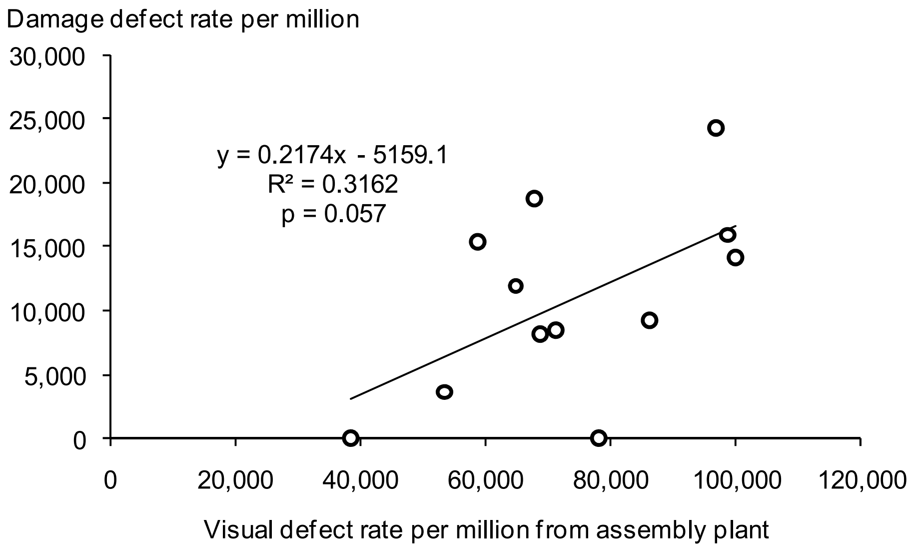


Figure 5-43. Relationship between damage defect rate at the service center and visual defects at the assembly plant

5.7 Summary

In this chapter, quality performance data for the supply chain of study was presented and analyzed. Following values for the major quality metrics and other findings are summarized.

During the period of analysis, the lumber grading accuracy at the lumber supplier was of 91 percent average. The door plant's average performance during the year of analysis was of 38,000 defects per million opportunities; and an on-time shipment performance of 97 percent. The assembly plant's defect rate was of 12,490 in average, although it decreased sharply during the year, from 14,000 in January to 6,418 in December. On-time shipping from the assembly plant was of 99 percent, and accounting for customer complaints, 94 percent. The service center completed orders on-time at an 86 percent rate.

The most common defects, as determined at the final inspection of each facility are presented. The lumber supplier recorded excessive wane as the most common cause for miss-graded lumber. At the door manufacturing plant, wood defects (e.g., checks, color, excessive mineral, wormholes) are by far the most frequent (48 percent of occurrences). Chip-outs, dents and scratches make up almost 60 percent of the total defects found during the final inspection at the assembly plant, and inventory errors are the main cause for not delivering on-time (56 percent). Most complaints from customers to the assembly plant are related to product non-conformances, backorders, and damage (60 percent). Finally, the main cause for not completing installations on time at the service level, are field representative errors and problems with custom parts, mainly countertops (59 percent).

The effect of species on performance of the lumber supplier and door plant was also analyzed. A significant difference exists between lumber grading accuracy for soft maple and red oak, which had values of 83 and 93 percent, respectively. At the door plant, looking at total defects at the final inspection, red oak doors had the lowest number of defects per unit, and soft maple doors the highest, although the latter was not significantly different when compared with doors made from hard maple and cherry. When the analysis is carried out by defect category, soft maple doors had the highest occurrence of wood defects; and finishing-related issues are most common in cherry doors, specifically smoothness and coverage.

Since the company currently does not have a formal lumber supplier evaluation program, a system based on capability index is suggested. The Company's acceptance criteria is based on whether a lumber load contains the grade mix specified in the purchase order; loads that have excessive amounts of low-grade material are rejected. It is believed that the new approach provides more useful information about the capability of suppliers than an acceptance-rejection criterion, by estimating the capability of the supplier to supply material of a certain quality. The method can easily be adapted to measure other attributes, like drying defects or color issues.

The impact of current practices on performance was presented throughout this chapter. The lumber supplier, for example, has improved its lumber grading accuracy at a 3.7 percent annualized over five years. Improvement rate for the door plant has been 35.6 percent yearly (over 3 years); and for the assembly plant, on-time shipping improved at a 1.2 percent over 4 years, and scrap at an 11.8 percent over three years. Lastly, the service center has improved its on-time completion rate by 3.4 percent annualized rate in seven years.

In the last part of this chapter, the relationship between quality performance and two major variables were investigated: namely, production volume and quality of inputs. Production volume was found to be significantly associated with quality performance throughout the supply chain. This can be explained by the negative effect of work pressure on quality, since a higher level of workload normally leads to more errors; reduction of detection rates; erosion of quality standards; a tendency of supervisors to prefer error solving ("firefighting mode") than error prevention; and errors cascading down in multi-stage processes. Managers normally make staffing decisions considering the average demand, and pay a "price" in lower quality during volume spikes.

Similarly, a regression analysis was carried out to determine the relationship between quality of incoming materials and quality of products at each step in the supply chain. No significant associations were found at all levels of the supply chain. There are several potential explanations for this happening. In the case of the door plant, it is possible that quality control practices during the manufacturing process are effectively filtering out most defects in the material being processed; this is supported by a significant regression between performance of intermediate processes (pick line, and the panel component of final inspection) and quality of incoming materials (lumber grade and panel quality, respectively). For the assembly plant, an association does not exist most probably because the major internal defect rate at this facility does not include a material component, even though product non-conformances are the most common cause for customer complaints. Lastly, at the service center, only the "damage" component of the quality indicator was found to have a significant relationship with the "visual" component (dents, chip-outs, and scratches) of the assembly plan's internal defect measure.

Chapter 6. Current State Analysis

In this section, the information presented in Chapter 4 and Chapter 5 is analyzed in order to answer some of the research questions that have been proposed. Specifically: How does the importance of the different quality dimensions change with the position in the supply chain? To what degree do the supply chain members collaborate for quality management processes? How does the supply chain of study compare with what are considered best practices in the research literature?

6.1 Map of Current Supply Chain Causes

The information presented in previous chapters can be summarized in a supply chain causes map, used in the analysis presented here (Figure 6-1). This graphic representation summarizes the major quality indicators, their components, and the significant relationships between metrics reported at different points in the supply chain.

In Figure 6-1, most of the links between causes and metrics (e.g., visual defects are about two thirds of causes for defects recorded in the internal defect rate at the assembly plant) come from the current measurement system in use at the different facilities, as described in previous chapters. However, some links that, although recognized by interviewees, are not currently part of the formal measurement system, or are assessed in qualitative evaluations. Such links are represented by a dashed line. For example, final customer (homeowner) claims are predominantly related to color variations and wood defects; however, since these claims occur after the initial installation has been completed, are not reported in the major indicator at the service center (OTC, see Section 4.5.2.1). Color variations are caused by, in order of frequency, by (1) process conditions, (2) finishing materials, and (3) variations in the substrate (wood). Since currently there is no formal record of these variances, the relationship between color variation causes and customer claims are represented by a dashed line. The percentages presented in Figure 6-1 (58, 27, and 15 percent, respectively for each of the previously listed causes) were estimated by counting the frequencies of each cause from reports issued at the door plant in a six-month period.

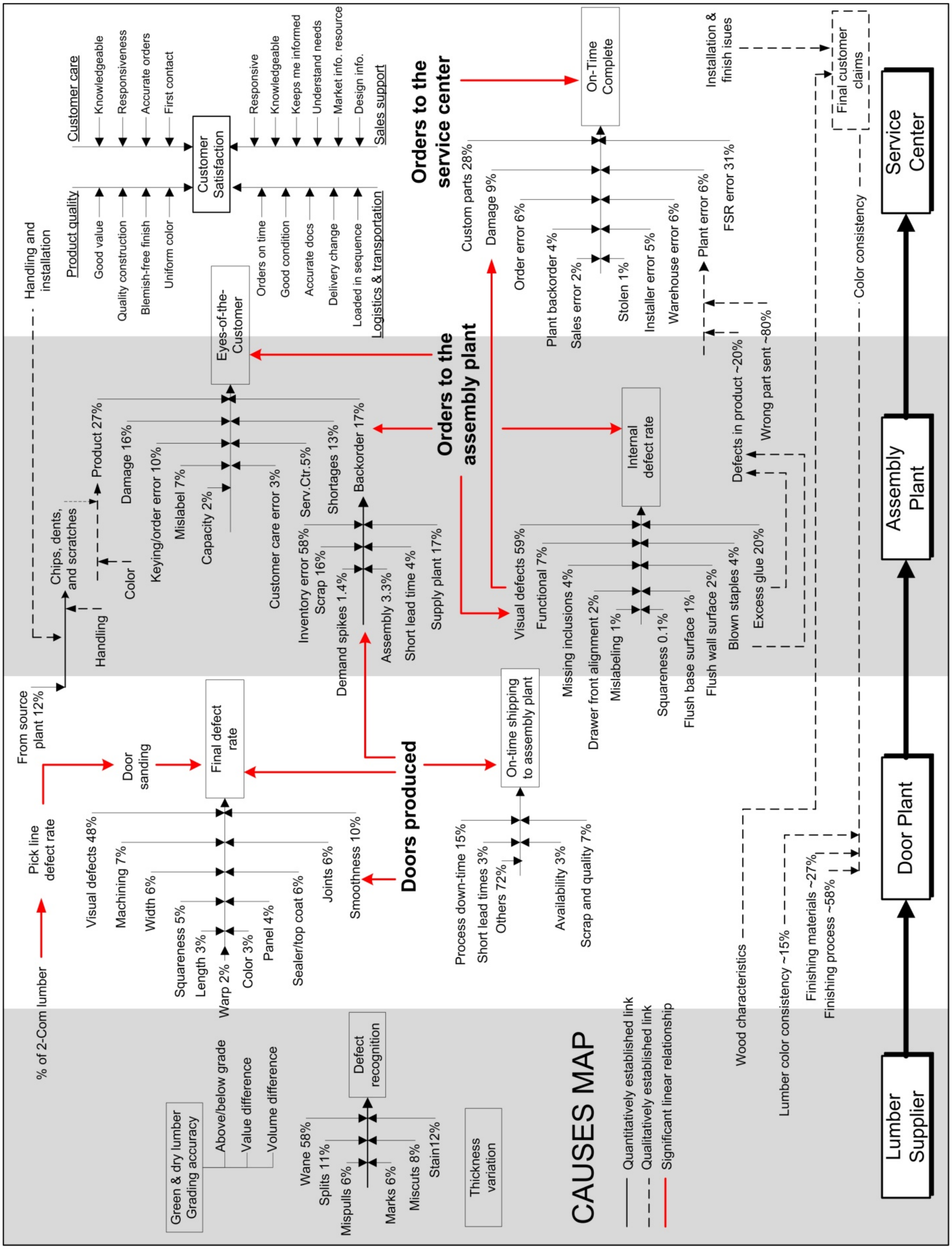


Figure 6-1. Supply chain current causes map

One of the purposes of this study was to learn how quality at some point of the supply chain affects quality downstream. For this purpose, performance data for a year was used to find significant associations between the variables; these are shown as red arrows in Figure 6-1. For example, backorders at the assembly plant are significantly associated with the production volume at the door plant. This is shown in Figure 5-36, and suggests that during peaks of demand, the components plant has some difficulty meeting a 100 percent on-time shipping to the assembly plant.

The relationship between production volume and quality performance was the most consistent throughout the supply chain. Some other relationships were explored in Section 5.6.

6.2 Quality Strategy and Internal Integration

Several studies support an association between internal integration, external integration, and supply chain performance (Closs & Savitskie, 2003; Germain & Iyer, 2006; Lee, Kwon, & Severance, 2007; Rodrigues, Stank, & Lynch, 2004; Sanders & Premus, 2005; Stank, Keller, & Daugherty, 2001). Thus, before evaluating integration in the kitchen cabinets supply chain, an analysis of internal integration is needed.

Internal integration is “the coordinated management of business processes and functions inside the firm, through a common set of principles, strategies, policies, and performance metrics” (Barki & Pinsonneault, 2005; Germain & Iyer, 2006). In this analysis, the focus is on integration of quality management, and particularly quality measurement processes. Some characteristics of internal integration mentioned in the literature are: ease of information-sharing between departments, an integrated database, cross-functional work, management of processes instead of functions, and an integrated production system (Barki & Pinsonneault, 2005; Germain & Iyer, 2006). Some practices in the Company that can be related to those listed above are described next.

The focal company of the study has deployed a company-wide continuous improvement effort, and quality improvement is part this strategy. Six-sigma and lean manufacturing techniques are part of the operations philosophy and are used in all of the company's facilities. A single-piece flow is a common goal shared among the managers interviewed for the study. Quality control and measurement practices are prescribed at the corporate headquarters with great detail and goals are set for major quality indicators. For example, corporate headquarters dictates the sampling procedure used at the door plant's final inspection and the dimensional tolerances to be observed throughout the production process. Quality performance information is used to evaluate managers and supervisors, and the performance of each facility is compared with goals during periodic assessments. The company maintains a dashboard (a dashboard is a visual display of the most important information of an organization's performance, designed in a way that information can be monitored at a glance, Few, 2006) with measures in key performance areas, one of which is quality. In this category, defect rate, cost of quality and scrap are reported for each facility. At the shop floor level, big displays show the main performance indicators for each production area, known as "glass house" (see Section 4.2.1). The number of quality improvement projects that each plant has to carry out is stated in the company's strategy, and these projects are performed by teams that include staff members from different areas.

This role played by corporate headquarters facilitates internal integration, and is consistent with some of the drivers of integration proposed by Pagell (2004) (top management support; consensus on strategy among functional managers; real-time, informal communication between managers of different functional areas; use of cross-functional teams). However, although internal integration is the main contributor to "cost containment" (a construct comprised of reduced inbound and outbound costs, warehousing costs, and increased turnover), it alone does not guarantee high supply chain performance. To achieve the later, external integration with suppliers and customers is necessary (Aryee, et al., 2008; Germain & Iyer, 2006; Lee, et al., 2007). The issue of supply chain integration is analyzed in the next section.

6.3 External Integration in the Kitchen Cabinets Supply Chain

One of the research questions of this study is to determine the degree of integration among the cabinet supply chain's constituents regarding quality measurement practices, and how this contributes (or not) to the supply chain performance. The literature review presented in Sections 1.6.2, 1.6.4, 1.6.8, and 1.6.9 contains information about different aspects of supply chain integration. Prior research and information presented in Chapter 4 and Chapter 5 are combined here in order to answer the above questions.

The degree of integration can be analyzed in light of the four characteristics of a joint quality management relationship listed by Levy et al (1995), namely: (1) growing confidence in supplier's quality, (2) reduction in inspection of incoming materials, (3) suppliers take a greater responsibility for quality, and (4) no double handling and reduced need of storage. In the supply chain of study, when the relationships between the door plant, assembly plant, and service center are considered, they clearly exhibit the first three characteristics listed above. There are no formal programs for inspection of incoming doors at the assembly plant, and the service center receives the cabinets in boxes from the assembly plant, and transports them - still closed - to the construction site without an inspection. Each plant is evaluated individually by corporate headquarters, and is responsible for sending high-quality products to the next internal or external customer. Regarding the fourth characteristic of integrated quality management, however, the company holds important quantities of inventory both at the door and assembly plants, and double handling inevitably occurs, which is typical of an assemble-to-order supply chain strategy, such as the Company's (customization is postponed until final assembly, Naylor, et al., 1999). The Company has achieved a relatively very short lead time with its current strategy. Intermediate inventories, however, also bring some of the disadvantages of conventional purchasing; for example, stocks can sometimes hide quality and production problems. No buffers exist from the assembly plant to the final customer.

Integration is more limited, however, when external suppliers are considered. Most of the lumber, with the exception of hard maple, is graded and tallied at the door plant, and paid accordingly. Immediately after grading, lumber is pre-surfaced to homogenize thickness. This practice in fact, makes the door plant in great part responsible for incoming lumber quality, and grade determined by the supplier is only considered for hard maple, which is not graded at reception and comes kiln-dried. The difference between lead times for products made of hard maple and soft maple is significant (24 and 70 days, respectively, see Figure 3-12) and illustrates the differences of two approaches to supply chain integration. It can be noted, therefore, that there is disconnect between the door plant and lumber suppliers, as they are not integrated in the quality management system of the Company.

The relationship between the door plant and lumber suppliers exhibits some of the characteristics of what Gryna et al. (2007, p. 356) define as a “strategic view” of the purchasing process: long term relationships based on trust and relatively few suppliers; and no inspection of incoming materials when these come from sister plants. However, some features of a more traditional, more adversarial, approach can also be observed, like inspection upon receipt of lumber loads, purchasing plans independent of the user business plan, and focus on price. The author considers that a strategic approach to the purchasing process is more conducive to supply chain integration because it leads to partnerships where supplier and buyer work for mutual benefit. Such approach can have positive implications for: buyer-supplier relationships, financial performance, product development time, improve product quality, and assure continuing supply (Batson, 2008; Carr & Pearson, 1999).

In addition of physical flow, integration must also be achieved in information flow; this facilitates integration (Pagell, 2004) by reducing transaction costs (comprised of coordination costs and transaction risk, according to Vickery, Jayaram, Droge, & Calantone, 2003). In the case study, the reach of quality information is consistently limited to the immediately adjacent supply chain partners, and very little interaction occurs with the customers’ customer and the suppliers’ supplier. The assembly plant communicates closely with the door plant and the service center. At the service center level, the branch works very closely with the assembly plant and the construction company, and feedback is constant until the installation work is complete. There is very little or inexistent communication, however, between the service center and the door plant. This could potentially lead to slow down response to customers' complaints.

Similarly, there seems to be potential for improvement in information sharing between the company's plants and their external suppliers. For example, the information flow between the door plant and lumber suppliers is unidirectional and limited to purchase order terms (grade mix, and color and length specs) and the grade bill (actual grade mix determined at the door plant). At the other end, although externally-acquired parts are an important source of variances at the service center, there is little participation of external suppliers in the definition of requirements or purchase order specifications. Using the terminology of Frohlich and Westbrook (2001), in their model of "arcs of integration", the Company seems to exhibits a "periphery-facing" integration (see Section 1.6.2).

The Company collects data about quality performance from all of its plants and posts this information on the corporate dashboard (see section 4.7). This reporting allows to identify gaps between performance and goals, and to make inter-plant comparisons of performance. It does not provide, however, feedback on the contribution of each supply chain entity to the Company's overall quality performance. Moreover, external suppliers' quality is not included in the computation of performance measures, limiting the usefulness of these indicators to point at the exact source of inefficiencies in the system. In this sense, quality performance measurement in the case study lacks system perspective and supply chain context. According to Chan (2003), "a supply chain must be treated as a whole entity and the measurement system should span the entire supply chain". In this sense, the measurement system does not foster integration in the supply chain of study.

Lastly, some success examples of the benefits offered by supply chain integration are briefly described. A manufacturer of office furniture linked its ordering and scheduling system with its suppliers and customers; this made the flow of material transparent to them (Walker, Bovet, & Martha, 2000). For example, within two hours of receiving an order, suppliers have access to the bill of materials, customer demands, shipment schedules and inventories. The company was able to reduce cycle times and improve its on-time delivery performance dramatically, while at the same time eliminate the need for costly intermediate inventories and double handling. Zara, a Spanish apparel manufacturer is able to take a new design from drawing board to store in two weeks (several months are typical in this industry), in great part as a result of having integrated the flow of information between its stores, the company's headquarters, designers, warehouse managers, and its production network, which is a combination of company-owned factories and small workshops for labor-intensive operations (Ferdows, et al., 2004). Weyerhaeuser Door links its computer system to its customers, suppliers, and employees, and all aspects of the manufacturing process. This allows the company to process orders in fifteen minutes instead of several weeks in the past, and delivering 97 percent on-time, compared with 67 of the industry. In the retail industry, opening its sales and inventory database to its suppliers is in part what made Wal-Mart the largest private company in the U.S. The company implemented collaborative planning, forecasting, and replenishment (CPFR), which greatly reduced carrying costs throughout the supply chain (Johnson, 2002).

6.4 Suppliers Quality Management

One important process in supply chain management is the strategic management of suppliers. Three main components of strategic management of suppliers are: supplier relationships, supplier evaluation, and supplier development (Carr & Pearson, 1999). During the last decades, the prevailing trend in some industries has been to reduce the number of suppliers to a few competent ones, known as rationalizing the supplier base (Batson, 2008), and improving the efficiency of those suppliers that are left; all this with the purpose of improving performance of the entire operation (Rogers, Purdy, Safayeni, & Duimering, 2007).

Regarding strategic supplier relationships, most research supports the development of collaborative rather than traditional transactional relationships (or cooperative rather than adversarial relationships). A collaborative relationship refers to working closely with few suppliers for a long time, and taking care that both buyer and supplier benefit from the relationship. In the case of study, lumber suppliers provide the main raw material to the supply chain. As presented in Section 3.8.1, relationships with lumber suppliers are based on long-term relationships and, although there are a relatively a small number of suppliers (about 10 percent of suppliers provided about 20 percent of the total lumber inputs to the door plant during the year of analysis), this is far from what is considered “best-in-class” (15 percent of suppliers accounting for 80 percent of expenditures in materials, according to Minahan, 2005). Having few suppliers gives the buyer more leverage and motivates it to work closely with strategic suppliers. Wang et al. (2004), for example, states that one of the ultimate goals of supplier development is the reduction of the supplier base. Some advantages and disadvantages of a single supplier system (SSS), cited by Thakur (2002) are listed in Table 6-1.

Table 6-1. Advantages and disadvantages of a single supplier system

Advantage/disadvantage	Explanation
----- Advantages -----	
Reduced variability and increased stability	Batches are larger, giving supplier more time to stabilize their process. Customer does not have to deal with several (or many) sources of variability.
Better availability of resources	Due to the increased scale, the supplier can in turn demand more quality from its suppliers
Captive assembly lines	Increased scale justifies having a dedicated assembly line at the supplier. This increases flexibility also.
Greater moral responsibility	The supplier has more responsibility for quality
Simpler and faster training	Customer only needs to conduct training at one supplier
Better document and sample control	Especially important for ISO certification
Minimized identification issues	Traceability becomes easier
One-stop corrective actions	Self-explanatory
Reduced cost of quality	Reduced cost of communications, travels, and training
----- Disadvantages -----	
Fewer brainstorming opportunities	Only one source of improvement ideas
Dependence of one supplier	No alternative source if supplier sends defective material. Risk can be controlled by early warning systems, such as SPC, and sharing quality information in real time, or buffer stock
Missed benchmarking opportunities	No comparisons are possible between suppliers. Can be countered by fostering (and assisting) continuous improvement of the supplier’s process
Emergency breakdown	Customer becomes more vulnerable to breakdowns and supplier. One solution is having a “dormant” certified supplier for emergencies

The Company has long-termed and good relationships with its lumber suppliers, and conflicts are solved directly and expediently. However, the flow of information about quality between the door plant and the lumber suppliers is mostly unidirectional. The door plant specifies lumber grades and other requirements in the purchase order, and sends back a grade bill to supplier which is the basis for payment. When quality issues arise, the door plant communicates directly with account managers, and issues are solved on a case-by-case basis. Occasionally, entire loads of lumber are rejected for excessive amounts of off-specs lumber, and rejection of boards is common (the rejection rate was about 0.26 percent or more than 31,000 board feet of lumber other than hard maple in a year, equivalent to 3.5 truckloads of lumber). Although the company does not pay for these rejections, reducing the amount of rejections by improving the internal processes of the suppliers or quality requirement could surely benefit both the door plant and the supplier. Suppliers do not participate in the development of grade mixes, and the company does not buy custom grades.

There is ample support in the literature for the development of formal supplier evaluation programs (Carr & Pearson, 1999; Chen, Yeh, & Yang, 2004; Fram, 1995; Muralidharan, Anantharaman, & Deshmukh, 2002), and authors state that these programs are associated with higher financial and market performance. The Company does not currently have a program for supplier evaluation. Lumber delivered to the door plant is graded and pre-surfaced, and batches that are judged significantly below minimum requirements are rejected. Evaluating suppliers based on rejections does not reflect the potential problems defective materials cause when processed (Chen, et al., 2004). Pre-surfacing incoming lumber facilitates a uniform drying and reduces warp during the process, but it is costly and the plant losses some information that could be used to assess the capability of the supplier’s process (by monitoring thickness accuracy, for example). In Sections 5.4.2 and 5.5, it was demonstrated that certain lumber quality attributes that are not currently being measured influence customer satisfaction. A simple system for evaluation of supplier capability was presented in Section 5.1.4, based on information readily available. Some other important variables could be included as well, like color, moisture content, thickness accuracy, and time performance.

The third element of supplier quality management, supplier development, is a systematic effort to create and maintain competent suppliers (Hahn, Watts, & Kim, 1990). Supplier development can go from just selecting suppliers based on conformance (narrow perspective), to efforts by the customer to improve the capabilities of suppliers (broad perspective), which usually benefit both parties (Rogers, et al., 2007). It is common, for example, among automotive companies, to have “supplier development representatives”, who visit suppliers’ plants regularly and teach them lean manufacturing techniques and variability-reduction methods. In fact, most automotive Original Equipment Manufacturers (OEMs) have a supplier development program in place (Batson, 2008). Examples of supplier development activities are recognizing supplier with certifications or awards, providing technical assistance, and enhancing communication with suppliers (Lo & Yeung, 2006). Typical benefits of supplier development programs for the supplier are: (1) retain current and potentially find new business, (2) improve overall business performance, and (3) improve relations with customers. Benefits for the customer are (1) reduced product development time, (2) meet production schedules, (3) improve product quality, and (4) assure continuity of materials supply (Batson, 2008).

The Company does not currently have a supplier development program. NHLA grading rules are the main standard for specification, and quality improvement is only motivated by a desire by the supplier to comply with purchase order requirements and avoid rejections. Since the Company pays suppliers according to grade and tally as determined at the door plant and pre-surfaces incoming material, there is no real drive to improve suppliers’ internal process performance. Lumber suppliers could benefit from the Company’s expertise in process improvement methodologies, and the Company could benefit from reduced variability in its lumber supplies.

6.5 Quality Measurement and Position in the Supply Chain

One of the research questions of the present study was to determine if quality measurement practices change with the position of a company in the supply chain. One study, conducted chiefly among automotive and electronics manufacturers, found no significant differences in quality management practices across the supply chain (Choi & Rungtusanatham, 1999), suggesting that these industries have made progress towards the adoption of quality management practices. Another study among American manufacturers of metal products, industrial and commercial machinery, electronic and electrical equipment, transportation equipment, and measuring equipment, concluded that the position of a company in the supply chain does not affect quality management practices, defined by the eight critical factors of Saraph et al. (1989, see Table 1-7) plus an Information Technology dimension (Roethlein, 2000, p. 110).

In this section, an analysis of how quality measurement practices (an essential part of any quality management system) varies (or not) in the supply chain of study is presented. For this purpose, quality management factors identified by Saraph et al. (1989) and other authors were used as a base for the analysis. These are listed in Table 6-2.

Table 6-2. Quality management factors that relate to quality measurement

Factor for quality measurement	Reference
Quality data and reporting	
Availability of cost of quality data	
Availability of quality data	
Timeliness of the quality data	(Flynn, et al., 1995; Forza & Filippini, 1998; Saraph, Benson, & Schroeder, 1989; Zu, 2009)
Quality data are used as a tool to manage/improve quality	
Quality data are available/visible to hourly employees	
Quality data are available to managers and supervisors	
Quality data are used to evaluate supervisor and managerial performance	
Process control	
Use of statistical tools to control and improve process	
Inbound quality measurement	(De-Toni, Nassimbeni, & Tonchia, 1995; Saraph, et al., 1989)
In-process quality measurement	
Outbound quality measurement	
Quality strategy and workforce management	
Quality strategy and goals are clearly defined	(Baldrige National Quality Program, 2009; Saraph, et al., 1989)
Quality goals are known by everybody	
Extent of involvement of employees in quality decisions	
Customer relationship	
Involve customers in quality improvement	(Zu, 2009)
Measure customer satisfaction	
Supplier management	
Involve suppliers in product development/specifications	(Saraph, et al., 1989)
Provide training/technical assistance to suppliers	

6.5.1 Quality data and reporting

- *Availability of cost of quality data*. The collection and reporting of cost of quality data (usually classified in prevention, appraisal, internal failure, and external failure costs. Gryna, et al., 2007, p. 29) is a new initiative in the company, and it was not yet fully deployed at the time of the data collection. Cost of quality, along with defect rate and scrap, is part of the three main performance measures reported monthly at the corporate dashboard. Cost of quality at the service center are more readily available since failure costs at this point are mostly external; man-hours spent on repairs and changes due to quality issues are monitored in detail through the customer service system (see Section 4.5). Among lumber suppliers, none of them record costs of quality formally.

- *Availability of quality data*. As seen throughout this chapter, all entities in the supply chain that are part of the focal company, from door plant to service center, have formal and well established systems for measuring and reporting data about quality performance. Availability of quality data varies widely, however, among lumber supplier. Supplier 4 has a well managed system of collecting and reporting quality data, which includes an intranet-based system to upload audits information for twelve plants. Supplier 3 collects only outbound quality information (lumber grade bill and package appearance). Supplier 5 keeps records for each batch of lumber, which includes inbound and outbound grade and tally, and kiln-drying records and checks. At the other end of the supply chain, the retailer level, quality data availability is limited to returns to the assembly plant and late deliveries.
- *Timeliness of quality data*. The use of an intranet database by Supplier 4 allows quality performance information to be updated constantly, and supervisors at each facility are responsible for feeding information to the database on a continuous basis. Supplier 3 has several checks during the process, and variances are recorded in each lot's record, which can be used to trace a customer complain back to the air-drying yard. However, all other suppliers keep only lagging quality indicators (grade mix and tally), which are not useful to for early detection of problems. At the door and assembly plants, quality data are updated daily, and in some cases more frequently; operators are responsible for reporting a process out of control so corrective action can be taken. At the service center, however, time spans are much shorter, one or two days for installation of a kitchen, and when quality issues are reported (a wrongly-labeled component, for example), it is very likely that the service center already missed the due date (re-orders take usually five days). At the retailer of kitchen and bath cabinets, only returns and rejections are reported once parts reach the construction site (cabinets are not inspected at arrival).
- *Extent to which quality data are used as tools to manage quality*. Among lumber suppliers visited for this study, only Supplier 4 collects quality data systematically and uses it to improve process and product performance; at monthly evaluations decisions are taken to close the gap between goals and actual performance. Quality data at the other lumber suppliers are only used mostly in a reactive way, when

customers complain. At the door and assembly plants, quality data is used on a continuous basis to take decisions for improvement. Workers report variances when measures fall outside what is specified in the quality control plans, and supervisors start correction actions. Improvement events are scheduled and an essential input is quality performance information. The service center personnel meet once a week to review, among other things, the major quality indicators, and take decisions to correct issues. At the retailer level, quality data is used only reactively, to re-order defective or wrong items.

- *Extent to which quality data are available to hourly employees*. During the visits, it could be observed that quality performance indicators are posted visibly at the Supplier 4, door plant, assembly plant, and service center. All other entities do not have a policy of making quality data available to hourly employees.
- *Extent to which quality data are available to managers and supervisors*. At the focal company's facilities, managers and supervisors are responsible for the collection and reporting of quality data, and take decisions every day based on this information. Data is contained in electronic spreadsheets and databases, accessible to responsible in each area through the company's network. At Supplier 4, quality supervisors at each facility have access to the quality database in order to update it and also look at information. This factor was also observed among other entities in the supply chain.
- *Extent to which quality data are used to evaluate supervisor and managerial performance*. At Supplier 4, quality data is used for compensation of plant personnel, as well as to evaluate supervisors and managers. In all facilities that belong to the focal company, monthly evaluations of quality performance are carried out and major quality indicators are posted in the corporate dashboard. These evaluations are a direct feedback to supervisors and managers, and they are expected to take actions to close gaps between goals and actual performance. No formal evaluation program based on quality data was observed at other lumber suppliers and at the retailer level.

6.5.2 *Process control*

- *Use of statistical tools to control and improve process*. The focal company has adopted as part of its continuous improvement effort, the use of six-sigma methodologies for improvement, and statistical tools are employed throughout all the transformation process, from the door pant to the service center. The use of statistical tools at all other entities of the supply chain included in this study have been found to be incipient or inexistent.
- *Inbound quality measurement*. All lumber suppliers scale and grade incoming logs, and Supplier 4 conducts weekly audits of grade and volume accuracy. Grade and tally is determined at the door plant as basis for payment, hard maple is not graded but rather spot-checked for grade and moisture content. No incoming quality control is carried out at the assembly plant, the service center, and at the retailer.
- *In-process quality measurement*. Supplier 4 has many checks and controls throughout the process, from the debarked to the loading of packages for shipment, and results from these controls are recorded and posted in the quality database. At the other suppliers, the only systematic in-process controls are periodic (usually weekly) audits at the green chain to monitor grading accuracy. Quality measurement practices at the focal company were described in detail in Chapter 4.
- *Outbound quality measurement*. All lumber suppliers conduct some sort of outbound control. This varies from just checking the packages for appearance (e.g. straps, no defects on outside, correct labels, number of boards) to comprehensive audits at the shipment dock. The door and assembly plants conduct a comprehensive inspection at the end of the process and inspect several attributes and detailed records are kept. Likewise, at the service center, the installer and supervisor complete checklists at the end of the installation work.

6.5.3 *Quality strategy and workforce management*

- *Quality strategy and goals are clearly defined and known by everybody*. Lumber Supplier 4 sets goals for major quality indicators (96 percent for grading accuracy, for example) but has not made an effort to have a formal quality management strategy. The focal company, as was explained in Section 6.2, has well defined strategy and goals set at corporate level, and makes sure to keep personnel informed about these policies.

- *Extent of involvement of employees in quality decisions*. At the focal company, employee input is essential in developing the quality control plans, which contain goals for critical attributes. Employees also participate directly on improvement events, suggesting and carrying out specific actions to achieve goals. At all other entities, employee involvement is minimal.

6.5.4 Customer relationship – Measuring customer satisfaction

The focal company conducts periodic (at least twice a year) customer satisfaction surveys (Section 4.6). Likewise, the kitchen cabinets retailer and the service center conduct periodic customer satisfaction assessments.

6.5.5 Supplier involvement and assistance to suppliers

These are probably the least developed factors of quality management in the suppliers' end of the supply chain of study. Involvement of lumber suppliers in the development of products or quality specifications is practically inexistent; and all purchases are based on NHLA grading rules, no custom grades are bought. Supplier development, as was explained in detail in Section 6.4, is not practiced. At the customer side, there is active participation of the focal company in designing products that may meet the final customer needs.

In summary, contrary to what previous research found in other industries, quality measurement practices vary widely in the supply chain of the study. The focal company has well developed strategies and goals for quality measurement and statistical tools are used in all of its facilities, quality data is continuously collected and used for process improvement. Being vertically integrated clearly facilitates the company to use a consistent approach through most of the transformation process, and reduces transaction costs. On the other hand, lumber suppliers' practices range from just using lumber grading for accounting purposes, to a very structured system for collecting and reporting process quality data at all steps of the production cycle. Although only data for three suppliers' deliveries to the door plant were available, it was found that variability in comparable species is lower at the supplier with the most sophisticate quality measurement system (see Section 5.1.4).

Some similarities observed are that all entities in the supply chain practice some sort of outbound inspection of materials, although with different level of sophistication; and supplier management is not well developed. The latter departs from the almost universal practice in the automotive industry of involvement with supplier's process improvement (Batson, 2008). Current inspection practices for incoming material at the door plant places the responsibility of lumber quality on the door plant.

6.6 Attribute Importance throughout the Supply Chain

Different dimensions of quality need to coexist throughout the manufacturing of a product in order to assure high-quality products. This includes physical attributes like conformance to specifications and intangibles like the courtesy of sales personnel. It is not sufficient to manufacture a product, like a kitchen cabinet, that performs greatly in use (*performance* dimension of product) and has visual appeal (*aesthetic* dimension of product); but the customer also expects the product to be delivered and installed on-time (*reliability* of service) and to receive prompt response when problem occurs (*responsiveness* of service). When designing a product, an organization tries to translate customer needs into product features, features into process features, and finally process features into process control specifications (Gryna, et al., 2007, p. 317); all these in a way to reflect in the product's features those quality attributes that are most valued by the customer.

Measuring quality performance in a supply chain environment presents some additional challenges compared to a single company; mainly because a supply chain consists of several (or many) suppliers and customers, and each customer may have a different set of priorities in regards to quality attributes. In order to maximize final customer satisfaction, the challenge is then achieving that quality attributes translate into value for the customers. Robinson and Malhotra (2005) state that in order to satisfy final customers the whole supply chain has to “commit, integrate, and coordinate to pursue coherent and innovative practices”. In this section, the relative importance given to certain quality dimensions throughout the supply chain is discussed. The analysis is based on what attributes are inspected at each stage of the supply chain. The assumption is that companies decide which attributes are important to measure based on the needs of the customer.

6.6.1 Product and Service Quality Attributes vs. Performance Measures

In the first part of the analysis, the focus is on which type of attributes are measured at each stage in the supply chain, with the purpose of determining if the quality performance measurement system is balances product and service measures. For this, two frameworks were combined: (1) product and service attributes, two categories used in previous research to understand quality requirements in the wood products industry (Hansen, et al., 1996); and (2) the classification by De-Toni et al. (1995), which separates the quality offered by a company in three components: inbound quality, internal quality (process), and outbound quality; the latter corresponds with product quality. A summary of the measures used throughout the supply chain and their classification is shown in Table 6-3.

Table 6-3. Product, process, and service attributes, and their measures

	Inbound quality	Process quality	Outbound (product) quality	Service quality
Lumber supplier	• Log scale accuracy • Log grade accuracy	• Debarker • Thickness accuracy • Best opening face • Pallet cants • Edger/trimmer • Ripsaw • Dip-treatment • Air- and kiln-drying	• Grading accuracy • Thickness accuracy • Packages audits • Lumber MC	
Door plant	Lumber • Grade and tally • Color specs (maple) • Spot-checks MC (hard maple)	• Pre-& kiln-drying checks • In process audits of 11 operations(dppm,s-score) • First-time yield for 3 operations (panel sanding, door sanding, door finishing) • Efficiency (%) • Scrap at every station • Color consistency (quali.)	Final inspection (dppm): • Length • Width • Squareness • Visual defects • Sealer/top coat • Color • Panel • Warp • Joints • Machining • Smoothness	• Shipping performance (%)
Assembly plant		• Walk-through audits • Finishing operation • Color consistency • Static loading tests • Scrap recorded at every station	Final inspection (ncppm): • Blown staples • Excess glue • Flush wall surf. • Flush base surf. • Drwr. Frt. align. • Mislabel • Squareness • Inclusions • Functional • Visual Eyes-of-the-customer (%) • Product • Damage • Mislabel	• On-time complete (%) • Backorder • Shortage • Order error • Customer care • Capacity
Service center		• No-charge items • Bone pile count	On-Time Complete (%) • Installer • Damage • Plant • Installation checklists (24 items)	• FSR error • Custom part • Backorder • Sales error • Order error • Warehouse • Trips x house • Time to fix Customer satisfaction survey • Concerns solved timely • Delivery confirmation • On-time delivery • FSR available, helpful • CS calls returned timely • CS resolves issues
Overall			Customer satisfaction survey • Product quality (4 items)	• Customer care (4 items) • Logistics & transportation (5) • Sales support (6)

An examination of Table 6-3 clearly shows that as the supply chain approaches the final customer, the service attributes of quality become more important. Most measurements at the lumber supplier and the door plant fall in the product-process categories, while the opposite is true for the assembly plant and the service center. This does not mean, however, that service attributes are not important upstream the supply chain. For the door plant, for example, it is important to receive prompt response and correction to its quality concerns from lumber suppliers; or receive lumber shipments on the promised date (on-schedule delivery received the maximum rating as quality attribute by the door plant, see Table 4-3).

One common problem with performance measurement systems is a lack of balance (Van-Aken, 2004), and research on organizational performance measurement advises, for example, that there should be balance between financial, internal process, customer, and sustainability measures (Kaplan & Norton, 1992); or balance between cost, non-cost, internal, and external measures (Neely et al., 2000). The author considers that, for quality measures, there should also exist a balance between product and service dimensions of quality. With this in mind, the lumber supplier for example, could include in their metrics mix some service measures, such as on-time delivery or timely resolution of customer concerns.

Probably unique to the supply chain of study is that there are almost no quality controls for incoming materials between entities that are part of the kitchen cabinet company (e.g., the assembly plant does not inspect parts coming from the door plant). Gryna et al. (2007), state that, under a strategic view of procurement, incoming inspection becomes unnecessary, resulting in higher efficiency in labor hours needed for inspection activities, staff required, and throughput time (Ericson, 2006). This view involves developing suppliers' capabilities.

6.6.2 Critical Quality Attributes vs. Performance Measures Used

In the second part of the attribute importance analysis, quality attributes considered critical by customers in the supply chain are compared with metrics used by suppliers; with the purpose of determining if measures used correspond with the needs of customers. Research gives ample support to the assertion that understanding customer expectation is necessary to implement successful quality-based strategies (Forbes, et al., 1994; Hansen & Bush, 1996). Garvin (1984a), for example, stated that firms should "carefully define the dimensions of quality in which they want to excel, and focus their energy in that area".

Two separate comparisons are made. First, the attributes of lumber quality (and lumber suppliers) most valued by the door plant are contrasted with the quality measures recorded at lumber supplier 4. In Table 6-4, those attributes that were assigned an importance rating of "important" to "extremely important" by the door plant's lumber purchaser are listed (from Table 4-3), as well as the corresponding metrics used by the supplier.

Table 6-4. Critical lumber and supplier attributes and measures used

Quality Attribute	Measure
--- Lumber Characteristics ---	
Accuracy of grading	Grade accuracy
Consistency of grading	Grade accuracy
Presence of stain	Grading audit category / Dip tank
Consistency of lumber thickness	Thickness accuracy
Adequacy and consistency of color	None
Presence of wane	Defect recognition / Edger
Packaging (appearance, stacking)	Package audits
Overall lumber appearance	Package audits
Only for kiln-dry lumber:	
Straightness of lumber	None
Presence of surface checks, end splits	Defect recognition
Accuracy of moisture content	Drying records
Consistency of moisture content	Drying records
--- Supplier Characteristics ---	
Competitive pricing	None
Order mix filled correctly	Package audits
On-schedule delivery	None
Ability to provide desirable length mix	Package audits
Ability to provide desirable width mix	Package audits

Shaded cells represent attributes not currently measured by the supplier

In Table 6-4, attributes that do not have a correspondent performance measure are color adequacy and consistency, straightness of lumber, competitive pricing, and delivery on schedule. Most remarkable in the list are color and on-time delivery, both have been found to be very important attributes from the door plant through the final customer. In order to have a balanced approach, the lumber supplier could benefit from including these attributes in its performance measurement system.

Secondly, an analysis of the attributes of product quality and logistics performance can be used to understand whether the measures used by the facilities within the Kitchen Cabinets Company are consistent with those attributes that are considered critical by the customer. Product and logistics were selected for reasons explained in Section 5.5. Table 6-5 lists the attributes for customer satisfaction in these areas, and the corresponding measures used from the door plant to the service center. Good value, an attribute of product quality, is not included since it is a measure of the customer perception of quality relative to price.

Table 6-5. Customer satisfaction attributes and quality measures in the supply chain

Function	Attribute	Door plant	Assembly plant	Service center
Product quality	Uniform color	DPPM category	None	None
	Quality of materials	DPPM	EOTC category	OTC category
	Construction & workmanship	DPPM	NCPPM and EOTC	OTC, Inst. checklist
	Blemish-free finish	DPPM categories	NCPPM	OTC category
Logistics	Accurate docs.	N/A	EOTC category	OTC category
	Orders on time	N/A	OTC	CSS
	Good condition	None	EOTC category	OTC category
	Loaded in sequence	N/A	N/A	N/A
	Delivery change notification	N/A	None	CSS

Shaded cells represent attributes not currently quantitatively measured by the supplier
CSS = Customer satisfaction survey conducted by the service center
DPPM = Defective parts per million (final inspection at the door plant)
OTC = On-time complete (final inspection at the assembly plant)
EOTC = Eyes of the customer (final inspection at the service center)
N/A = Not applicable

Color variation is the chief cause of final customer complains, and that is reflected in the relatively high importance given to this attribute in the customer satisfaction survey. The Company has several mechanisms in place to monitor color consistency, from a specific item in the final inspection at the door plant, to periodic checks of color consistency and matching with master samples at both the door and assembly plants (Section 4.2.4). Suppliers of finishing materials have a full-time representative at the plants, and every batch of finishing material is subject to several tests and checks.

Additionally, since color variation can be a very subjective attribute, efforts are made to “educate” the customer on the natural variability of wood, through the Company’s website and also printed materials.

However, color consistency is not monitored in a quantitative fashion at the assembly plant nor at the service center; and color consistency of incoming lumber is checked only during the grading at lumber reception, where it might not be easily appreciated as lumber is in its rough-sawn state. According to the service center, color variation problems are more frequent within the components of a door (e.g., rails and central panels), rather than between doors, which suggests that most problems at this point originate in the substrate (e.g., grain direction) and not so much in the finishing process. The door plant places more importance on color variation problems caused by the application process or the finishing material, since these can result in entire batches of doors off-color (a batch at the finishing line has typically 200 parts, between doors and drawer fronts). Thus, the share of color variation issues on the main quality indicator at the door plant (3 percent, see Figure 5-17) does not really reflect the potential extent of the problem, since samples are drawn from several batches of production. A one percent of color defects in the final defect rate (DPPM) could represent a much higher percentage of defective doors.

Similarly, soft and hard maple are considered the species with most problems of color variation at the door plant (mentioned by the lumber purchaser, and supported by DPPM breakdown, in Figure 5-19); but at the service center level, cherry is cited as the species with most color problems among final customer claims, which might be in part due to the higher share of cherry in the product mix of the service center (35 percent, compared to 20 percent at the door plant).

Also, there is an apparent disconnect between the quality attributes inspected at the door plant’s final inspection and those at the end of the assembly cells, since none of the items at the assembly line’s inspection can be directly related to door defects. While this makes sense from the assembly plant’s point of view (doors defects in the NCPPM calculation would penalize the assembly plant’s performance), a better way could be devised to account for these occurrences, since doors are the most common cause for the assembly plant not sending an order complete or on time. Rather inconsistently, when calculating the performance after orders are shipped, the assembly plant does take into account errors by the service center (the “Future 09” category of defects, which are caused by errors originated at the service center, see Table 4-11).

Final customer claims are not included in the final performance indicator at the service center, understandable considering that there is a time lag of about 30 days from the day of installation of a kitchen to the inspection by the homeowner. But there is no formal measure of final customer satisfaction. Color and wood characteristics are the main causes for final customer claims, but these attributes are not being controlled quantitatively. The service center communicates solely with the assembly plant when there are quality issues, it does not communicate with the door plant. This can lead to a time lag of several days until correcting the problem.

6.7 Effect of Intermediate Inventories and Feedback Delays

As mentioned in previous sections, the Company maintains intermediate stocks at their components plants as part of their inventory strategy, and these stocks are replenished using a MIN/MAX approach. Doors stay approximately 15 days in storage before being sent to the assembly plant. While this practice might be instrumental to the company in keeping a more reliable response time, it has some negative implications for quality performance, which are illustrated in Figure 6-2; in this causal-loop diagram, defect rates at each facility are represented as stock, which is increased by special causes of variation, and decreased by improvement activities. Since inspection is not perfect, there are some defective items that go undetected and are stored at the intermediate inventories. When the next customer places an order, these defective units are shipped, and then, one of two things happens: (1) the defective component is detected during the next plant’s process and are scrapped or repaired, or (2) the defective product is shipped to the customer, where it can cause a quality claim. In both cases, Customer satisfaction is negatively affected. Furthermore, since the improvement activities depend in great part on the feedback provided by the next customer, intermediate inventories will add to this feedback delay; meanwhile, the systematic cause of variation is not corrected and more defective units are produced. A way to reduce the time for feedback is to make quality-related information available to every supply chain member through an information system that connects suppliers and customers and is updated continuously.

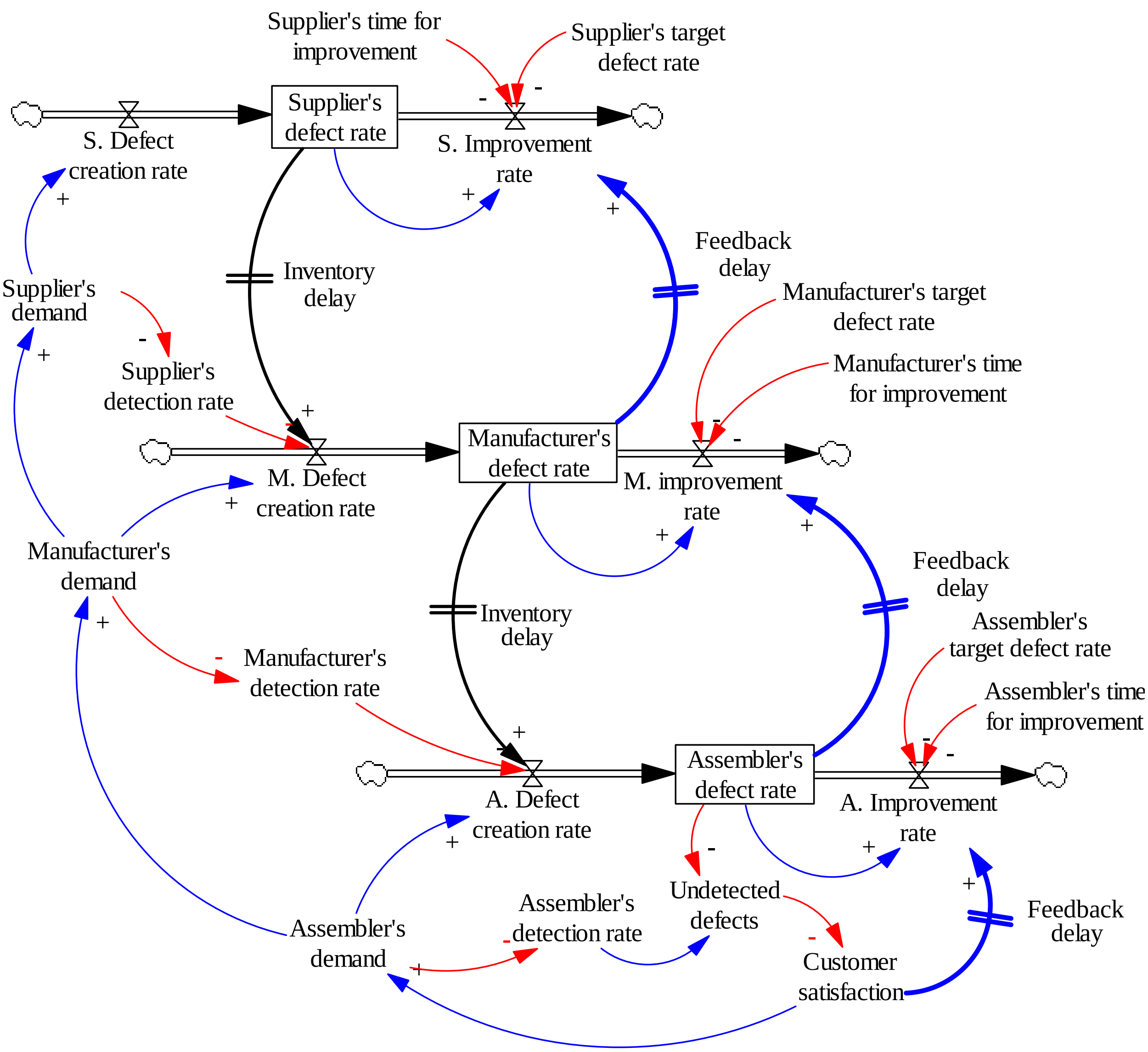


Figure 6-2. Effect of intermediate inventories and feedback delay

There is potential for improvement, therefore, from reducing intermediate inventories, or at least shifting unfinished components to the assembly plant. Additionally, this reduces the potential for damage and postpones the application of finishing closer to the customer, which reduces the number of SKUs in stock (e.g., one unfinished door instead of five doors of the same style and species but different color).

6.8 Alignment of Current Measures with Customer Needs

One of questions proposed for this research was to investigate how aligned are the current measures and standards with the actual customer needs. It has been established in Supply Chain Management literature (see Sections 1.6.4 and 1.6.8) that quality management, of which measurement is a critical process, needs to be aligned with the customers' requirements in order to significantly contribute to the supply chain success. This issue can be addressed by analysis of one example: the use of lumber grades.

Hardwood lumber grades are based on the amount and size of "clear cuttings"; lumber of higher grades yield a larger percentage of defect-free parts than lower grade-lumber. Some provisions in the grading rules deal with species-specific characteristics, like for example color specifications in maple, which set the minimum percentage of sapwood for individual boards (sapwood is desirable in this species for its white color); however, the main focus remains on maximizing yield, not final product quality as seen by the customer. In part to address this, some lumber manufacturers offer "proprietary grades", catering to very specific uses and niches (the components plant did not acquire proprietary grades at the time of the study). By stipulating a specific grade mix for each species in the purchase order, the components plant is basically making a tradeoff between yield at the rough-mill and cost; and not necessarily considering quality from the customer's point of view. Color, for example, which is an important issue at the final customer's end, is inspected visually by lumber graders when the material arrives in its rough-cut state; at the service center, color issues are not included in the installation inspection checklist nor it is listed as a separate attribute in the major quality performance metric. Likewise, the assembly plant does not include color among the attributes for its internal and external quality metric (NCPPM and EOTC). Thus, apart for the inspection at the receiving end of the component plant, lumber color is not systematically evaluated and recorded. Several audits are conducted to control color consistency between cabinet components at the components and assembly plant, but this evaluation is more likely to detect finishing process or finishing materials variances, rather than lumber color consistency issues. The interviewee at the service center considered that color-related customer complaints are more common for within-door variations, suggesting substrate-related issues are most frequent source of customer claims.

6.9 Implications for the Secondary Wood Products Industry

Since this is a single-case study, it is important to indicate the relevance of the findings presented in this chapter to the wood products industry. For this, some considerations about the particularities of the supply chain of study are listed below.

- The supply chain studied is an integrated manufacturer of kitchen cabinets; with manufacturing and service facilities that processes lumber (purchased externally) into components, assembles these components into cabinets and, although not in all cases, carries out the installation at the final customer's home. Since most of the supply chain entities studied are owned and managed by the same corporation, it is more likely that this supply chain will have a higher degree of internal integration than a more fragmented supply chain. Quality policies are prescribed at the corporate level and managers are evaluated based on performance goals set at the company's headquarters. One of the most challenging aspects of managing a supply chain is dealing with different organizational cultures and management approaches, let alone different information systems and quality management methods; therefore, working under the same corporate umbrella certainly benefits integration in the supply chain of study.
- The focal company is among the three largest manufacturers of kitchen cabinets in the U.S (over 5,000 employees in 2004). A larger company will likely have access to more resources to allocate for continuous improvement initiatives. Company size also allows significant leverage when negotiating terms with its suppliers, and to implement a supplier development program (although such a program did not exist at the time of study).

- The focal company has successfully implemented a continuous improvement program, which includes in its methodologies lean manufacturing and six-sigma, which are known to dramatically reduce in inventories, defects, and lead time. The Company has been awarded the ISO 14,001 certification, and the Kitchen Cabinets Manufacturer Association's Environmental Stewardship Program. One of the components plants has received an internationally recognized award for operational excellence in the application of lean manufacturing principles.

Taking the above into account, it can be said that the opportunities for improvement found in this case analysis will likely apply to other companies in the wood products manufacturing sector, where lower degrees of vertical integration are more common. Likewise, the size of the typical company in the industry is much smaller, according to the Census Bureau's 2002 figures, the average number of employees for a kitchen and bath cabinet company in the U.S. was 13.3 employees, with a value of shipments of $1.5 million; the same figures for a non-upholstered wood furniture company are 28.5 and $3.2 million, respectively (U.S. Department of Commerce, 2004a, 2004b).

Lastly, regarding quality management activities, the Company has a well established system of internal quality control policies. Most of the opportunities for improvement identified are related to external quality (i.e., interaction with external suppliers and customers). Companies that have yet to implement sound internal quality management practices will likely benefit from the recommended practices.

6.10 Summary

The kitchen cabinets company has put in place a remarkable quality control and improvement system that spans all of its components, assembly plants, and service centers. The manufacturing philosophy implemented is conducive to the early identification of defects, their causes and elimination. The adoption of standards such as the ISO requires the facilities to have rigorous documentation practices. These practices were found to be consistent throughout the facilities owned by the firm. Each plant is evaluated by its performance, measured in the same scale (defects per million, costs of quality, scrap), and goals for the improvement of these measures are set at corporate level. Undoubtedly, the relatively strong market performance of the company is in great part the result of the practices just described.

When viewed from a supply chain perspective, however, some opportunities for improvement were identified during the study. Probably the greatest departure from what is extensively recommended in the literature is the lack of a formal supplier development program. Particularly, lumber purchases are carried out using a traditional approach, with very little participation of suppliers in the development of quality requirements, and limited or inexistent information sharing of production plans. The corporate quality reporting system does include quality-related measures for each one of the Company's facilities, but this reporting is internally focused, lacking a systems perspective; and does not reflect the relative contribution of each plant to the overall performance. Also, by not including measures of external suppliers' performance, the corporate reporting does not capture performance across the supply chain (Lambert & Pohlen, 2001).

Regarding quality measurement, although the metrics currently used are instrumental in identifying and correcting defects at each facility, they do not facilitate the rapid identification of causes when these originate farther upstream the supply chain. Likewise, quality performance information is shared only with the immediate supply chain partners. Lastly, an attribute that was consistently regarded as extremely important by interviewees throughout the supply chain is color. Great effort is invested in maintaining consistent color at the components and assembly plants, mostly by doing color matching with master samples. However, no company-wide measure of performance for color was in use at the time of the data collection. Final customer claims are mostly related to color and wood issues, but these are not included in the last facility's set of performance measures.

Chapter 7. Supply Chain Quality Performance

In this chapter, the calculation of supply chain performance measures for quality is described and applied to the case study. Previous analysis has found that while current practices contribute to the competitive position of the company, they do not facilitate integration of quality management processes with external suppliers and customers, and can potentially lead to sub-optimization. An alternative approach to supply chain quality performance measurement is proposed, that takes advantage of information readily available and provides managers a clear view of quality performance and the interrelations in the supply chain of study. The supply chain measures will be used to evaluate the impact of current and proposed practices on performance.

7.1 Need for Supply Chain Measures

The need for supply chain (SC) performance measurement has been summarized by Lambert (2001) as a need to: (1) go beyond internal measures, expanding the line of sight from a single entity to the overall SC network; (2) align strategy and activities in the SC, a more difficult task given the complexity of today's supply chains; (3) differentiate the supply chain, in order to gain competitive advantage; and (4) encourage cooperative behavior between supply chain members.

Some frameworks for SC performance measurement proposed in the literature were presented in section 1.6.4. Most of this literature focuses on measures of logistics performance, specifically measuring responsiveness (i.e. time performance), flexibility to changes in demand, and cost effectiveness. Research is limited, however, regarding SC quality performance measurement. Ross (1998, p. 252) lists the development of effective performance measurements among the six main processes of supply chain quality management; and presents eight quality dimensions for the supply chain, which resemble the product and service dimensions identified by Garvin (1984) and Parasunaman (1988). The author also states that sub-optimization can be avoided in part by designing measures that reflect the performance of the entire channel. Up to recently, even GM and Sears, which historically owned much of their supply base and distribution channels, have measures that spanned their entire chains.

As seen in Section 4.7, the Company does report performance indicators for all of its plants on a corporate dashboard separately; however, it does not integrate these indicators into supply chain measures of performance, spanning the entire supply chain (Lambert, 2001). Walker (2005) lists the need to measure performance globally among his five principles for supply chain networks, calling it the “visualization” principle. The same author states that SC measures should “extend outside the four walls” of a single supply chain entity. This chapter describes an example of development process for a supply chain quality measurement system that considers the entire supply chain as a single entity and that reflects performance across the entire system. The approach used six-sigma measures of performance, and was based on methodologies proposed by Van-Aken & Coleman (2002), Lambert and Pohlen (2001), and Dasgupta (2003) Figure 7-1.

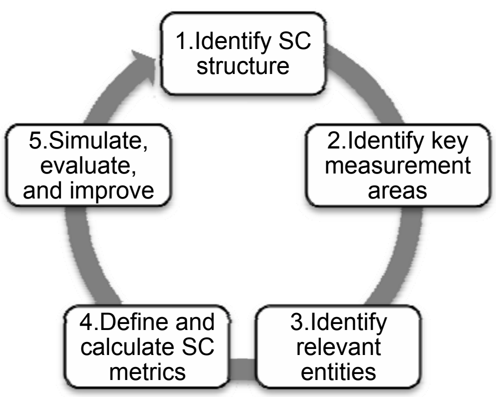


Figure 7-1. Supply chain quality measures development process

The *first* step in the development process, identifying the supply chain structure, corresponds with the first phase of this research, developed in Chapter 3. The supply chain structure comprises the lumber supplier, the door plant, the assembly plant, and the service center. Although not all the entities in the supply chain were included, the performance system presented in this chapter can be easily expanded to include other trading partners.

In the *second* phase, the critical performance areas in which the company must excel in order to achieve customer satisfaction are recognized. It is important at this stage that the areas identified are consistent with the company's strategy. Also at this stage, the critical factors of quality for each performance area are identified. Measures for these factors are developed later. In the case studied for this research, the functional areas for customer satisfaction listed in Table 4-16 will be used as a framework, specifically: (1) customer care, (2) product quality, (3) logistics, (4) sales support. Using of these performance areas is advantageous because they are compatible with the company's customer satisfaction measurement system already in place, and measures developed can be linked directly to the critical attributes of quality. Figure 7-2 illustrates the importance of each area and level of satisfaction with the Company's performance assigned by customers, according to a satisfaction survey conducted by the Company (see Section 4.6). The area under each rectangle represents the "rating" of the Company, which takes into account not only how well the Company is performing in a certain area in the eyes of the customer, but also how important is that area for customer satisfaction.

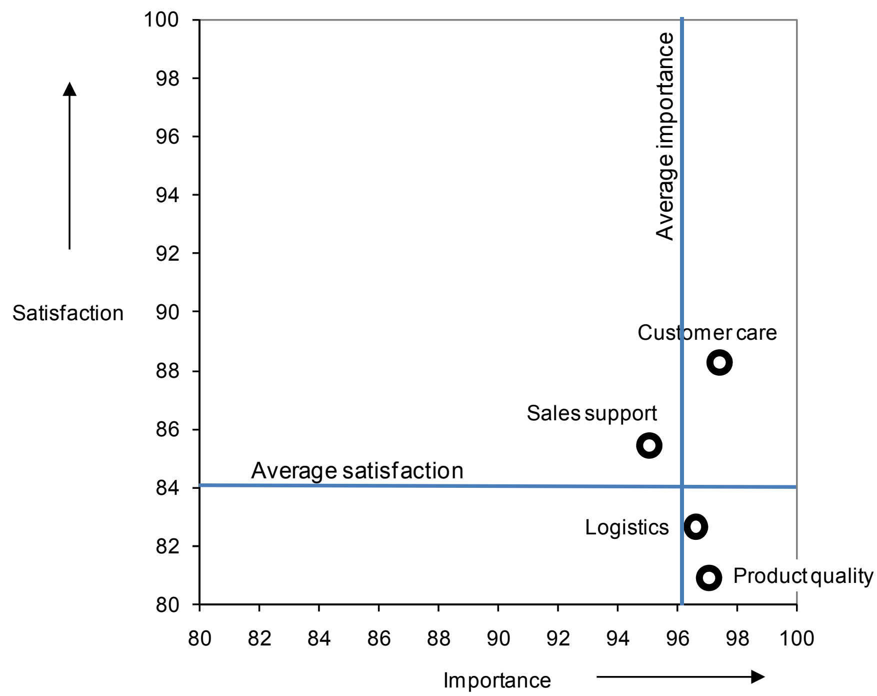


Figure 7-2. Importance and satisfaction of customer satisfaction components

It is clear from Figure 7-2 that logistics and product quality are the areas which improvement will have the most impact on customer satisfaction, since expectations for these attributes are high but performance is relatively low. The example developed in this chapter will focus on these two areas of customer satisfaction. Furthermore, measures will be calculated for the critical factors in the two performance areas “delivering orders on-time” in logistics’ quality (Rahman, 2006); and “quality of construction” in the product quality area (Figure 7-3).

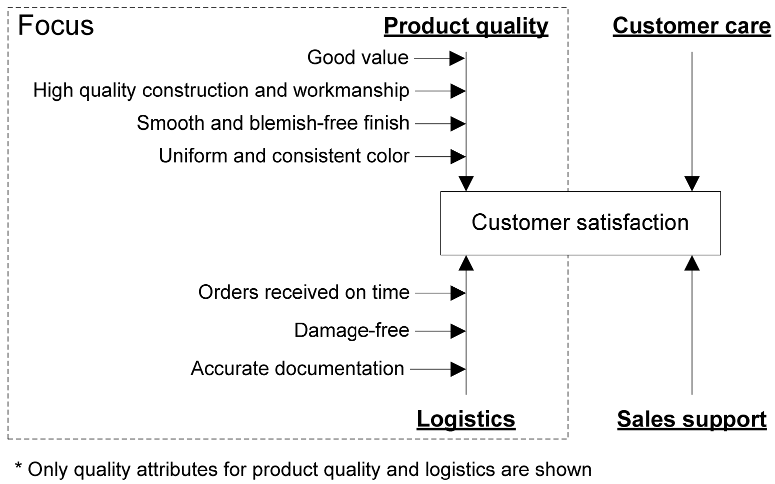


Figure 7-3. Key measurement areas and critical factors of quality

In the *third* phase of supply chain quality measurement development process, the relevant chain entities are identified. Depending on the quality area, the measurement process can include different groups of supply chain entities. For example, responsiveness can include third party logistics providers, whereas for product physical quality these might not be relevant.

In the *fourth* step, the SC measures are defined and calculated. As mentioned before, six sigma metrics were selected for this purpose. The advantages of these metrics were explained in 4.2.6.

Finally, in a last step, the system is tested under simulated conditions to test its robustness and sensitivity, and depending on the analysis of the results, the SC measurement system is corrected or adjusted.

In the following sections, the calculation process is explained, and quality data for the year of analysis are used to compute the current state's quality performance. Finally, alternative practices are suggested and then evaluated using the same measurement framework.

7.2 Six-Sigma measures for Supply Chain Quality Measurement

Although very limited in number, some studies have explored the use of six-sigma to measure supply chain quality performance. Dasgupta (2003) proposed using six-sigma metrics to measure supply chain performance, and he mentions that the major advantage of this approach is that six-sigma metrics allow comparison between processes on the same scale, irrespective of their nature. He applied such approach to a market research enterprise in order to assess time performance.

A six sigma-based methodology was proposed for supplier development by Wang et al. (2004). In order to evaluate suppliers, the authors developed a ranking system, using principal component analysis (PCA), a statistical tool to analyze multidimensional data sets, by reducing them to lower dimensions.

Fontenot et al. (1994) describe how a Malcolm Baldrige Award recipient used six-sigma to measure customer satisfaction. The authors state that customer satisfaction is truly a multi-stage process, because it results from the actions taken at all steps before the product or service reaches the customer. The measurement process is based on the answers to a customer satisfaction survey, where the level of critical satisfaction attributes is assessed by asking the customer to rate his/her satisfaction in a scale (e.g., 1 to 10). A minimum level of satisfaction is defined, and responses that fall below that level are considered defects. For example, if in a sample of 100 customers two customers rate a product/service below five, which is the minimum satisfaction level, the defect rate is 0.02, or 20,000 defects per million, which corresponds to a sigma level of 3.6 (the normal distribution cutoff for a probability of 0.98 plus a 1.5 shift). It must be noted, however, that although fewer defects in specific quality attributes are associated with higher customer satisfaction, the relationship is not entirely proportional; thus, not all gains in defect-free performance translate in proportional gains in customer satisfaction (Behara, Fontenot, & Gresham, 1995). It is even possible to attain higher levels of customer satisfaction without improvements in defect-free products by focusing in what is really important to customers (customers' expectations).

Graves (2001) presented a discussion of the value of using rolled throughput yield (RTY) in situations where different types of products and/or services are compared. This situation can be seen in the kitchen cabinets supply chains, where lumber is processed into doors and other components, which in turn are assembled into kitchen cabinets and then installed in the final customer's house; thus the transformation process adds to the product's complexity. Furthermore, there is a flow of not only physical products with different level of complexity, but also of services at each step (transportation, installation, customer service). RTY facilitates the process of selecting those processes which improvement will have the most significant impact in overall quality and cost reduction. A major advantage of RTY is that it considers the losses at all steps in the transformation process, not only the final result. The author mentions some considerations when processes are in series or in parallel.

7.3 Computational Process

In this section, the procedure for supply chain six-sigma metrics calculation is laid out. It is based on the work by Breyfogle (1999), Dasgupta (2003) and Graves (2001, 2008).

In section 4.2.6, the concept and calculation of defects per opportunity (DPO) were explained. In a supply chain environment, we can calculate the DPO at each level of the value stream by sampling each supply chain entity's output, counting the number of defects, and then dividing by the opportunities to have a defect. The advantage of this approach is that it can be used to compare the performance of different processes, like a manufacturing process (doors) and a service process (customer service). However, in order for this measure to be meaningful, it is very important that defects and opportunities for a defect are carefully defined. Efforts must be made to make sure that the opportunities to have a defect reflect the attributes that are really important for customer satisfaction; otherwise, the defect rate will be underestimated by using numerous and irrelevant attributes.

Throughput yield, or simply yield (Y), is the probability of a unit going through a process without being reworked or scrapped. In a supply chain environment and for large samples, the yield at facility "i" can be approximated by using Equation 10 (Breyfogle, 1999, p. 137). This is derived from a Poisson probability distribution.

$$\mathrm{Y_i}=e^{-DPO_i} \qquad \text{Equation 10}$$

Once the yield for every SC entity is calculated, the overall supply chain Rolled Throughput Yield (RTY) performance can be calculated using Equation 11:

$$\mathrm{RTY}=\prod_{i=1}^{n} \mathrm{Y_i} \qquad \text{Equation 11}$$

The overall DPO for the entire supply chain can then be calculated using the inverse of Equation 9, as follows:

$$\mathrm{DPO_{SC}}=-\ln(\mathrm{RTY}) \qquad \text{Equation 12}$$

Sigma score is a capability indicator commonly used in six-sigma (see section 4.2.6.4). It is calculated by finding the cutoff value of the standard normal distribution for the complement of DPO, and adding 1.5 to account for long-term shifts in process variability:

$$\mathrm{Z_{SC}}=N^{-1}(1-\mathrm{DPO_{SC}})+1.5 \qquad \text{Equation 13}$$

In a typical supply chain, there are processes in series and in parallel. An example of processes in series is the door plant supplying its products to the assembly plant. To calculate rolled throughput yield for process in series, Equation 11 is used as stated. Processes in parallel can be exemplified by several lumber suppliers providing raw materials to the door plant. To be considered in parallel, however, these processes should be interchangeable. For processes in parallel, the following expression is proposed to calculate a weighted average for the *i-th* supply chain position (Graves, 2008).

$$Y_i = \sum_{j=1}^{n} \left(p_j \times DPO_j\right) \qquad \text{Equation 14}$$

In Equation 14, "n" is the number processes in parallel for the supply chain level "i", p_j is the percentage of the input to the next SC level supplied by entity "j", and DPO_j is the defects per opportunity at the entity "j". The yield calculated this way can then be used in Equation 11 to compute the overall SC throughput yield.

Dasgupta (2003) proposed a process to evaluate SC performance in performance a specific business process (e.g., product realization). First, the supply chain structure is identified, which includes deciding which links are "managed"; second, the critical characteristics of the business process are identified (e.g., defect-free products); third, for each SC entity, set performance standards for each critical characteristic; and lastly, compute performance indicators.

Following the described process, the calculation of rolled throughput yield (RTY) for the supply chain of the study is illustrated in Figure 7-4. Once RTY is calculated, it can be easily transformed into defects per opportunity and from there to sigma score (Z).

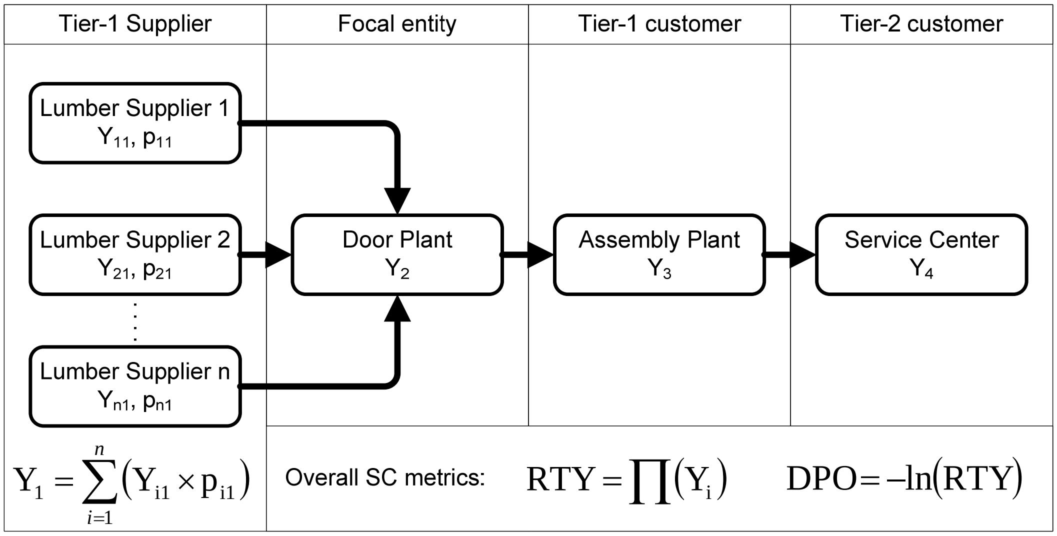


Figure 7-4. Calculation for supply chain rolled throughput

It must be remembered that individual yields are calculated based on the DPO at each stage of the supply chain (Equation 10), and DPO in turn is calculated as the ratio between number of defects and opportunities for defects. The defects have to be defined to represent a certain quality factor to be monitored, and this might not be a trivial task. There are methodologies to identify the critical attributes of a product considering the customers' requirements (see for example Witell & Löfgren, 2007).

As was mentioned in the previous section, six-sigma can also be used to measure customer satisfaction. Following Fontenot's (1994) approach, given a certain attribute to be measured by a customer satisfaction survey using a scale from, say, one to ten, the company defines a level below which the customer is considered to be dissatisfied with the company's performance, and thus is considered a defect. If *n* customers answered to a question about attribute *i*, then the equivalent defect rate would be calculated by Equation 15. Equation 13 can then be used to calculate the sigma level of customer satisfaction.

$$\mathrm{DPO_i} = \frac{Dissatisfied\ customers}{n} \qquad \text{Equation 15}$$

7.4 Measures for Supply Chain Performance

Based on the information presented in the previous sections, supply chain measures of performance have been developed for those performance areas and attributes that have the most impact on customer satisfaction: time performance (logistics) and product quality. A great part of the data needed to calculate these metrics are already collected by the Company on a regular basis. Figure 7-5 and Figure 7-6 illustrate the sequence used to calculate supply chain measures for time performance and quality of the product, respectively.

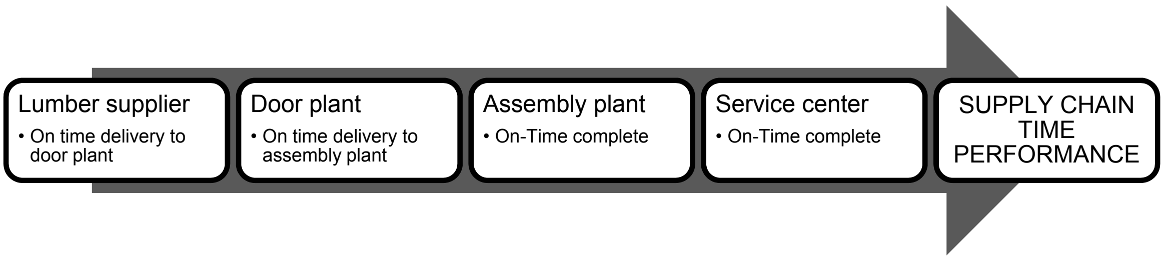


Figure 7-5. Supply chain metrics: time performance

On-time delivery of lumber to the door plant is not currently recorded. Hard maple is the species most likely to cause disruptions in production, since it is bought dry and with very little buffer against late deliveries; thus, a future measure for delivery performance of lumber could initially include hard maple deliveries.

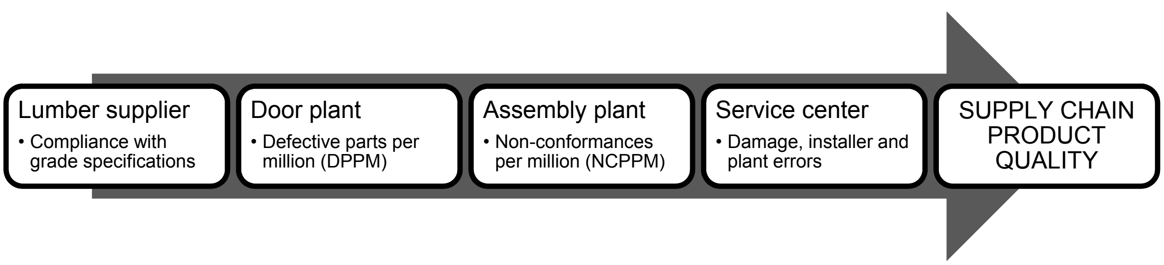


Figure 7-6. Supply chain metrics: product quality

The service center records defect rates for 12 attributes, although most of them are related to quality of service; only damage, installer and plant errors are categories relevant for quality of construction. Defects per million opportunities and non-conformant parts per million are recorded at the door and assembly plant, respectively, and all the attributes considered in these measures are related to the quality of product's construction and finish.

7.4.1 Defects Definitions

As mentioned in the previous sections, it is important to carefully define what will be considered defect, so the measures calculated are meaningful, easy to operationalize, and facilitate prioritizing which areas are in most need of improvement. Table 7-1 lists some examples for definitions of defects, based on the data collected in the study.

Table 7-1. Defect definitions for time delivery and product quality

Supply chain level	Quality characteristic	Defect definition
	---------- Time performance ------------	
Lumber supplier	On-time delivery to door plant	Loads delivered after P.O.'s due date
Door plant	On-time delivery to assembly plant	Components sent after due date
Assembly plant	On-time delivery to service center	Order not shipped on, or before, due date
Service center	On-time completion	Kitchen cabinet not installed until due date
	------------ Product quality ------------	
Lumber supplier	Quality conformance of lumber	Load dies not meet grade requirements
Door plant	Quality conformance of door	Non-conformance as defined in Table 4-7
Assembly plant	Quality conformance of cabinet	Non-conformance as defined in Table 4-9
Service center	Kitchen cabinet's quality of construction	Damage, installation errors, plant errors
	------------ Overall performance ------------	
Supply chain	Customer satisfaction	Satisfaction level less than 80 percent

7.4.2 Time Performance Calculation

In this section a sample calculation for a measure of supply chain time performance is shown. The door plant does not currently have a formal system to record on-time delivery of lumber purchases (Section 5.1.4). At the moment, cherry, soft maple, and oak are purchased green and therefore the timely delivery of lumber is not as critical as the accurate scheduling of pre- and kiln- drying of these species. However, hard maple is purchased kiln-dried, and is an important percentage of total lumber usage (38 percent in the year of analysis), therefore late deliveries of this species could potentially lead to disruptions in the tightly scheduled production. In the example, on-time performance of lumber deliveries was not included in the calculations, since the plant does not record this information. Table 7-2 shows the calculation process using the equations in Section 7.3. Figure 7-7 and Figure 7-8 show the results in a graphic manner.

Table 7-2. Calculation of supply chain measures of time performance

	Door plant			Assembly plant			Service center			**Supply Chain**	
	Late delivery rate	Yield	Sigma score	Late delivery rate	Yield	Sigma score	Late delivery rate	Yield	Sigma score	**Rolled throughput yield (%)**	**Sigma score**
Jan	0.021367	97.89%	3.53	0.01300	98.71%	3.73	0.138900	87.03%	2.63	**84.1%**	**2.50**
Feb	0.020071	98.01%	3.56	0.01200	98.81%	3.76	0.132300	87.61%	2.66	**84.8%**	**2.53**
Mar	0.014275	98.58%	3.69	0.01300	98.71%	3.73	0.112700	89.34%	2.74	**86.9%**	**2.62**
Apr	0.017429	98.27%	3.61	0.01000	99.00%	3.83	0.126200	88.14%	2.68	**85.8%**	**2.57**
May	0.047375	95.37%	3.18	0.01200	98.81%	3.76	0.050800	95.05%	3.15	**89.6%**	**2.76**
Jun	0.032118	96.84%	3.36	0.00900	99.10%	3.87	0.089800	91.41%	2.87	**87.7%**	**2.66**
Jul	0.057417	94.42%	3.09	0.01500	98.51%	3.67	0.099200	90.56%	2.81	**84.2%**	**2.50**
Aug	0.025242	97.51%	3.46	0.01300	98.71%	3.73	0.135200	87.35%	2.64	**84.1%**	**2.50**
Sep	0.014623	98.55%	3.68	0.00800	99.20%	3.91	0.157100	85.46%	2.56	**83.6%**	**2.48**
Oct	0.023730	97.65%	3.49	0.00900	99.10%	3.87	0.131200	87.70%	2.66	**84.9%**	**2.53**
Nov	0.021044	97.92%	3.54	0.00700	99.30%	3.96	0.111900	89.41%	2.75	**86.9%**	**2.62**
Dec	0.009744	99.03%	3.84	0.00600	99.40%	4.01	0.090900	91.31%	2.86	**89.9%**	**2.77**
Average	0.025370	97.50%	3.46	0.010583	98.95%	3.81	0.114683	89.20%	2.74	**86.1%**	**2.58**

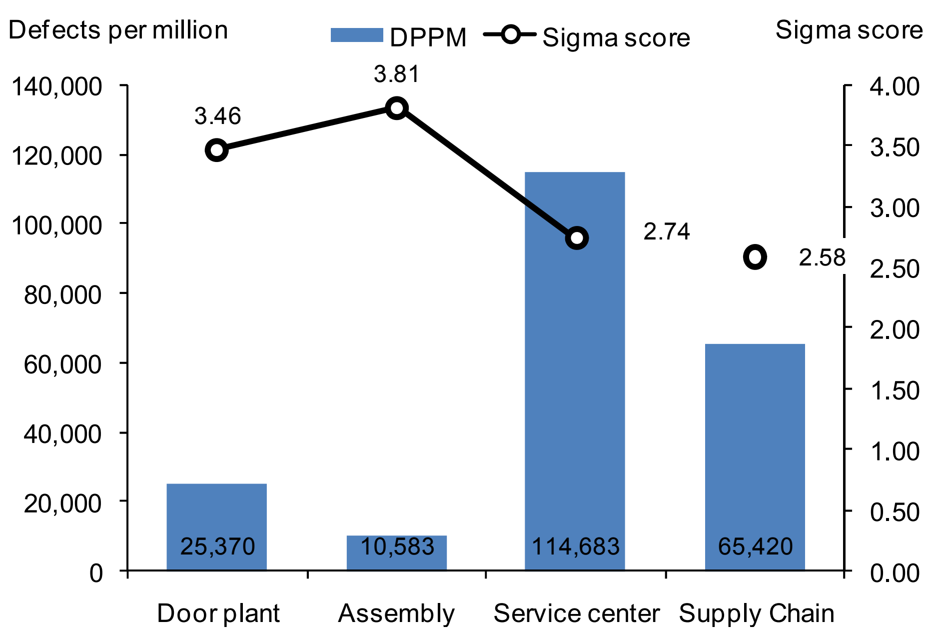


Figure 7-7. Supply chain time performance – Defect rate and sigma score

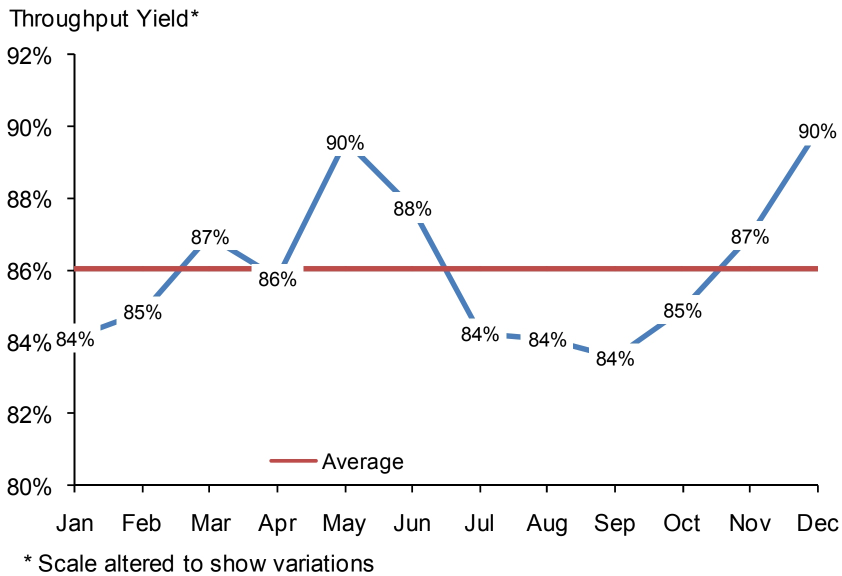


Figure 7-8. Supply chain time performance– Rolled throughput yield

An appropriate interpretation of the results shown above is that, in the supply chain of study, an order which parts were not pulled from stock, has an 86 percent chance of being delivered to the customer on time; or that of every 100 orders starting at the door plant, 86 orders are delivered on-time. Note that although the door and assembly plants are performing at on-time rates between 97 and 99 percent, the overall result for the entire supply chain is much lower, with a sigma level of 2.58. As was illustrated in Figure 5-15, rolled throughput yield is very sensitive to the number and yield of consecutive processes included in the calculations. A simple average of yields at all three steps in the supply chain would have resulted in a time performance of 95 percent, but this approach, contrary to rolled throughput yield, does not reflect the real effect of poor performance at one point in the supply chain on the overall performance (Pyzdek, 2000). Adopting throughput yield as measure of supply chain performance helps management to focus improvement efforts at weak processes, even though others might be performing at or above target values.

Figure 7-8 shows a linear analysis of rolled throughput yield for the year of analysis. Clearly, values for this indicator follow a similar pattern to the one exhibited by the service center, and the latter in turn, has a strong association with the number of orders served by the branch. Note, for example, that an order processed in September (when yield is at its lowest) is about six percent less likely to be delivered on time than in December (when yield is at its maximum). The company would benefit, therefore, of efforts to smooth out these differences.

Any performance measurement system should help its users to (1) identify problems early enough so corrective action can be taken without incurring in costly rectifications, and (2) assign priorities to problems which resolution will have the most impact on quality improvement (Graves, 2001). In Figure 7-8, it can be observed that the overall yield drops for five consecutive months from May to September. Such behavior could trigger a corrective action when performance drops for two or three consecutive periods, before the decline in on-time delivery is too large. To meet the second condition, it is necessary to look closer into the causes for late deliveries throughout the supply chain. This analysis can be made by using the information in Figure 7-9.

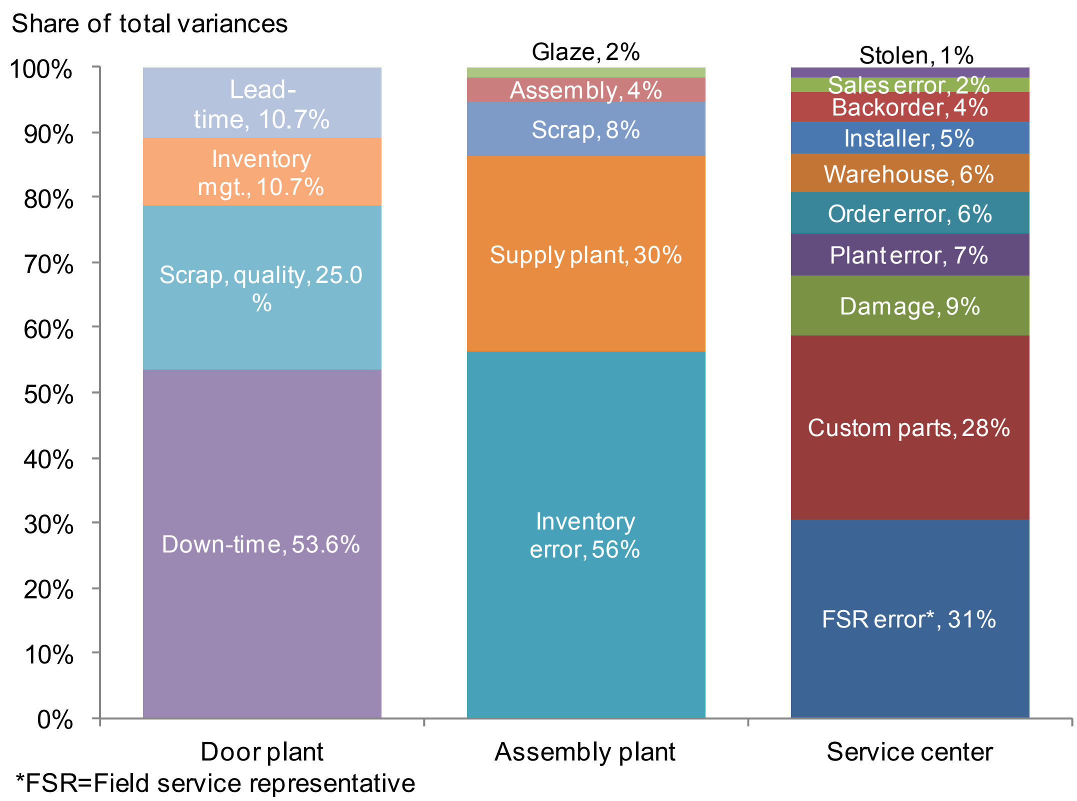


Figure 7-9. Supply chain time performance – Causes for late deliveries

In Figure 7-9, at the service center level, the causes for late deliveries that can be traced back to the assembly plant are: damage, plant errors, and backorders; all these making up to 20 percent of total causes for not delivering on time. At the assembly plant, 30 percent of causes are due to the source plant, and 63 percent (see Figure 5-25) specifically to doors. Thus, it can be said that about four percent (0.20x0.30x0.63=0.04) of late deliveries by the service center are caused by errors at the door plant level. At the door plant, downtime, quality issues, and inventory management account for 89 percent of late shipments to the assembly plant. Thus, if these occurrences are trimmed in half, for example, the potential impact at the service center level could be a two percent reduction in late deliveries (0.44x0.04=0.02).

Similar analysis can be made with late deliveries caused by assembly “plant errors” (7 percent at the service center). About four fifths of these errors consist of receiving the wrong items from the assembly plant, because of inventory errors. Thus, reducing inventory errors by a third, for example, could potentially result in a two percent reduction in late deliveries to the customer (0.07x0.80x0.33=0.02).

Improvements in on-time delivery are closely associated with improvements in customer satisfaction, as surveys conducted by the Company suggest (Section 5.5). Thus reductions in late delivery rates should be pursued determinedly. The Company currently has a short lead time compared to industry standards (Cumbo, et al., 2006), but achieving a hundred percent of orders delivered on-time - one of the Company’s goals - requires tackling issues at their origin, which in a significant part are located far upstream in the chain.

7.4.3 Product Quality Performance Calculation

In this section a sample calculation for a supply chain measure for product quality is explained. Lumber suppliers’ performances are included in the calculations, using Equation 14, a sum of the weighted average of the individual lumber suppliers’ defects rates. For this example only three suppliers are included, those who sold about one-fifth of the total lumber inputs to the door plant. The defect rate for lumber suppliers will be computed according to Section 5.1.4, this is, a non-conformance is any load that does not comply with the grade requirements of the purchase order. Other attributes that can be included are: moisture content, thickness accuracy, and compliance with length and color specifications (the latter for hard and soft maple only). A sample calculation is shown in Table 7-3.

Table 7-3. Sample calculation for lumber suppliers' quality performance

	Supplier 3	Supplier 4	Supplier 5
Lumber loads	16	12	12
Failures (off-grade loads)	2	2	0
Defects per unit (DPU*)	0.125000	0.166667	0.000000
Share of total lumber	36%	26%	37%
Weighted DPU_i	0.045517	0.044086	0.000000
Overall DPU ($\sum DPU_i$)		0.089604	
Yield (exp^{-DPU})		91.4%	
Sigma score $[N^{-1}(Y)]$		2.87	

* Unit in DPU is defined as each load of lumber

Since the door and assembly plants' measures of internal quality performance (DPPM and NCPPM) already include the critical attributes of quality of construction and workmanship, they will be included directly in the calculations. For measuring quality performance at the service center, however, only those attributes that directly affect the quality of construction will be considered, that is: damage (irreparable chips, dents, and scratches), installer-caused defects, and the portion of plant errors that consists of products with some defect (about 20 percent, according to Figure 6-1). Table 7-4 shows calculations for individual lumber suppliers' performance, Table 7-5 shows the computation process for supply chain measures of product quality, and Figure 7-10 illustrates the overall results for the year of analysis.

Table 7-4. Calculation of lumber suppliers' quality performance

	Lumber supplier													
	Lumber Supplier 3							Lumber Supplier 4						
Month	Loads	Off-grade	DPU	Yield	Sigma score	Share of total	Weightd DPU	Loads	Off-grade	DPU	Yield	Sigma score	Share of total	Weightd DPU
Jan	14	2	0.1429	86.7%	2.61	62.0%	0.0885	3	0	0.0000	100.0%	6.00	12.1%	0.0000
Feb	9	0	0.0000	100.0%	6.00	38.5%	0.0000	10	0	0.0000	100.0%	6.00	41.3%	0.0000
Mar	9	0	0.0000	100.0%	6.00	46.8%	0.0000	5	0	0.0000	100.0%	6.00	22.1%	0.0000
Apr	4	0	0.0000	100.0%	6.00	30.6%	0.0000	5	0	0.0000	100.0%	6.00	26.1%	0.0000
May	3	0	0.0000	100.0%	6.00	11.9%	0.0000	19	1	0.0526	94.9%	3.13	51.5%	0.0271
Jun	6	0	0.0000	100.0%	6.00	20.6%	0.0000	17	0	0.0000	100.0%	6.00	42.2%	0.0000
Jul	6	0	0.0000	100.0%	6.00	23.9%	0.0000	8	0	0.0000	100.0%	6.00	27.3%	0.0000
Aug	9	0	0.0000	100.0%	6.00	26.3%	0.0000	16	1	0.0625	93.9%	3.05	41.7%	0.0260
Sep	6	0	0.0000	100.0%	6.00	16.6%	0.0000	17	1	0.0588	94.3%	3.08	39.4%	0.0232
Oct	16	2	0.1250	88.2%	2.69	36.4%	0.0455	12	1	0.0833	92.0%	2.91	26.5%	0.0220
Nov	10	0	0.0000	100.0%	6.00	31.3%	0.0000	12	0	0.0000	100.0%	6.00	35.7%	0.0000
Dec	3	0	0.0000	100.0%	6.00	15.2%	0.0000	14	0	0.0000	100.0%	6.00	54.3%	0.0000
Average	95	4	0.0223	97.8%	3.51	30.0%	0.0067	138	4	0.0214	97.9%	3.53	35.0%	0.0075

Table 7-5. Calculation of supply chain measures of product quality

	Lumber suppliers overall performance			Door plant			Assembly plant			Service center			**Supply Chain**	
Month	Weighted Avrg. DPU	Yield	Sigma score	Defect rate	Yield	Sigma score	Defect rate	Yield	Sigma score	Defect rate	Yield	Sigma score	**Rolled throughput yield (%)**	**Sigma score**
Jan	0.088538	91.5%	2.87	0.038917	96.2%	3.27	0.01400	98.6%	3.70	0.012963	98.7%	3.73	**85.7%**	**2.57**
Feb	0.000000	100.0%	6.00	0.040583	96.0%	3.25	0.01538	98.5%	3.66	0.022222	97.8%	3.51	**92.5%**	**2.94**
Mar	0.000000	100.0%	6.00	0.030583	97.0%	3.38	0.01541	98.5%	3.66	0.015493	98.5%	3.66	**94.0%**	**3.06**
Apr	0.000000	100.0%	6.00	0.033833	96.7%	3.33	0.01611	98.4%	3.64	0.029126	97.1%	3.40	**92.4%**	**2.93**
May	0.027129	97.3%	3.43	0.040917	96.0%	3.25	0.01484	98.5%	3.68	0.000847	99.9%	4.64	**92.0%**	**2.90**
Jun	0.000000	100.0%	6.00	0.040500	96.0%	3.25	0.01239	98.8%	3.75	0.009796	99.0%	3.84	**93.9%**	**3.05**
Jul	0.000000	100.0%	6.00	0.058333	94.3%	3.08	0.01197	98.8%	3.76	0.016667	98.3%	3.63	**91.7%**	**2.88**
Aug	0.026050	97.4%	3.45	0.041833	95.9%	3.24	0.01191	98.8%	3.76	0.018028	98.2%	3.60	**90.7%**	**2.82**
Sep	0.023153	97.7%	3.50	0.030667	97.0%	3.38	0.01166	98.8%	3.77	0.045977	95.5%	3.20	**89.5%**	**2.75**
Oct	0.067560	93.5%	3.01	0.035917	96.5%	3.31	0.01101	98.9%	3.79	0.030000	97.0%	3.39	**86.5%**	**2.61**
Nov	0.000000	100.0%	6.00	0.031833	96.9%	3.36	0.00878	99.1%	3.88	0.007942	99.2%	3.91	**95.3%**	**3.17**
Dec	0.000000	100.0%	6.00	0.028167	97.2%	3.41	0.00642	99.4%	3.99	0.001212	99.9%	4.53	**96.5%**	**3.31**
Average	0.014205	98.6%	3.69	0.037674	96.3%	3.29	0.012490	98.8%	3.74	0.017523	98.3%	3.61	**92.1%**	**2.91**

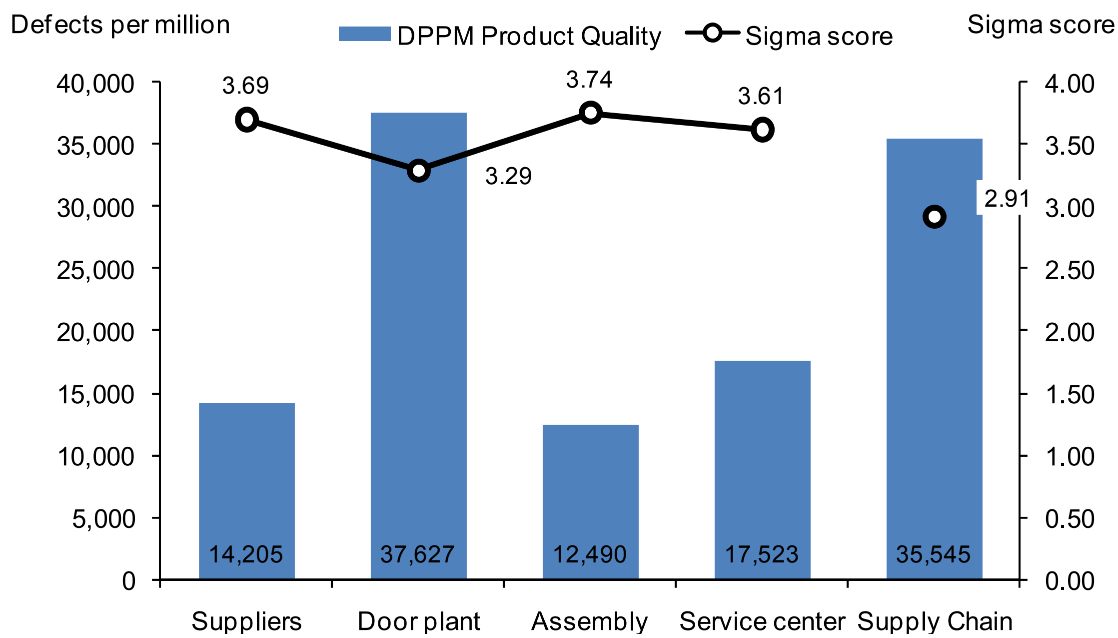


Figure 7-10. Supply chain product quality performance – Defect rate and sigma score

In the case of product quality, it is clear in Figure 7-10 that the defect rate at the door plant is the highest among the supply chain entities. Overall, the supply chain performed at a 2.91 sigma level during the year of analysis, which according to some authors (Harry, 1998; Ravichandran, 2006), it is in the U.S. “industry average” range. No benchmark data is available about other companies in the same industry sector.

A linear analysis (Figure 7-11) of throughput yield reveals that for the year analyzed, a product had a 92 percent chance of going through the lumber-to-kitchen cabinet transformation process without being repaired or scraped. The lowest yield was observed in January (86 percent), caused by lumber Supplier 3 sending a high number of loads that did not meet specifications. The highest yield occurs in December (96 percent), and it is mostly related to the level of activity (production output) in that month, which was the lowest.

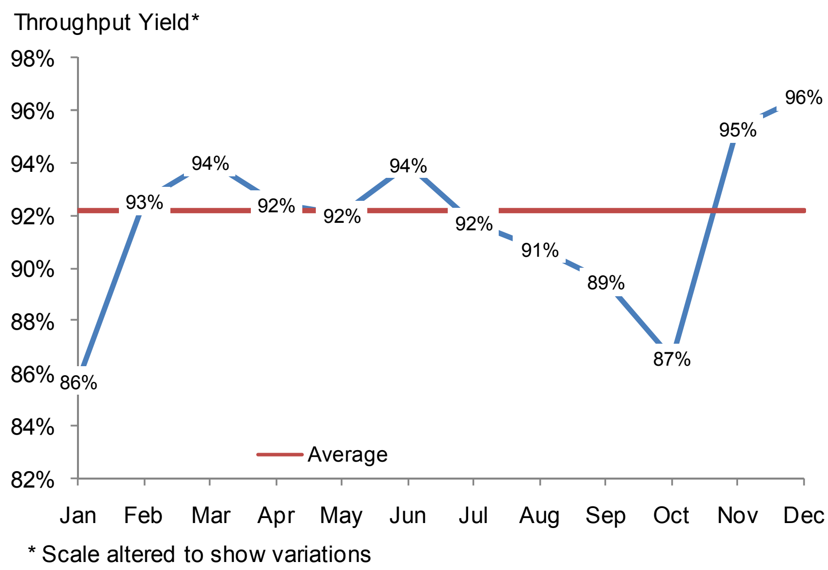


Figure 7-11. Supply chain product quality performance – Rolled throughput yield

A look at individual yield curves for each supply chain entity can help to identify which has more influence on yield. Figure 7-12 clearly shows that the behavior of the entire supply chain yield closely follows that of the lumber suppliers.

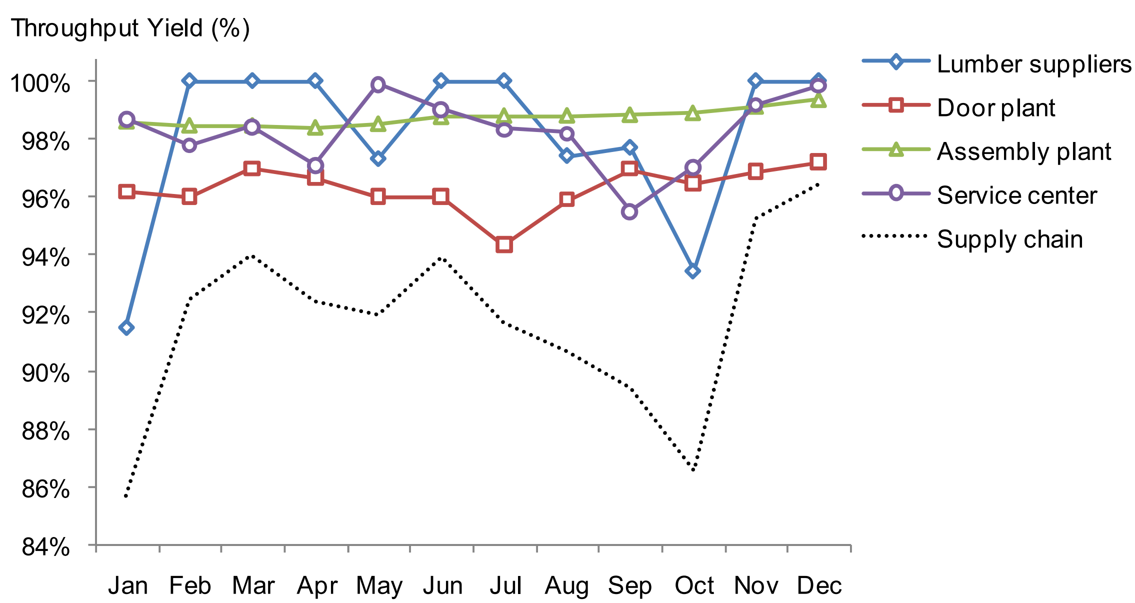


Figure 7-12. Individual and collective throughput yields.

As with time performance, the analysis of product quality is not complete if defects and their origin are not analyzed. Figure 7-13 shows the defects that are monitored during final inspections at each step in the supply chain. Lumber supplier figures represent the percentage of each type of defect on the volume of lumber that was miss-graded (as determined by audits); for example, wane represented three fifths of the total volume of lumber that was incorrectly graded by lumber inspectors.

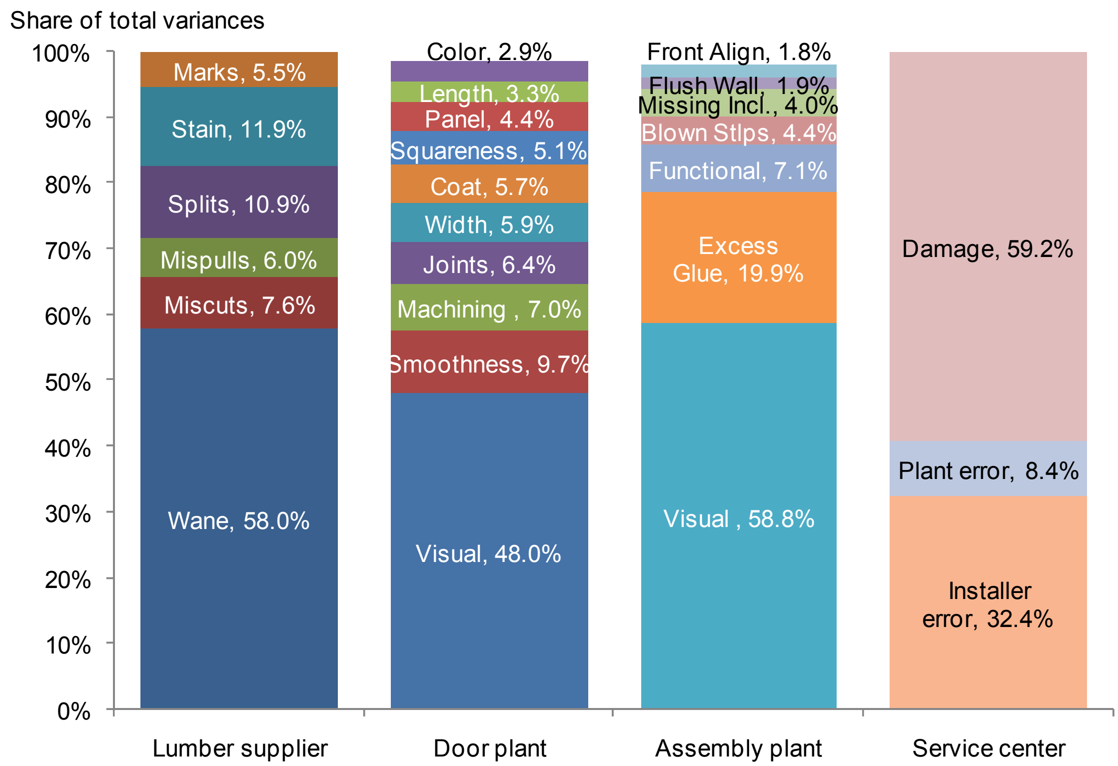


Figure 7-13. Supply chain product quality performance - Causes

At the service center, the defects that can be traced back to the assembly plant are plant errors and damage. Plant errors consist mostly of excess glue and blown staples. Damage appears usually in the form of dents, chip-outs, and scratches, which are grouped into the “visual” defects category at the final inspection in the assembly cells. Part of the damage happens during the assembly plant process, but an estimated 12 percent is originated at the very last steps of the source plants’ processes (Figure 6-1) and after the final inspection, therefore no records are kept at the door plant that could be used to monitor damage that occurs from the end of the finishing line to the reception of parts at the assembly plant. Nevertheless, it can be estimated that a 50 percent reduction in damage from packing to the shipping at the components plants can potentially result in a 3.5 percent reduction in defects at the assembly plant and 2 percent reduction at the service center (0.12x0.5x0.59=0.035 and 0.12x0.5x0.59x0.59=0.02).

The previous analysis is based on several assumptions based on fragmented information. The link between lumber quality and final product quality is not easily established, in part because the current approach for quality measurement at the assembly plant does not facilitate the quantification of materials that were sent defective from the source plants (none of the defect categories inspected at the end of the assembly cells relates to quality of the parts being assembled). Under the current measurement system it is not possible, for example, to estimate the impact of introducing a higher percentage of low-grade lumber into the mix on the quality as seen by the installation personnel at the service center.

7.4.4 Customer Satisfaction Calculation

For this sample calculation, results from a past survey will be used to calculate customer satisfaction levels using Equation 15. The computation process is shown in Table 7-6. The results are represented graphically in Figure 7-14. Satisfaction is highest for customer care, with a sigma level of 3.6. It is important to note that the definition of a “dissatisfied” customer is not trivial. For this exercise, a customer response of less than 3 (in a 1-to-5 scale, with 5 maximum satisfaction) is considered a failure, or defect. If 4 is used as cutoff value, results change significantly, and sales support ends up with the highest sigma score. Thus this decision must receive careful consideration.

Table 7-6. Customer satisfaction computation and results

	Customer care	Product quality	Logistics and transportation	Sales support	Overall*
Respondents	169	164	163	121	249
Dissatisfied	3	7	5	4	11
DPU	0.017751	0.042683	0.030675	0.033058	0.044177
DPPM	17,751	42,683	30,675	33,058	44,177
Sigma level	3.60	3.22	3.37	3.34	3.20

* Data for overall satisfaction was not available, so a proxy measure was used: customers who were willing to recommend the company’s products were considered satisfied with the overall performance

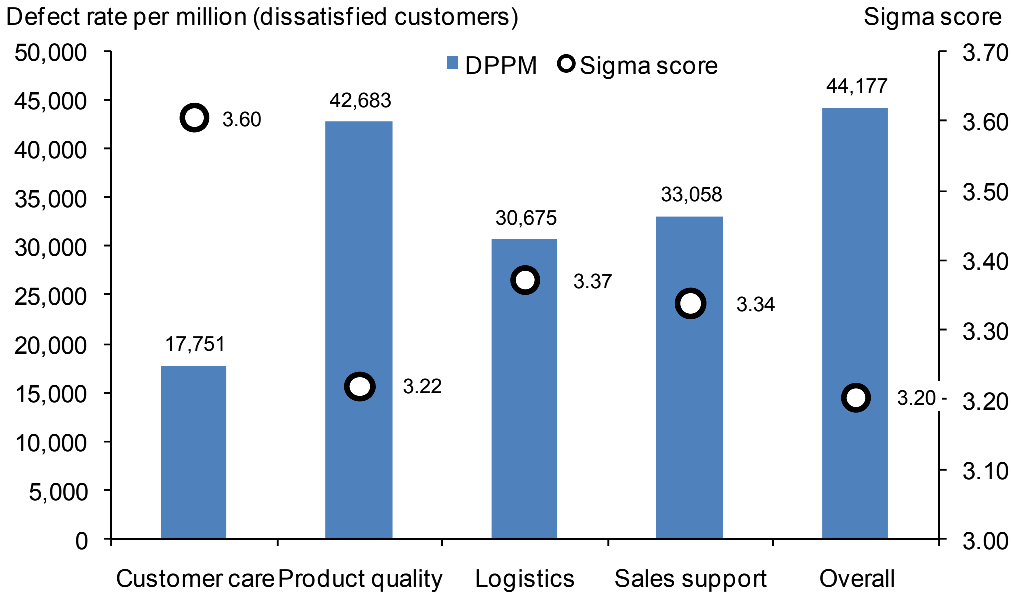


Figure 7-14. Customer satisfaction measures of performance

The interpretation of customer satisfaction results is not as straightforward as with, for example, product quality. It must be remembered that gains in customer satisfaction for key performance areas, like logistics or sales support, does not necessarily translate into proportional gains in overall customer satisfaction. Management should prioritize improvement efforts in those areas that result in the largest gains in overall customer satisfaction, based on previous data. An example of how this can be approached can be found later in this chapter.

Clearly, using six-sigma measures for customer satisfaction provides quantitative measures, easily compared with performance in other areas, like time or product quality performance. One potential use is to make comparisons between performance and satisfaction on different years, to determine the impact of quality improvements on customer satisfaction using a consistent scale.

7.4.5 About Sigma Scores

In the previous sections, supply chain measures were calculated using historical data; among these were sigma scores for individual plants and for the supply chain. No data about other companies in the same industry was available at the time of the study, thus no comparisons of performance can be made. However, some benchmarks can be found in the six-sigma literature regarding sigma scores; two examples are listed in Table 7-7. Using these guidelines, plants in the supply chain of study would rank in the “industrial average” or “capable” categories. No such guidelines exist regarding entire supply chains, where the interpretation of yield and sigma score might not be straightforward. By multiplying the yields of each entity in the supply chain, it was implied that every step has the same importance on the overall performance. This practice might appear controversial in some situations, especially when more components are added, like for example hardware suppliers or transportation operators. An alternative approach is to use a weight-based sigma score, which is calculated by assigning importance weights to each step in the process. Weights could be determined, for example, by estimating the importance of each component on customer satisfaction or based on quality costs. Ravichandran (2006, 2007) provides some guidelines to use this approach.

Table 7-7. Sigma score and

Sigma score	Category	Authors
5-6	World-class	
3-5	Industrial average	(Harry, 1998; Ravichandran, 2006, 2007)
1-3	Non-competitive	
66	Six-sigma	
65	Very capable	(Raisinghani, et al., 2005)
64	Capable	
63	Not capable	

It must be noted that the figures obtained using the proposed performance measurement system should be used as tools to identify and prioritize opportunities for improvement, and not as ultimate targets. Deming warned against using “numerical quotas”, and about their unintended consequences (Jankowski, 2006) .

Lastly, the numerical calculations should be taken as an example of the application of the suggested performance measurement system, since only a fraction of the supply chain members was included.

7.5 Simulation of Performance Measurement System

With the purpose of assessing the effect of different scenarios on supply chain quality performance, the measurement system described in the previous section was incorporated in an electronic spreadsheet format. The relationships described in Section 5.6 and illustrated in Figure 6-1 were used to calculate performance indicators at one point in the supply chain based on certain variables. For example, the strong linear association between defect rate and production volume was used to calculate the former based on a historic or randomly generated demand. The use of Visual Basic for Applications (VBA) programming code in combination with spreadsheet formulas, and other software's capabilities provided enough flexibility to allow the generation of randomly generated variables, or alternatively the use of historical data in the calculations, based on a Monte Carlo approach. Monte Carlo simulations are stochastic techniques based on random numbers and probability distributions. For this study, the use of such technique allowed the systematic analysis of the influence of different variables (and changes in those variables) on the performance of the entire supply chain and its components. If the effect of changes in demand were of interest, this variable was first randomly generated and then scaled up or down by a factor corresponding with the desired shift in demand, and all performance measures were automatically recalculated; or, if the impact of changing the content of 2-Common lumber in the raw material mix was analyzed, different percentages were randomly generated, and demand was kept at fixed levels. The simulation set-up is represented in Figure 7-15.

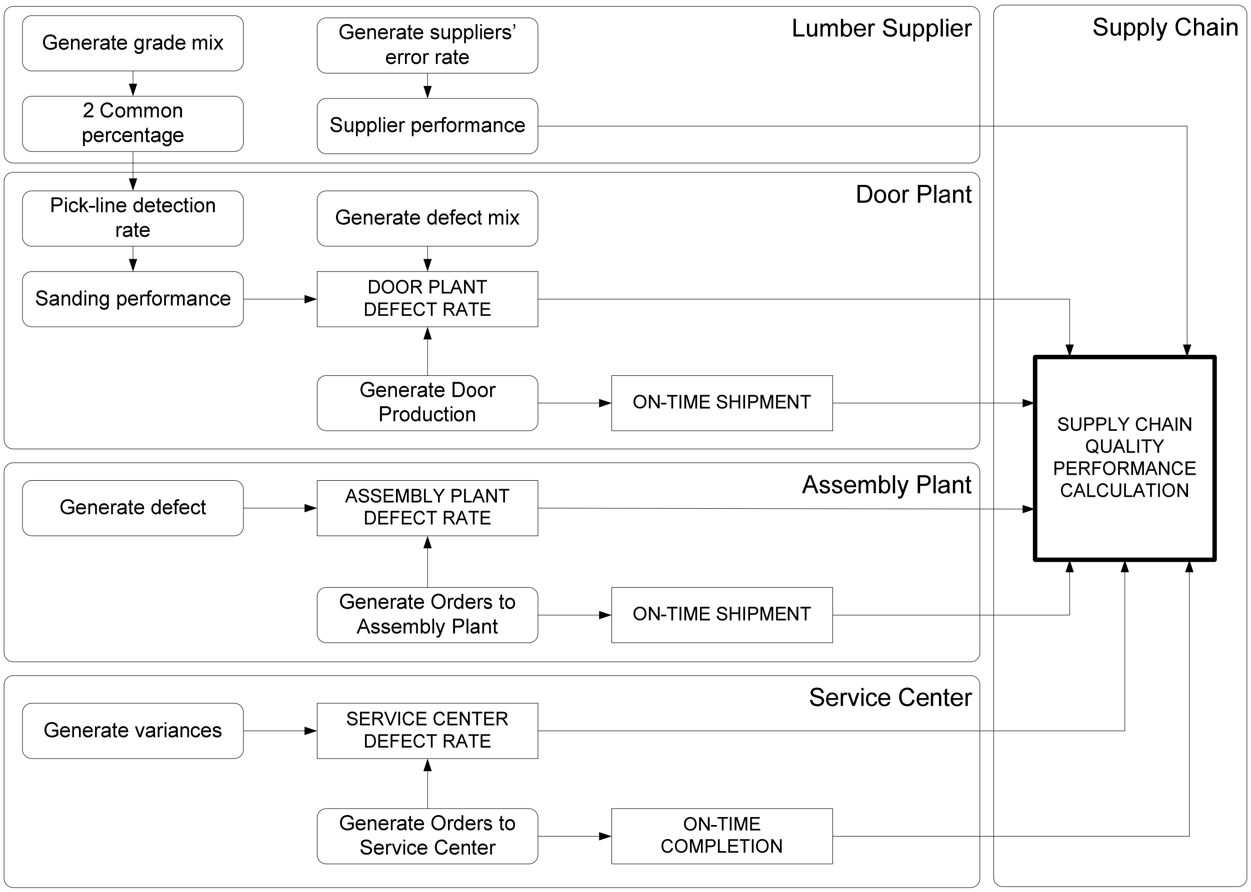


Figure 7-15. Monte Carlo simulation for supply chain quality performance measurement

The first step to enter the formulas and writing the VBA code was to estimate the probability distributions of the variables included in the model. A combination of tools was used for this purpose. First, a scatter plot and histogram helped to decide between potential distributions. Then, software products were used to run goodness-of-fit tests on each distribution: the Input Analyzer by Rockwell Software® (Version 7.1.00), statistical software SPSS® Version 13.0, and the Data Analysis Toolpak included in Microsoft Excel® Version 2007. In a few cases, a transformation of the response variable yielded a better fit. The results of this analysis are shown in Table 7-8.

Table 7-8. Distribution fits and goodness-of-fit test of quality variables

Category	Variable	N[1]	Random generation equation and parameters[2]	Sq. error/ SD[3]	p-value[4]
Missed grade lumber load	Misses Supplier 3	110	Poisson (0.03636)	0.000	<0.01
	Misses Supplier 4	164	Poisson (0.08536)	0.000	<0.01
	Misses Supplier 5	110	Poisson (0.00000)	0.000	<0.01
Percent of 2-Com	% 2C Red oak	14	Gamma (0.00342, 7.73)	0.009	>0.15
	% 2C Cherry	14	0.04 + 0.1 * Beta (1.62, 1.86)	0.019	>0.15
	% 2C Soft maple	14	0.03 + LogNormal(0.0369, 0.0196)	0.001	>0.15
Demand/orders	Door plant	12	Normal(0.0277;36,136)	0.004	>0.15
	Assembly plant	12	Triangular(-1,870;-1,050;2,920)	0.038	>0.15
	Service center	12	Triangular(-56;16.8;48)	0.009	>0.15
Time performance	Door plant On-Time	17	[1.01-8.4E-8*Production] +	N/A	<0.01
			[-0.01+0.02*Beta(2.26,2.26)]	0.020	>0.15
	Assembly plant OTC	12	[0.99-6.7E-7*Orders] +	N/A	=0.05
			[-0.01+0.02*Beta(10.9,10.9)]	0.011	>0.15
	Service center OTC	58	[-5.60+-0.14*Orders] +	N/A	=0.00
			[-0.13+0.25*Beta(3.46,3.06)]	0.005	>0.15
Door plant quality Performance	Final defect rate	12	[8,985+0.08*Production] +	N/A	=0.02
			[Triangular(-8,090;-1,380;14,300)]	0.085	>0.15
	Defect percentages	1,538	Poisson for 11 defect categories	0.000	<0.01
Assembly plant Performance	Final defect rate	12	-5,290+9.47*Orders	N/A	=0.01
	Eyes-of-the-Customer	12	[0.95-1.2E-6*Orders]+	N/A	=0.03
			[-0.01+0.02*Beta(4.75,4.75)]	0.023	>0.15
	Defect percentages	3,000	Poisson for 10 defect categories	0.000	<0.01
	Backorders	12		N/A	=0.04
Service center performance	Product quality	12	Product quality component	N/A	N/A
	Defect percentages	58	Poisson for 10 defect categories	0.000	<0.01

[1] N = number of raw data points
[2] Parameters calculated with Input Analyzer by Rockwell Software
[3] Mean square error of fitted distribution and actual data / Standard Deviation
[4] p-value: (1) Kolmogorov-Smirnov goodness-of-fit test (high values denote a good fit) for continuous distributions. (2) Chi-square test for discrete distributions (low values denote a good fit). (3) Significance of lineal regression where appropriate.

Any simulation has to be tested to determine how its results resemble those of the actual system. This is known as validation (Kelton, 2004, p. 540). Validation is an iterative process, and several modifications are made during this phase until there is a good level of satisfaction with the model outcomes. In a second phase, the model is used to investigate the impact of changes in the inputs or parameters on the actual system's behavior. Thirdly, the model's structure is changed to see how these changes affect the results. The supply chain performance measurement model was tested following the process just described; this is illustrated in Figure 7-16, and detailed results and analysis for each phase follow.

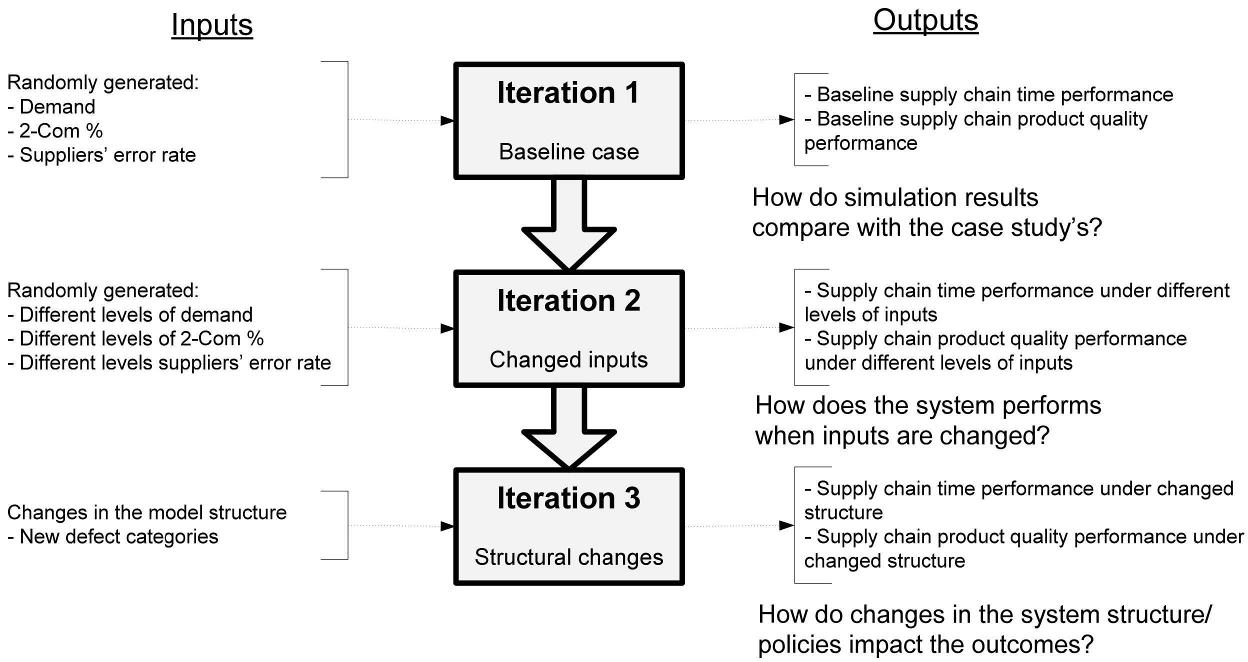


Figure 7-16. Iterations of the supply chain performance measurement model

When validating the simulation, some way of measuring how accurately the model's outcomes follow the actual system's behavior is needed. For this purpose, two major measures were used: (1) when simulation and historical averages had to be compared, a T-test comparison of means was used, assuming two tails and unequal variances; and a significance of 0.05; and (2) upper and lower bounds of one standard deviation were calculated for the simulation averages, and assuming a normal distribution, it can be said that approximately three out of ten data points generated in the simulations fall outside these limits. The one standard deviation bounds in combination with the historical average provide a good measure of how close the simulation results are to the historical values.

7.5.1 First Iteration: Baseline case

In the first iteration, all input variables were randomly generated and performance measurements calculated. These "baseline case" results were compared with historical values for the period of analysis. The complete results of ten validation runs of the simulation model appear in Appendix C. In the next sections, selected results are shown and commented.

7.5.1.1 Production Volume Generation Module

Production volumes in all supply chain facilities were found to have the strongest influence on defect rate, both in time performance and product quality. Thus, the first component of the supply chain performance measurement simulation is a production volume generator. The decoupling point in this supply chain is the assembly plant, from which point all orders are executed to against customer orders; but in the case of the components plants, these produce mostly to stock, as was explained in Section 3.10. The purpose of this module is not forecasting demand but rather to randomly generate production volumes at the different facilities. Production volume was generated using a systematic and a random component, the latter following a specific probability distribution (see Table 7-8 for a list of distribution and parameters). Figure 7-17 illustrates the results of the ten validation runs for the production volume generator. Since data for only one year was available, a seasonal factor was not included, which explains in part the lower variability of generated data. For the three facilities, no significant difference existed between the historical and simulated averages.

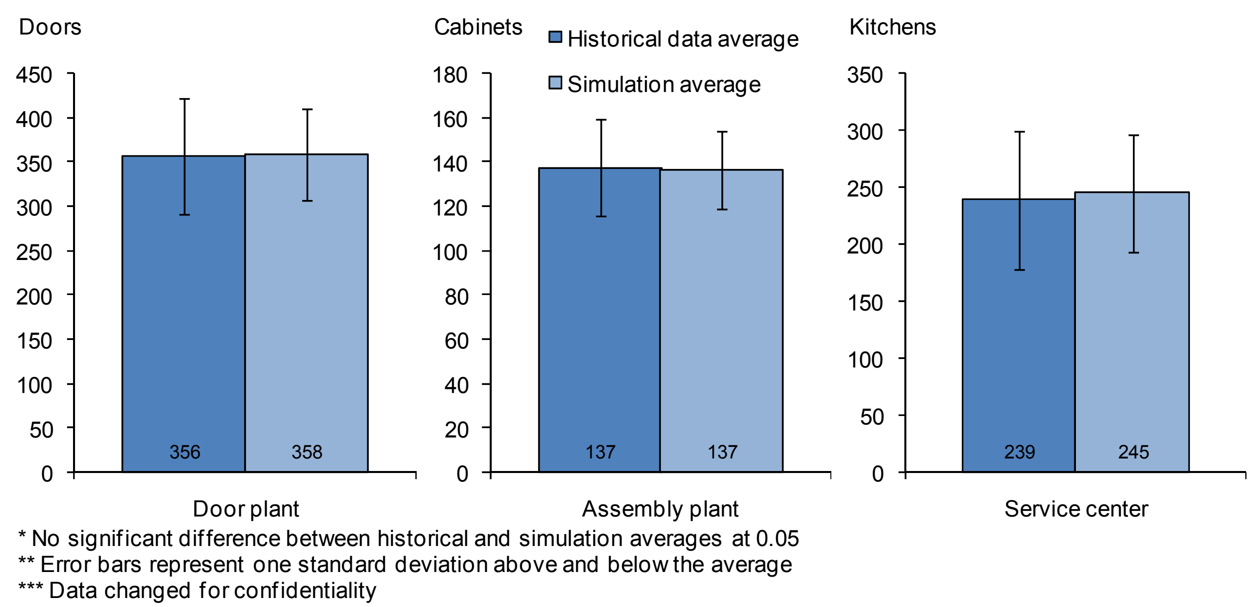


Figure 7-17. Production volume generator validation results for 12 months.

7.5.1.2 Defect Generation Module

Modules of VBA code were written to simulate: (1) the generation of defects at the final inspection of the door plant, (2) generation of defects at the final inspection of the assembly plant, (3) variances occurred after cabinets are shipped from the assembly plant, and (4) variances that prevent the timely completion of installation works at the service center. These defect generators used historical data to calculate the parameters and the Poisson probability distribution to generate defects occurring; based on this, measures like defect rate and share of each defect category could be calculated. The Poisson distribution approximates Binomial probabilities when the number of trials is large and the number of successes is small (roughly n>30, and nxp<10, where p is the probability of success in each trial), and allows for a more efficient computational process (McPherson, 1990, p. 126). The process of generating defects is depicted in Figure 7-18.

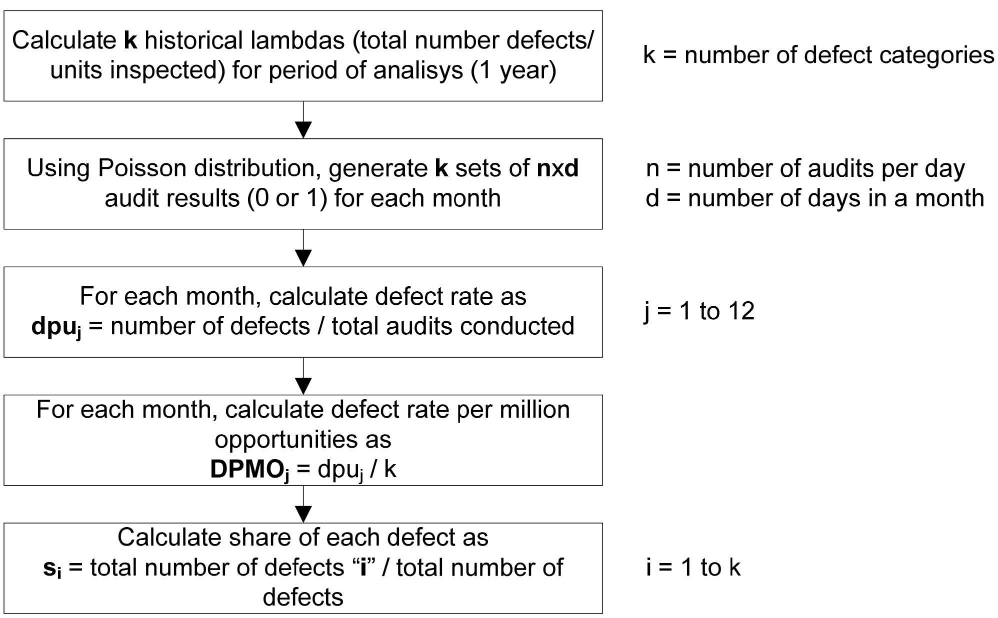


Figure 7-18. Defect generator process.

Figure 7-19 shows the results for ten runs of the defect generator for the final inspection at the door plant. The percentages were calculated simply by dividing the number of defects generated in each category by the total number of units inspected, as shown in Figure 7-18.

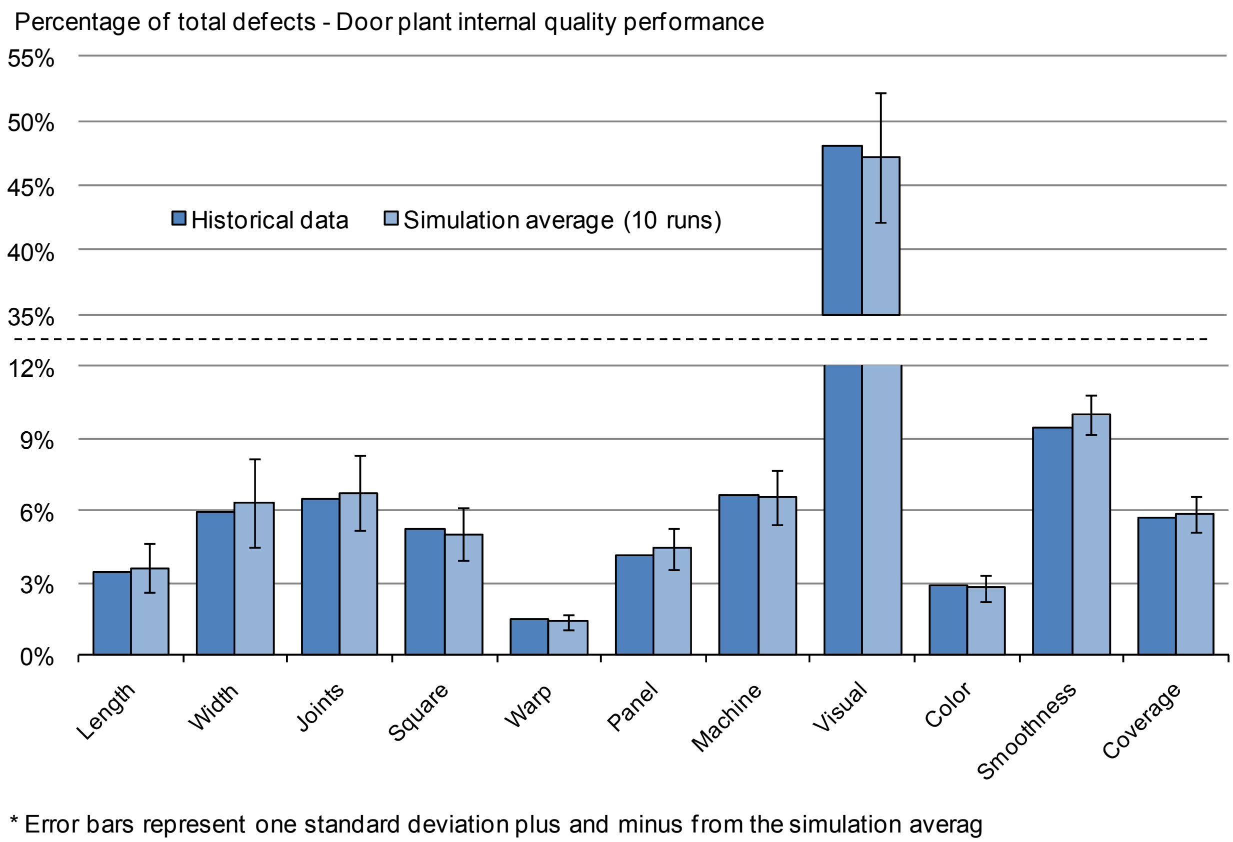


Figure 7-19. Validation results for the door plant's defect generator

As shown in Figure 7-19, the historical averages for all defects fall within one standard deviation above and below the simulation average. The main quality measure, defects per million opportunities, was calculated with the same set of data from the defects generator, and is presented in Figure 7-20, along with the historical and simulation averages. The one-standard deviation bounds were calculated using the simulation data. For the ten runs, the simulation average is two percent higher than the historical average, and the latter falls within the one-standard deviation bounds.

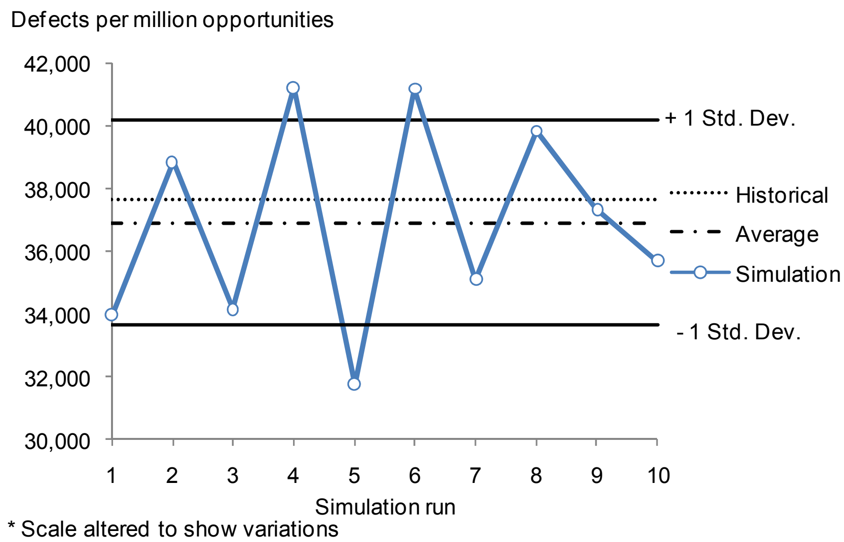


Figure 7-20. Validation results for the door plant's defect generator - DPMO

Results for the defect generator for the assembly plant are shown in Figure 7-21 and Figure 7-22. As with the door plant defects, the historical values are very close to the historical ones, and the standard deviation bounds include the historical value in each case.

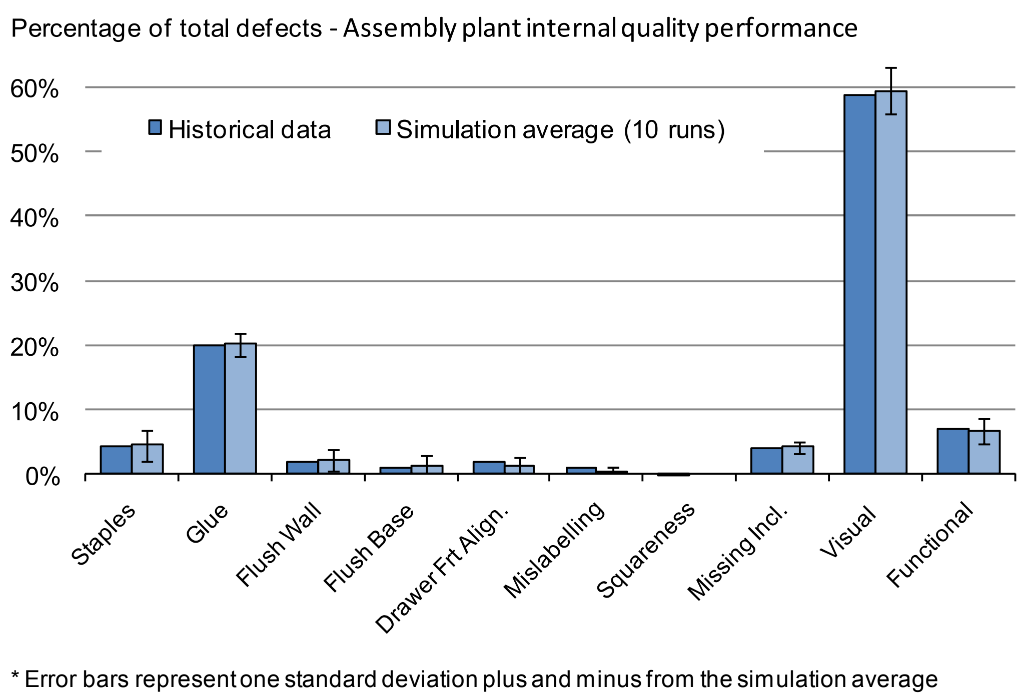


Figure 7-21. Validation results for the assembly plant's defect generator

Defect per million opportunities calculated from the simulation results are compared with historical values in Figure 7-22. In this case, the simulation average is just 0.2 percent of the historical value, and the smallest simulation value is 3.6 percent smaller (5th run).

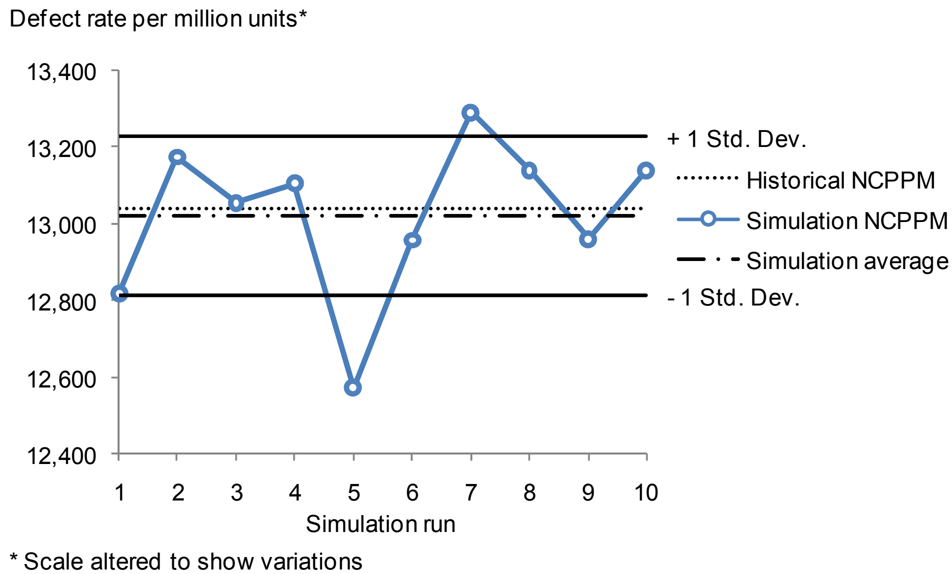


Figure 7-22. Validation results for the assembly plant's defect generator - DPMO

In a similar way, defect generators were programmed for the assembly plant's external defect rate (eyes-of-the-customer) and for the service center variances that prevent the timely completion of installation works. The results for these simulations can be found in the Appendix C.

7.5.1.3 Lumber Supplies – Percentage of 2-Common Lumber in the Mix

The quality of the raw material affects process performance, as was described in Section 5.6.2.1 and Figure 6-1. Thus, a module for the generation of 2-Common lumber contents in the raw material mix was included. The probability distributions for each species listed in Table 7-8 were used to randomly generate percentages for a one-year period. Results for ten simulation runs of the module are shown in Figure 7-23.

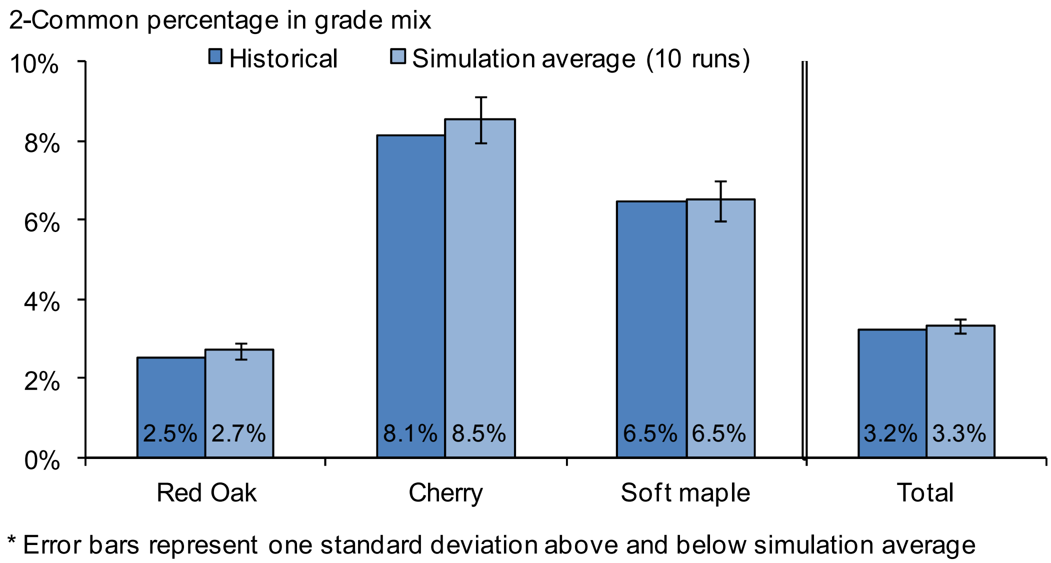


Figure 7-23. Validation results for the 2-Common lumber content generator

7.5.1.4 Lumber Supplies – Error Rate from Lumber Suppliers

A supplier's error rate is the fraction of the total number of lumber loads received that misses the grade requirement. This was considered the main quality measure of supplier performance in the performance measurement system proposed, and thus a module for the generation of error rates was included in the simulation. Specifically, every time the percentage of 2-Common lumber exceeds the maximum allowed, it is considered a defect, or error. For example, if a supplier sends 20 lumber loads in a month and one load contains excessive amounts of low grade lumber, its defect rate would be 1/20=0.05, or 5 percent. Only three suppliers were included, and their error rates were combined using a weighted average (see Equation 13). In a real-life application, all suppliers should be included, and the information needed is readily available from the grading process at reception. Also, this approach to measure supplier performance was selected in part because the data was available to the researcher, but in an actual application it is recommended to include other factors in the calculation, such as timely delivery, accurate moisture content, color consistency, or excessive number of rejects. Suppliers' defect rate would have then several components and better reflect the quality dimensions important to the door plant.

Figure 7-24 shows the results of ten simulation runs of this module. Results for the third supplier are not shown, because according to historical data, it had a zero error rate for the period of analysis. In actuality, this third supplier delivered only hard maple, which is not graded at arrival and the grade mix in the bill is taken at face value.

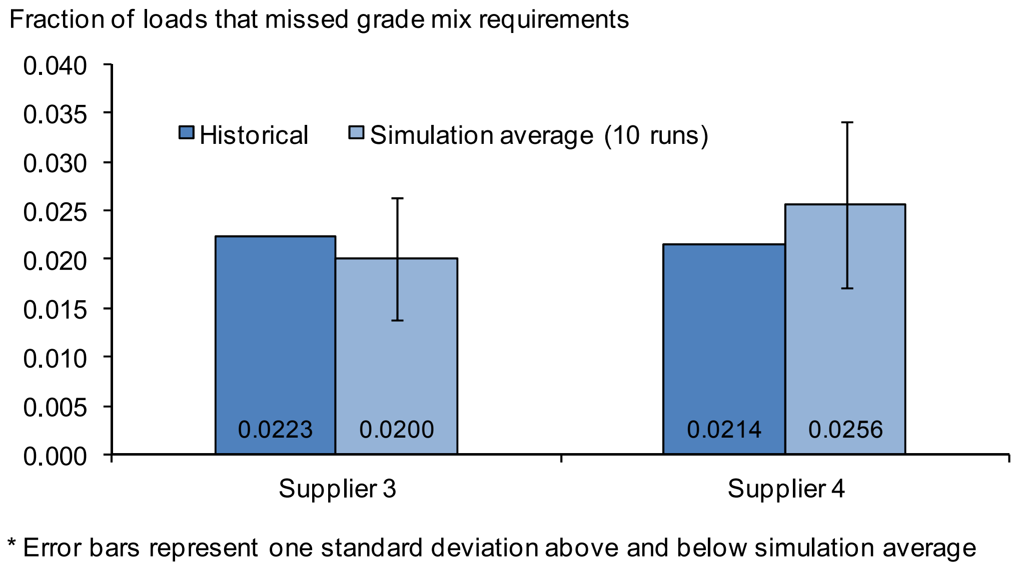


Figure 7-24. Validation results for the lumber supplier error rate generator

7.5.1.5 Time Performance in the Supply Chain

During the analysis of historical data (Chapter 5), and for all supply chain entities, time performance, measured as the percentage of orders shipped on or before due date, was found to be strongly associated with the production volume or level of activity; the latter measured by the number of doors produced, cabinets shipped, or installation of kitchen and bath cabinets completed. These linear associations were used to model time performance as a function of production. As an example, the on-time complete (OTC) measure at the assembly plant was modeled using a systematic component (linear regression equation with demand as independent variable), and a random component following a Beta distribution. This is shown in the following equation.

$$F_{OTC}^{-1}=(a+b\times Orders)+[c+d\times Beta^{-1}(y,\alpha,\beta)] \quad \text{Equation 15}$$

In Equation 15, “*a”* and “*b”* are respectively the intercept and slope of the linear equation between OTC and orders to the assembly plant. The parameters *c* and *d* are scale parameters for the random component of OTC; α and β are shape parameters of the Beta distribution; and finally *y* is a uniformly distributed random number between 0 and 1. Time performance at the other facilities was simulated in the same manner. Figure 7-25 shows the average of ten simulation runs for time performance at the assembly plant using randomly generated demand at the assembly plant for a year. The region delimited by the one-standard deviation bounds does not include three historical values, most probably because the demand simulation algorithm does not include a seasonal factor, and because simulation averages are smoothed-out due to the central limit theorem. The simulation and historical averages were not significantly different at 0.05. Results for time performance module at the other facilities are shown in Appendix C.

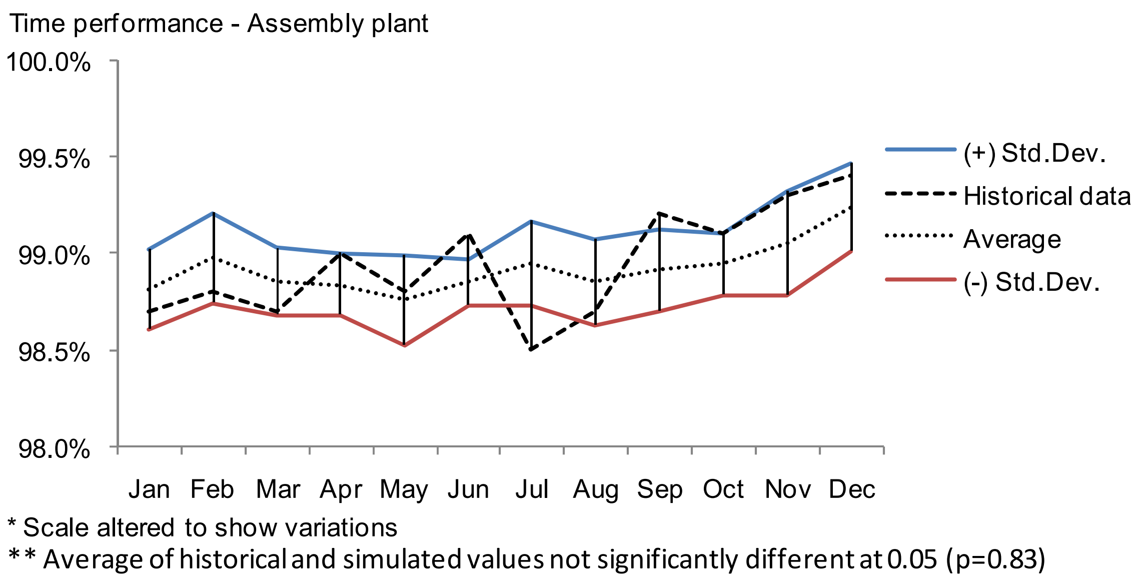


Figure 7-25. Validation results for assembly plant time performance

Figure 7-26 shows supply chain time performance throughout the year of analysis and compares simulation results with historical values. There is no significant difference between simulated and historical averages, and the simulation values seem to follow historical ones closely.

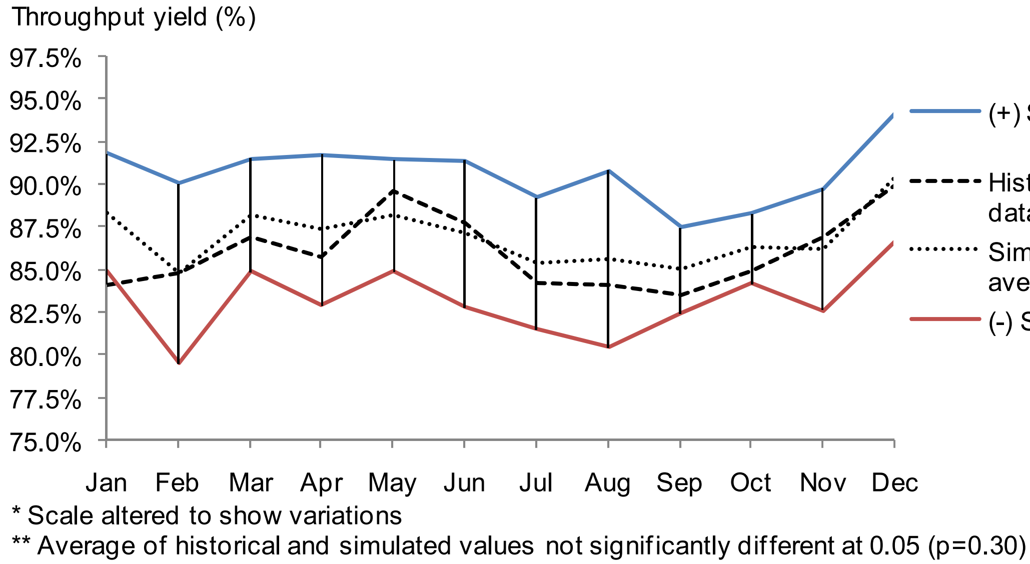


Figure 7-26. Validation results for supply chain time performance (throughput yield)

Figure 7-27 shows the average defect rate per million for the year of analysis. The differences between simulation and historical values are of 20, 4, 1, and 2 percent for the door plant, assembly plant, and service center, respectively.

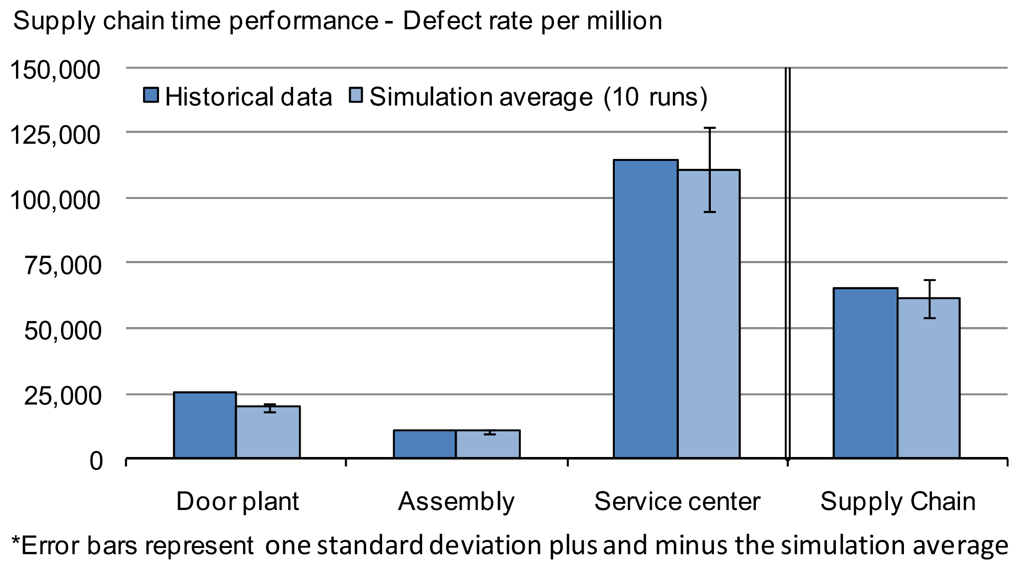


Figure 7-27. Validation results for supply chain time performance (defect rate per million)

7.5.1.6 Supply Chain Product Quality Performance

Product quality performance was simulated based on demand, percentage of 2-Common lumber, and failure rate from lumber suppliers. In Figure 7-28, the defect rate per million for the year of analysis are shown. The simulation average seems to follow the general trend of the historical value, although it fails to replicate the extremes in March, July, and September, mainly because the generation of demand does not include seasonality and the smoothing resulted from averaging 10 simulation runs. Results for other facilities can be found in the Appendix C.

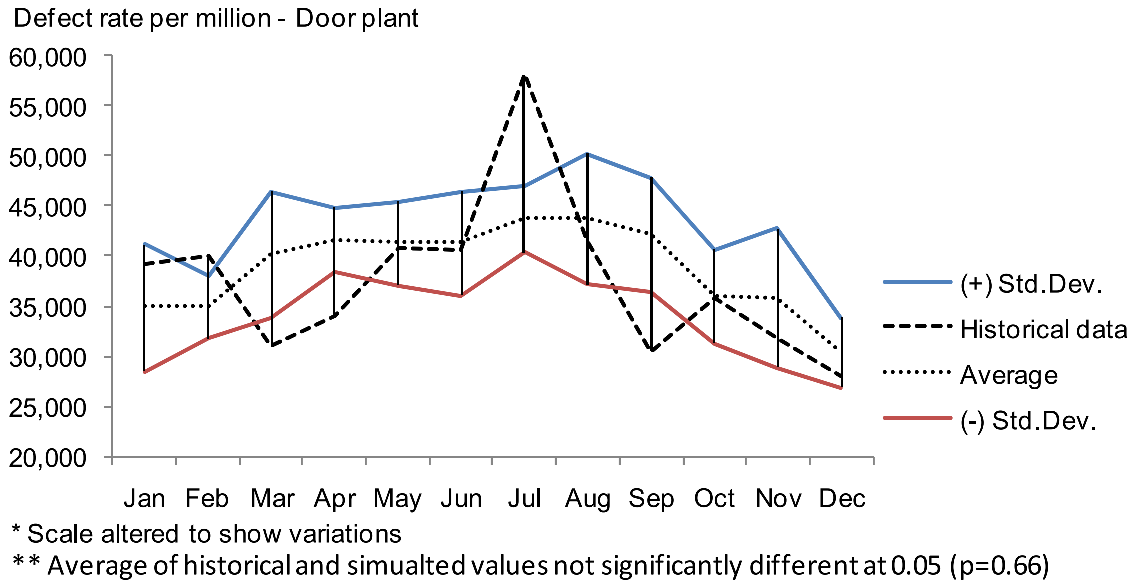
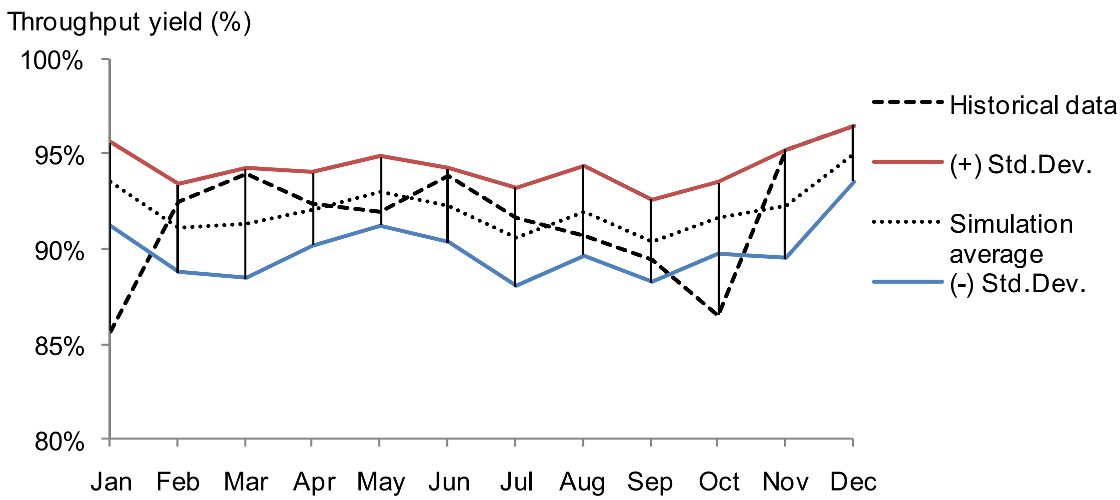


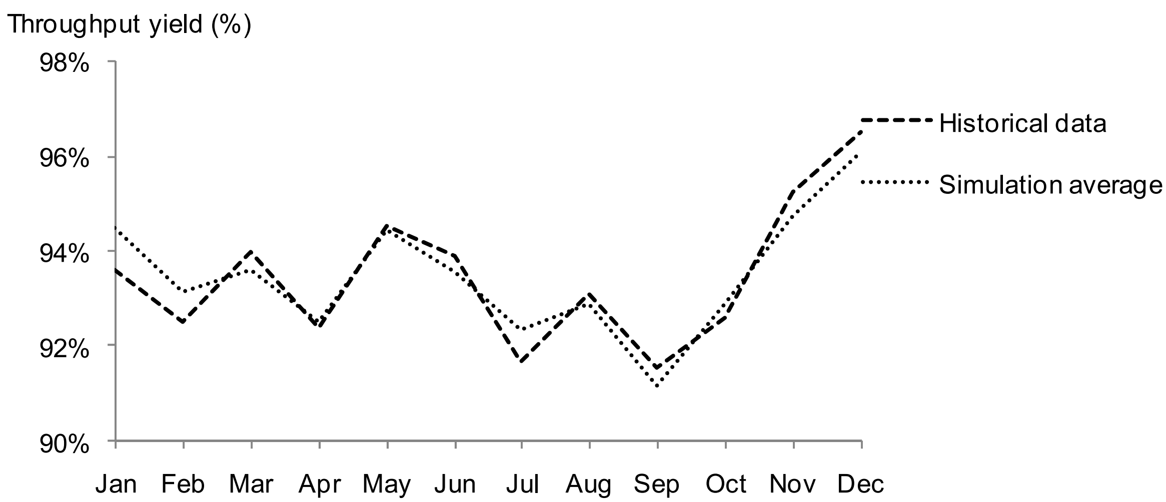
Figure 7-28. Validation results for the final defect rate at the door plant

Figure 7-29 and Figure 7-31 show the simulation results for the overall supply chain product quality performance. No significant difference exists between the average of historical and simulated values. The simulated throughput yield in the year of analysis (Figure 7-29) departs significantly in January and October, due to high error rates at the lumber supplier side in those months. This can be demonstrated if throughput yield is recalculated excluding lumber suppliers, and plotted again, as in Figure 7-30. There we can see very little difference between simulated and historical values.



* Scale slatered to show variations
** Average of historical and simulated values not significantly different at 0.05 (p=0.73)

Figure 7-29. Validation results for supply chain product quality performance (throughput yield)



* Scale slatered to show variations
** Average of historical and simualted values not significantly different at 0.05 (p=0.97)

Figure 7-30. Validation results for supply chain product quality performance (throughput yield, excluding lumber suppliers)

Sigma scores for each entity and for the overall supply chain are depicted in Figure 7-31. Note that, for the period of analysis, all entities performed at a sigma score above 3.0, which according to some authors is considered U.S. industry average (Harry, 1998; Raisinghani, et al., 2005). When the entire supply chain is considered, however, the sigma score is 2.91.

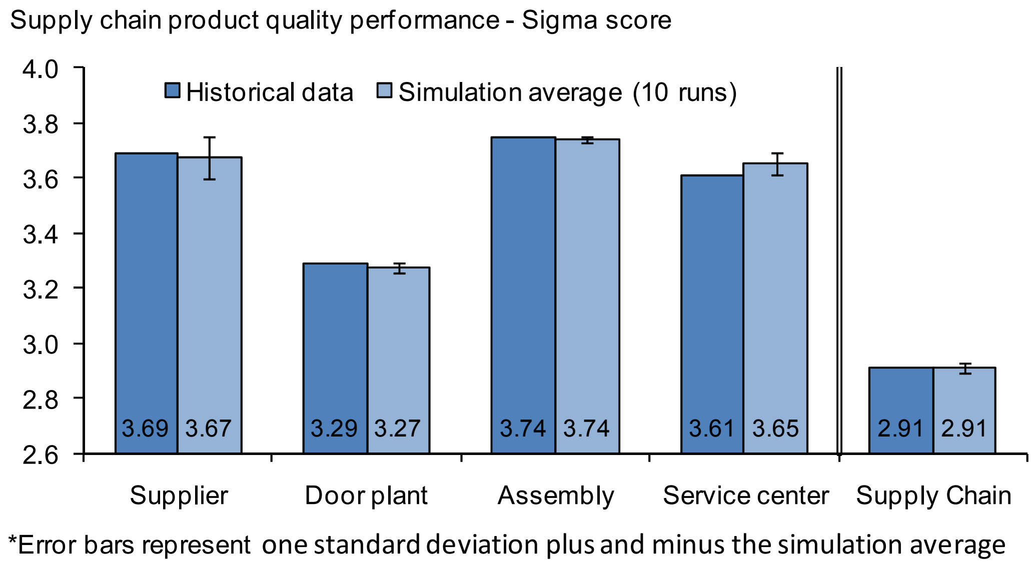


Figure 7-31. Validation results for supply chain product quality performance (sigma score)

7.5.1.7 Summary of the First Iteration

From the results of the baseline case simulation, it can be said that the simulation model closely resembles the behavior of the actual system. The defect generators yield results very close to the historical values, in terms of share of defects and average defect rate for the period of study. The relationships between production volume and time performance and defect rate have proven to be good predictors of time and product quality performance. Compared with historical data, the model's results for product quality were more accurate than those for time performance.

The demand generation module does not include seasonality, and this causes part of the discrepancies with historical values. Lastly, the calculation of supply chain results is very sensitive to low values at any of the entities included, a characteristic already discussed when describing throughput yield. While this seems to unfairly penalize highly performing entities, it actually helps to emphasize the need for improvement at low-performing facilities, because poor performance of one entity in the supply chain impacts the performance of all others members.

7.5.2 *Second Iteration: Testing Model under Different Inputs*

In the second part of the simulation, the effect of changes in the inputs on the supply chain quality performance was investigated. Changes to three variables were considered, listed in Table 7-9. Results are presented in the next sections.

Table 7-9. Inputs to the second iteration: changing inputs

Data	Description
Production	Changes in production volume: from -75% to +100%
Percentage of 2Common in lumber mix	Change in 2Common lumber content from -100% to +200%
Lumber supplier error rate	Historical values for one year from -50% to +200%

7.5.2.1 Quality Performance at Different Levels of Production

For this iteration, the baseline demand at the assembly plant was increased or decreased a percentage, from minus 75 percent to plus 100 percent in 25 percent increments. As was stated in Section 5.6.1, there is a strong inverse linear relationship between performance (both time and product quality performance) of the supply chain and the production volume at each plant. The results, both for time performance and product quality are shown in the next figures.

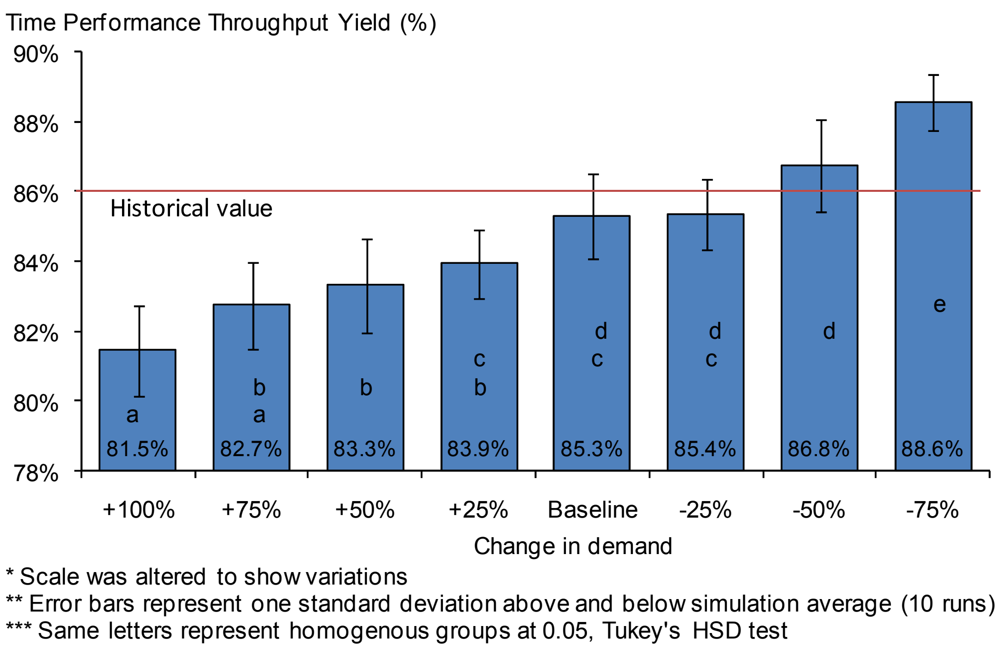
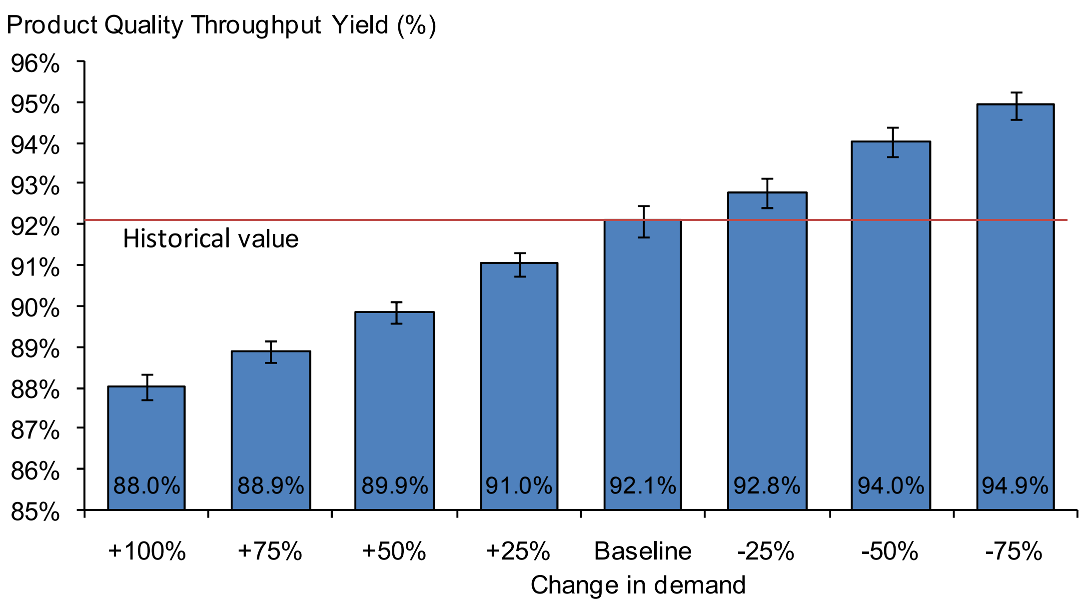


Figure 7-32. Supply chain time performance at different levels of demand

In Figure 7-32 and Figure 7-33, throughput yields for different levels of production are presented, as well as the historical value. The baseline case, meaning no change in demand, returned a throughput yield value about 0.8 percent lower than the historical one. As expected, time performance improves with decreasing production. There is, in average, a one percent increase in supply chain throughput yield for every 25 percent decrease in production volume. The rate of change, however, is not constant; the increments in performance are higher when production decreases from the baseline case.

Simulation results for product quality performance under different levels of production can be seen in Figure 7-33. As with time performance, quality performance improves when production volume decreases, at a rate of approximately one percent for every 25 percent drop in production output. The change in yield in this case follows an almost linear behavior in the range of production volumes considered for the simulations. The baseline average matches the historical average (92.1 percent).



* Scale was altered to show variations
** Error bars represent one standard deviation above and below simulation average (10 runs)
*** All results are significantly different at 0.05, Tukey's HSD test

Figure 7-33. Supply chain product quality performance at different levels of demand

Simulation values can also be compared against past data for a particular level of demand, since demand changes throughout the year. For example, in August, the overall demand for the supply chain was 25 percent higher than the average, and the throughput yield for time performance was 84.1 percent, and the yield for a 25 percent increase in demand in Figure 7-32 was 83.9 percent; in fact just 0.2 percent lower than the historical value.

Implications

These results illustrate the challenge of variable demand in a "lean" production system, since production is carried out against firm customer orders (rate-based rather than the more traditional time-phased approach). U-shaped lines, split lines, load leveling, production smoothing, and in-process "supermarkets" are lean-manufacturing tools to control production rate (Tapping, et al., 2002, pp. 50-66). Historical values of production volume (Figure 7-17) show high variability throughout the year (an average coefficient of variation of 20 percent for the three facilities), which has a detrimental effect on quality performance. Clearly, there are potential gains in quality performance of the supply chain from efforts to balance production rate throughout the year. These efforts could go from policy changes in order-taking to a re-design of the production process to facilitate changing variable throughput (e.g., use of U-shaped lines).

7.5.2.2 Quality Performance at Different Contents of 2-Common Lumber

The impact of changing incoming material quality on the performance of the door plant and the supply chain was investigated by changing the percentage of 2-Common lumber in the lumber mix entering the door plant process. Figure 7-34 presents the results of these simulations as the defect rate per million opportunities at the door plant's final inspection. The baseline case (no change in 2-Common percentage) resulted in a defect rate 1.3 percent above the historical level (or 500 defects per million opportunities. Defect rate increases at an average rate of 4.3 percent, or 1,500 defects per million opportunities, for every 50 percent increase in 2-Common lumber content in the raw material mix.

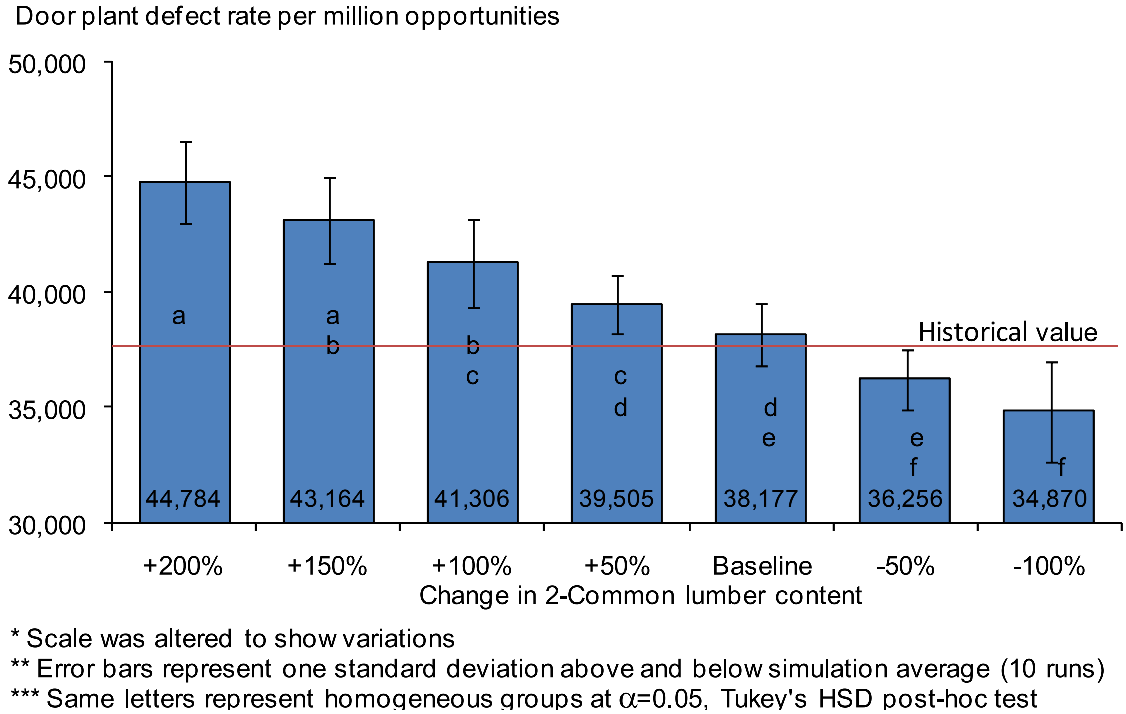
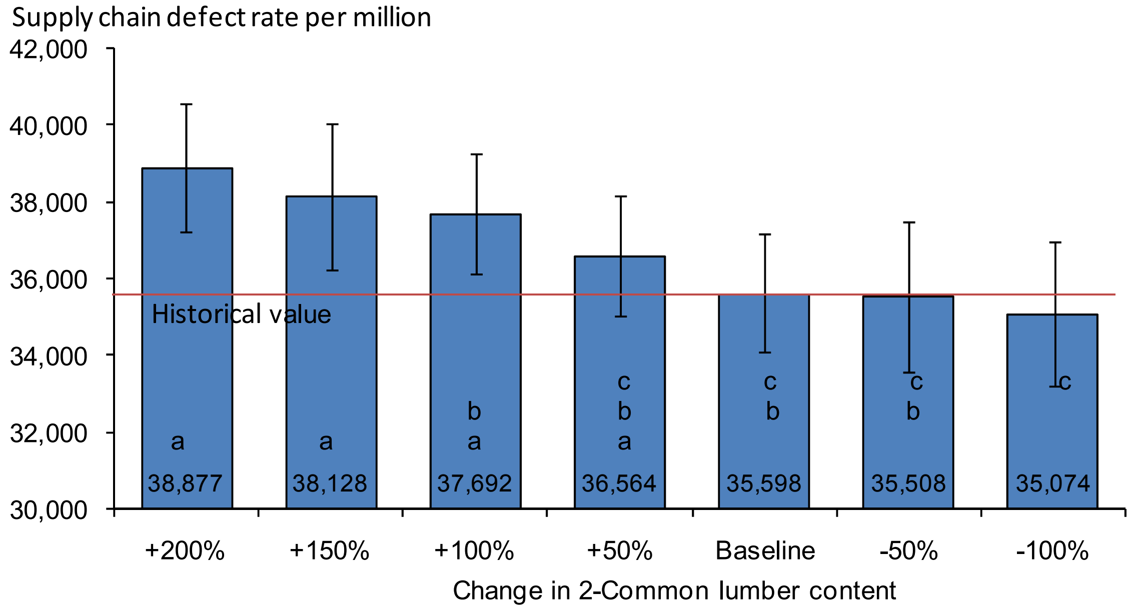


Figure 7-34. Door plant defect rate at different percentages of 2-Common lumber

The impact of changing low-grade lumber content on the supply chain performance is presented in Figure 7-35. In average, defect rate increases 1.7 percent increase for every 50 percent increase in 2-Common lumber content. The baseline case resulted in a defect rate less than one percent lower than the historical value.



* Scale was altered to show variations
** Error bars represent one standard deviation above and below simulation average (10 runs)
*** Same letters represent homogenous groups at 0.05, Tukey's HSD test

Figure 7-35. Supply chain defect rate at different percentages of 2-Common lumber

Implications

Results show the potential effects of variations in 2-Common content. The baseline average, 3.2 percent (weighted average across species), is approximately 50 percent of the maximum content specified in purchase orders (5.8 percent), thus, it can be expected a 4 percent rise in defect rate at the door plant level if suppliers would send lumber with the maximum allowed 2-Common content. Likewise, if the components plant would stop receiving low-grade lumber, a four percent drop it could be expected in the defect rate. In addition to yield considerations, the potential effect on the defect rate should be taken into account when making grade mix decisions.

7.5.2.3 Quality Performance at Different Levels of Lumber Supplier Error Rate

For this iteration, the effect of different levels of lumber suppliers defect rate (the fraction of loads with excessive amount of low-grade material) was investigated. The impact on the supplier's performance and on the overall supply chain is shown in Figure 7-36.

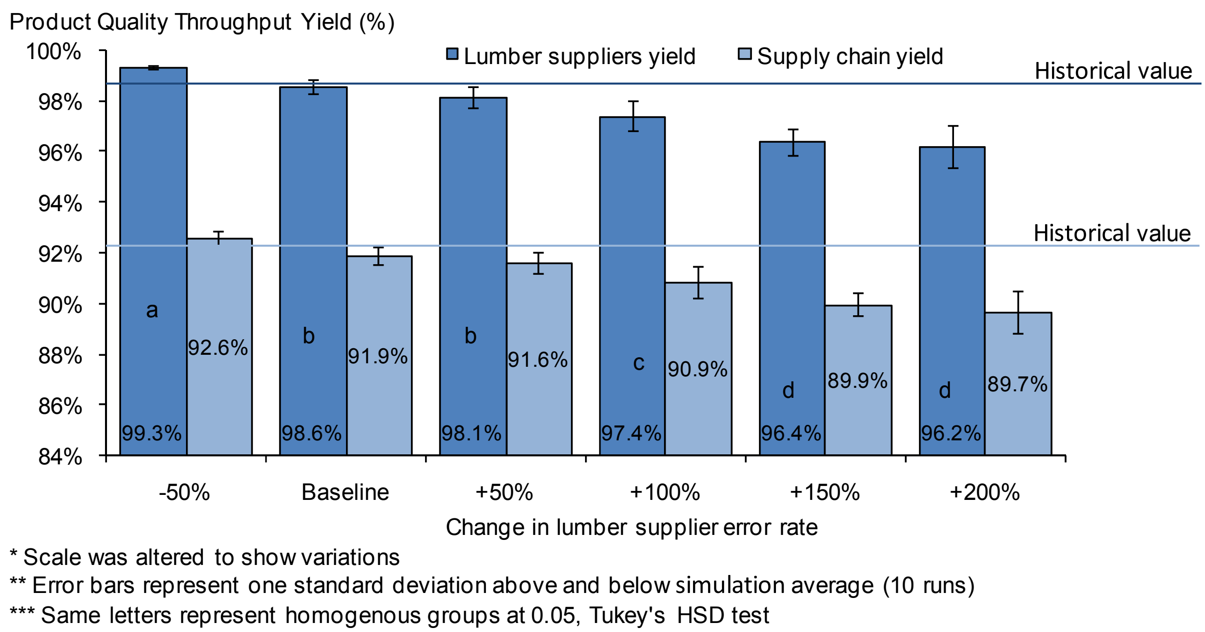


Figure 7-36. Product quality throughput yield at different levels of supplier error rate

From the previous figure, supply chain product quality decreases by an average of 0.7 percent every time the lumber suppliers combined error rate increases by 50 percent. Using an example, if lumber suppliers to the door plant double the number of loads with missed grade relative to the baseline case, the supply chain yield will drop two percent points.

Implications

As Figure 7-36 illustrates, there are potential benefits from decreasing error rate at the lumber suppliers. Some ways that the company could facilitate this are:

- Sharing the variability-reduction techniques with lumber suppliers. This has proven effective in the automotive and electronic industries (Walker, et al., Vickery, et al., 2003; 2000).
- Providing feedback to lumber suppliers about performance in terms of not only grade mix compliance, but also about variability and standing with other suppliers.
- Sharing information with suppliers about how their quality affects the Company's quality of outputs. This practice develops commitment to quality from suppliers.

7.5.3 Third Iteration: Addition of a Defect Category

Current quality measurement practices in the kitchen cabinets supply chain provide each facility with valuable tools to prevent defects and reduce variability. However, as was established throughout this dissertation, these practices do not facilitate the rapid identification of root causes when these are originated at other facilities, or external suppliers; nor they facilitate establishing the impact of changes at one point of the supply chain on the overall performance. Ideally, when a product-related quality claim is made to the service center, for example, the quality manager at that center wants to be able to point where in the supply chain the root cause was located.

In this section, the potential use of including a specific defect category to the final inspection at the assembly plant is investigated. Currently, it is a complex task to identify and quantify the exact source of a product-related issue at the service center. The assembly plant's final inspection does not include among its defect categories issues in the materials, like panels, doors, and drawer fronts. Figure 7-37 depicts the inspection process at the door and assembly plants. In addition to checks and inspections throughout the door manufacturing process, there is a final inspection when doors come out from the finishing line. Defective doors are separated and repaired when possible. There exists, however, some defective units that are incorrectly judged acceptable and are shipped to the assembly plant, an inspection error known as Type II error (considering a product defective when it is in fact, free of defects, is the other type of inspection error; Lee & Unnikrishnan, 1998). At the assembly plant, parts pickers separate defective doors, as do personnel at the assembly cells. Again, there is a fraction of doors with defects that go undetected to the service center.

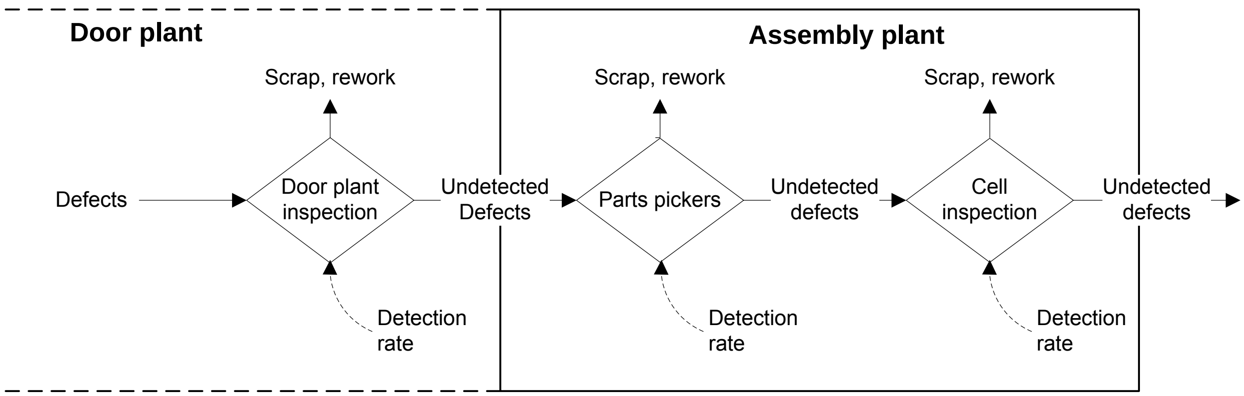


Figure 7-37. Inspection and detection rate in the cabinets supply chain

According to records from the external quality measure used at the assembly plant, 28 percent of defects reported by the plant's customers are related to a non-conforming product, and from the same records, 63 percent of these issues are related to doors. Thus, it can be estimated that 17.5 percent of the variances can be attributed to non-conforming doors. For this iteration of the simulation, a new category of defect was included at the assembly plant's final inspection; and a detection rate was included, given by:

$$\text{Inspection detection rate} = \frac{\text{Number of defects detected during process}}{\text{Total number of defects in incoming parts}} \quad \text{Equation 16}$$

To simplify the modeling process, only Type II inspection errors were considered. Table 7-10 lists the defect categories currently recorded at the assembly plant's final inspection. The new category is listed at the bottom, and it has three categories: finishing, substrate (meaning wood defects), and construction. Initial estimates of the defect rate of this category and subcategories were taken from the door plant's final inspection records. The view in Table 7-10 shows the defect rate at a 50 percent detection rate.

Table 7-10. Existing and new defect categories at the assembly plant's final inspection

Category	Variances		Defect rate	
1. Blown Staples		**942**		**0.008838**
Drawers	210		0.001970	
E/P Frame	253		0.002374	
Top/Bottom	479		0.004494	
2. Excess Glue		**4,657**		**0.043690**
White	3,245		0.030443	
Hot melt	1,412		0.013247	
3. Flush Wall Surface		**448**		**0.004203**
Frame To Endpanel	167		0.001567	
Back/hangrail to End	281		0.002636	
4. Flush Base Surface		**396**		**0.003715**
Pine rail to end	303		0.002843	
Frame To Endpanel	93		0.000872	
5. Drawer Frt Alignment		**307**		**0.002880**
6. Cab Mislabelling		**237**		**0.002223**
Wrong door / dra frt	54		0.000507	
Wrong color	79		0.000741	
Wrong style	104		0.000976	
7. Cabinet Square		**68**		**0.000638**
8. Missing Inclusions		**670**		**0.006286**
Paperwork	559		0.005244	
MGD Pack	93		0.000872	
Blind Panel	18		0.000169	
9. Visual		**8,716**		**0.081771**
Chips	5,651		0.053016	
Dents	1,481		0.013894	
Scratches	1,584		0.014861	
10. Functional		**1,692**		**0.015874**
Doors	512		0.004803	
Shelves Not Seated	221		0.002073	
Drawers / Trays	249		0.002336	
Door bumpers/hex dots	710		0.006661	
11. Door defects		**24,064**		**0.225763**
Finishing	4,400		0.041282	
Construction	7,047		0.066116	
Substrate	12,617		0.118364	

The simulation model thus modified was executed ten times at different levels of detection rate; and results were used to calculate the share of each defect category on total defects and the defect rate per million cabinets, and its door component. The outcomes are presented in Figure 7-38 and Figure 7-39 .

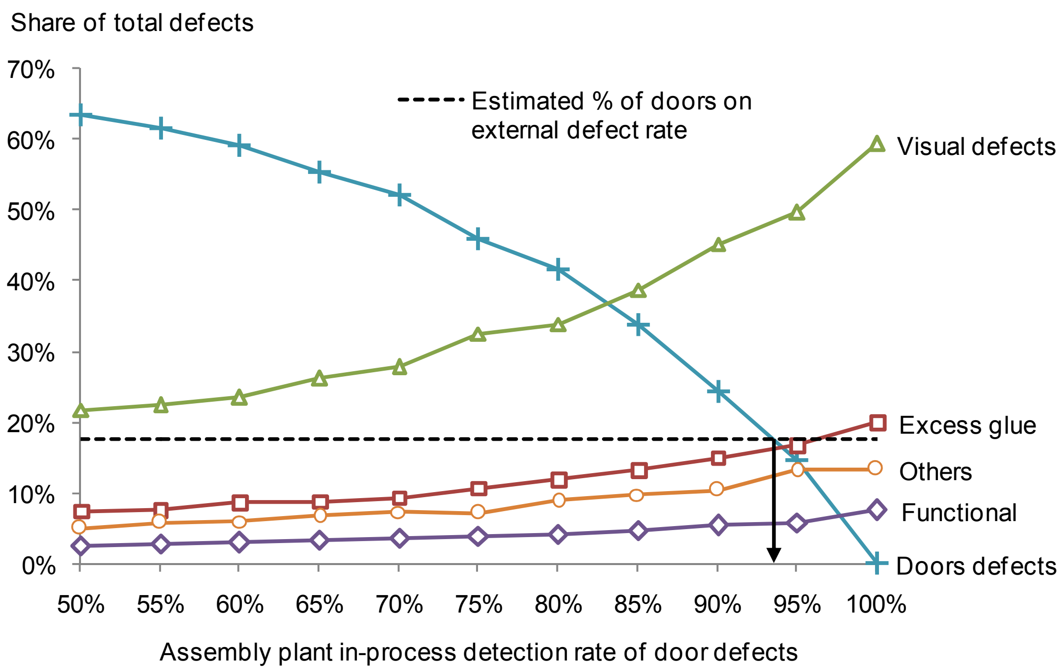


Figure 7-38. Share of defects at final inspection at different in-process detection levels

As can be expected, Figure 7-38 shows a declining percentage of door defects on the total as detection rate increases. When there is perfect inspection (100 percent inspection), there is no door component. If, as estimated, 17.5 percent of door defects go undetected, the intersection of the door component with 17.5 indicates the current detection rate: about 94 percent. Figure 7-39 shows that in average, the defect rate at the assembly plant's internal quality indicator falls 9.7 percent for every 5 percent improvement in the detection rate. Increasing the detection rate will also have a positive impact on the external quality performance of the plant and, maybe more importantly, on the overall supply chain's quality performance.

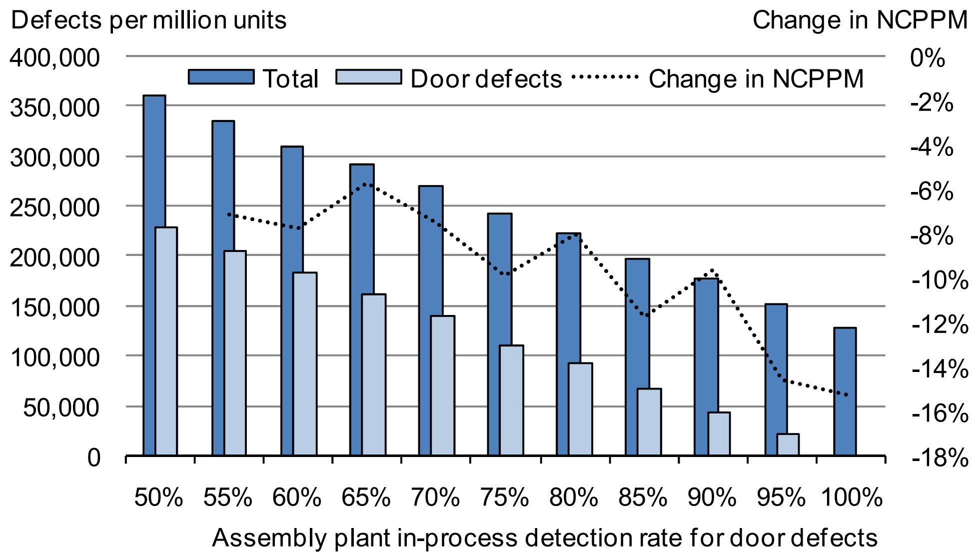


Figure 7-39. Defect rate per million units at different in-process detection levels

Implications

Individual enterprises and the supply chain as a whole benefit when defects can be traced back to their true origin in a clear and timely manner. Although adding another category to an inspection checklist does not by itself ensure a lower defect rate, it facilitates the improvement process by pointing at the true causes of quality issues. The example developed in this section demonstrates how such information could be used to focus improvement efforts and measure progress towards the target. Similar benefits could be achieved, for example, from including color issues among the key quality performance measures.

7.5.4 Connecting Supply Chain Performance with Customer Satisfaction

A supply chain can only achieve success if customer satisfaction is accomplished. Lambert (2001), for example, defines supply chain management in terms of the integration of all the processes in value stream that add value to the customer. Thus, a research about quality is not complete if its relationship with customer satisfaction is not included in the analysis. In this section, an attempt was made to link the supply chain quality performance with customer satisfaction. Major inputs for this analysis were results from six customer satisfaction surveys ordered by the company (Section 5.4.3) and quality performance during the period of analysis described previously in this chapter (Section 7.4). The customer satisfaction survey includes four performance areas (customer care, sales support, logistics, and product quality) and overall customer satisfaction. In this section a potential approach to estimate the link between supply chain logistics performance and customer satisfaction is developed. Figure 7-40 illustrates the process followed.

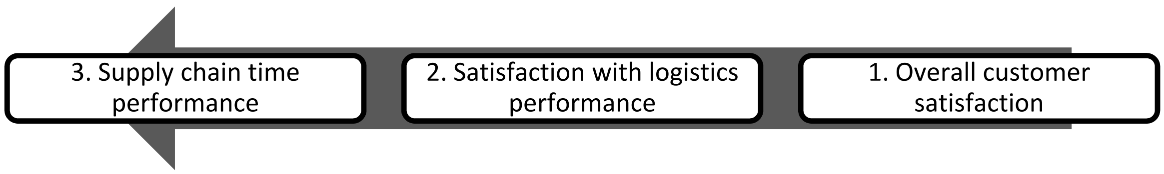


Figure 7-40. Link between supply chain performance and customer satisfaction

To find the first link, from overall satisfaction to satisfaction with logistics performance (1 and 2), the approach followed was a simple linear regression between these two variables, with data from the customer satisfaction surveys. Figure 7-41displays the results of lineal regression between overall customer satisfaction and customer satisfaction with logistics performance. The data available for this analysis, only six points, do not allow for statistical precision (a minimum sample size calculation, with alfa=0.05 and power=0.9, yields a sample size of 18, using approach by Hsieh, Bloch, & Larsen, 1998), but are enough for an initial estimate of the affect of improvements in satisfaction with logistics on overall satisfaction.

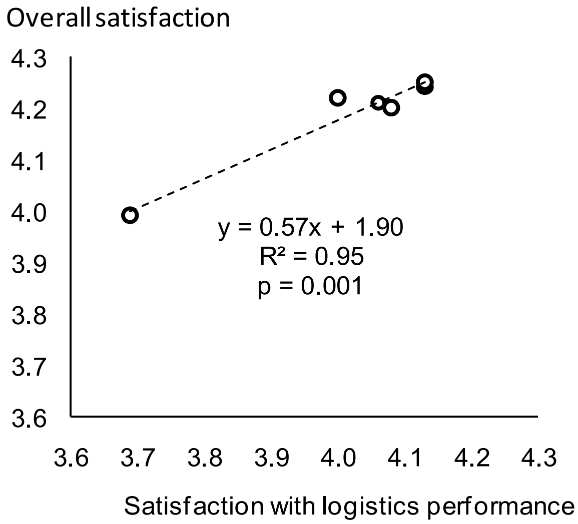


Figure 7-41. Relationship between overall customer satisfaction and satisfaction with logistics performance

An interpretation of Figure 7-41 is that, assuming a linear behavior, customer satisfaction improves about 0.57 in the satisfaction scale used with every point increase in satisfaction with logistics. The next step is to estimate the effect of supply chain performance on satisfaction with logistics performance. For this, the following assumptions were made:

- The goal of the company is to achieve a customer satisfaction of 5.0, which corresponds with a supply chain throughput yield of 99.9997% (a six-sigma level).
- The difference between the goal and the current satisfaction (satisfaction gap), is directly proportional to the difference between the targeted yield and current yield (yield gap).
- A 50 percent annualized improvement rate for all plants in the supply chain; meaning that every year, the satisfaction gap is reduced in half, relative to the previous year.

Using these assumptions, it can be estimated that, customer satisfaction with logistics improves 0.06 points with every percentage point of improvement in throughput yield [(5.00 - 4.13) / (99.9997% - 86.0161%) = 0.06]. Although this assumption might be controversial, since there is no support for assuming a linear behavior, it can be easily refined by using historical data, not available at the time of study. The previous parameter estimates are summarized at the top of Table 7-11.

Table 7-11. Supply chain time performance and customer satisfaction

Target yield (corresponding to a six-sigma level = 3.4 defects per million)	0.9999966
Annualized rate of improvement (to close performance gap)	50%
Change in satisfaction with logistics for every % improvement in time performance	0.06
Change in overall customer satisfaction with every change in logistics satisfaction	0.57

Year	Throughput yield (Y_i)[b]				Improvement (ΔY_i)[c]	Satisfaction	
	Door plant	Assembly plant	Service center	Supply chain		Logistics (LS_i)[d]	Overall (S_i)[e]
0[a]	0.9749	0.9895	0.8916	0.8602		4.13	4.25
1	0.9875	0.9947	0.9458	0.9291	0.0689	4.56	4.49
2	0.9937	0.9974	0.9729	0.9643	0.0352	4.78	4.62
3	0.9969	0.9987	0.9865	0.9821	0.0178	4.89	4.68
4	0.9984	0.9993	0.9932	0.9910	0.0089	4.94	4.71
5	0.9992	0.9997	0.9966	0.9955	0.0045	4.97	4.73

[a] Year zero corresponds with the initial state
[b] Calculated as $Y_i=Y_{i-1}$ + $YieldGap_i$ x 50%, where i is the current year and $YieldGap_i=Y_{Target}-Y_{i-1}$
[c] Yield improvement $\Delta Y_i=Y_i-Y_{i-1}$
[d] Satisfaction with logistics performance: $LS_i=LS_{i-1}+0.06 \times \Delta Y_i$
[e] Overall satisfaction: $S_i=S_{i-1}+0.57 \times (LS_i - LS_{i-1})$

The first line in Table 7-11 (year zero) lists the historical average throughput yield values for each supply chain entity and for the overall supply chain, as calculated in Section 7.4.2; and the values for customer satisfaction for the last year for which data were available. In Figure 7-42, the results of these calculations are illustrated.

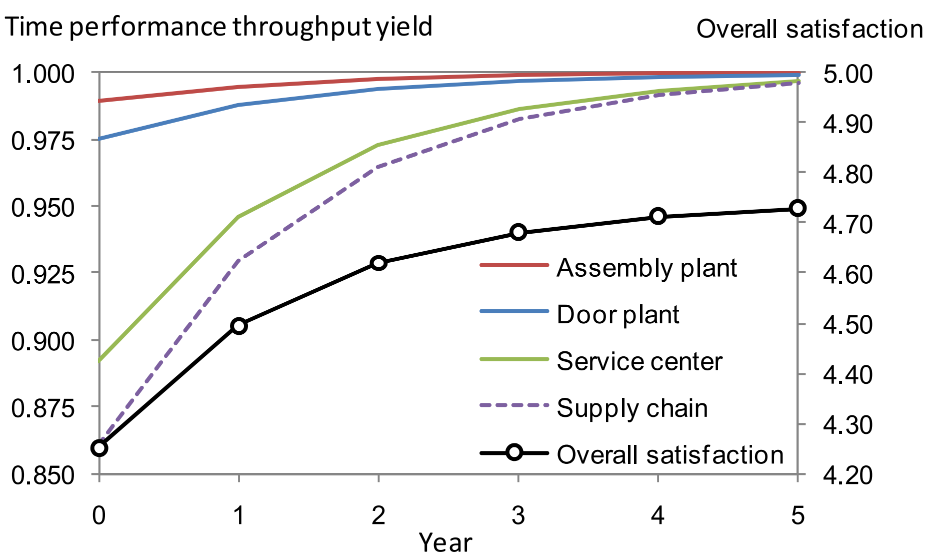


Figure 7-42. Results for simulation of impact of supply chain performance on customer satisfaction

An interpretation of results shown in Figure 7-42, is that, from approximately the fourth year, any further improvements in overall satisfaction have to come from improvements in the other areas of performance, like product quality or customer care. For simplicity, this analysis excludes interactions between the different areas of performance (it is very unlikely, for example, that a customer will separate clearly product from logistics performance); but provides a decision-making tool to effectively direct improvement efforts. To shorten the time needed to approach the target customer satisfaction level, for example, management might decide to accelerate the rate of improvement at the service center level, since this will have the greatest impact on overall performance, and hence customer satisfaction. Harry (2000), stated that as a company moves towards a six-sigma performance level, it becomes more difficult to make further improvements (similar to the law of diminishing returns in economics); and the use of more complex or radical tools are necessary, like experimental design, changes in product and process design, or significant technological changes.

Implications

A balanced approach to quality measurements requires considering the effects of improvements on customer satisfaction. This helps to keep the focus on what is important and no falling in the “numerical quotas” trap that Deming referred to. The approach suggested in this section connects supply chain performance with customer satisfaction using historical data. Results of the sample calculations illustrate that customer satisfaction goals cannot be reached by improvements in one aspect alone (e.g., product quality).

7.6 Summary

In this chapter, the need for supply chain measures of performance, identified in Chapter 6, was addressed. A system for measuring supply chain quality performance using six sigma metrics was suggested. It is believed that such a system has characteristics of effective supply chain performance measurement: (1) it spans the entire supply chain, (2) reflects quality across all entities, and (3) reflects the contributions of each member to the overall performance. Although this study focuses on quality, the proposed system can be expanded to cover other performance areas as well, such as safety, inventory performance, or costs. Similarly, the study deals chiefly with solid wood components of the cabinet door, but the measurement system can be extended to cover other supply members, such as forest operations, suppliers of finishing materials, and “custom parts” suppliers. When more components of the supply chain are included, it is advisable to use a weighted-based approach, assigning importance weights to metrics from different supply chain members, based on cost or other criteria (for details, see Ravichandran, 2006; Ravichandran, 2007).

One year-worth of performance data was used to calculate supply chain time and product quality performance. No benchmark data was available, thus no comparisons can be made with other companies or industries. The system is useful in identifying opportunities of improvement in the supply chain, and to estimate how changes at some point in the supply chain affect the overall performance. The metrics can also be used to evaluate supplier performance when multiple suppliers are used.

The performance measurement system was incorporated into an electronic spreadsheet-based Monte Carlo simulation model. The objective of the simulation model was to (1) estimate supply chain quality performance under changing variables, such as different percentages of low-grade lumber in the raw material mix, or different levels of demand; and (2) estimate performance under structural changes to the current model. Two changes to the current measurement system were simulated: adding a door-defect component to the final inspection at the assembly plant, and linking supply chain performance to customer satisfaction. The former illustrated how a change in current measures could help to estimate the defect detection rate, and use this feedback to more effectively focus improvement efforts. The second change, linking customer satisfaction with supply chain performance, provides a tool to estimate the effect of improvements in key performance areas on the overall customer satisfaction and the contribution of each supply chain member to the latter. Again, this information is useful to prioritize improvement efforts, considering goals in customer satisfaction.

Chapter 8. Conclusions and Future Research

Supply chain management and the “performance measurement revolution” are two of the most significant developments in business management of the last two decades. According to supply chain management, companies no longer compete as single entities, but rather as parts of large, complex networks. The success, if not survival, of businesses depend on recognizing and embracing this reality. Most organizations have also realized that substantial improvements are only possible when an effective measurement system is in place. A balanced approach, driving the correct behavior and alignment with strategy are common characteristics of such a system found in the literature.

In a movement that started in the early 1980’s, growing competition and an ever-increasing sophistication of the customer have driven companies to focus on quality improvement. A great number of firms have implemented continuous improvement programs; and many trade associations and government agencies have a quality award program. Invariably, quality improvement programs involve measurement activities, since improvements are very difficult if there is not a way to measure progress towards an objective. Particularly, two specific approaches for improvement, six-sigma and lean manufacturing, have received great attention, in large part because of the success achieved by its two classic exponents: Motorola and Toyota, respectively. For example, sixty percent of respondents to a 2006 survey among U.S. manufacturers cited six sigma and lean manufacturing as their primary improvement method (Blanchard, 2006).

The American wood products industry has not been unaffected by these developments. Global sourcing is considered the main reason for many companies closing manufacturing operations and reinventing themselves as importers and distributors. Some others have instead turned to quality-improvement and cost-reduction programs in order to achieve sustainability and growth. Most firms in this sector, however, have not yet leveraged the benefits of supply chain management (cost reduction, inventory reduction, and improved delivery, among others) to improve their operations. This is evident by the long lead times (six months from forest to customer are not uncommon), and large inventories (the industry's inventories-to- shipments ratio has remained virtually unchanged during the period 1992-2008, while that of other durable goods industries have decreased).

The motivation for this study originates from the aforementioned developments. An extensive literature review identified a need for research about quality measurement in a supply chain environment and the application of supply chain management principles in the wood products industry. An exemplary wood products supply chain was studied in detail, with the purpose of gaining understanding of current quality measurement practices and their impact on performance. A case study methodology was selected because it suited the main objective of the research effort. During the data collection phase of this study, six manufacturing facilities, one retailer and one service center were visited. Thirty semi-structured interviews were conducted with key personnel at these sites. In this chapter, the results from the study are summarized, followed by suggestions for future research.

8.1 Conclusions

The conclusions from this research can be listed in relation to the three major objectives proposed.

8.1.1 Determine quality performance measurement practices in a secondary wood products supply chain

The quality measurement practices in the supply chain of study were determined and described in great detail in Chapter 3 and Chapter 4 of this dissertation. The focal enterprise of this supply chain has deployed a company-wide continuous improvement initiative, which includes extensive measurement and documentation activities. Corporate headquarters prescribes with a high level of detail the quality control and measurement practices to be utilized by all facilities in the company; for example, daily audits are conducted every day at different stages of the manufacturing process. Results from these audits are reported and displayed in all production areas. Statistical process control charts are recorded at key processes, like lumber drying and parts thickness. Some quality measures used are defects per million opportunities, defects per unit, sigma score, first-time yield, and on-time complete. A corporate “dashboard” is maintained, containing major quality metrics for each plant. Goals for these metrics are set at the corporate level, and managers are evaluated in part based on the progress towards these goals. Performance data for major quality measures are presented in Chapter 5.

Practices at an external supplier to the kitchen cabinets company were also studied as part of the supply chain. This supplier has implemented a well developed system for quality control and measurement, not common among hardwood lumber manufacturers judging by visits to other facilities. Measurements are taken at each step of the process and at regular frequencies. An intranet database was developed to store, update, and report quality control results. This greatly facilitates the alignment of the activities of all twelve plants under this system. Quality performance in most areas is measured as the percentage of a desired level, which is set by the quality function. Lumber grading accuracy is the most important measure of external quality.

8.1.2 Evaluate the impact of these practices on supply chain’s performance

The current quality measurement practices constitute a powerful competitive advantage for the supply chain studied, and are in great part the source of the relatively strong market position of the company. Some specific results from current practices are listed in Table 8-1.

Table 8-1. Improvement from current practices throughout the supply chain

Supply chain entity	Performance measure	Initial value	Current value	Target value	Annualized rate of improvement	Time (years)*
Lumber supplier	Grading accuracy	82.0%	95.0%	96%	3.7%	5
Door plant	Defect rate per million	90,912	37,674	1,667	35.6%	3
Assembly plant	On-time shipping	96.1%	99.6%	99.0%	1.2%	4
	Scrap per unit	2.26	1.76	0.00	11.8%	3
Service center	On-time completion	72.4%	88.5%	90%	3.4%	7

* Time over which the value of performance measures changed from the initial to their current value

It is important to note that in Table 8-1, the annualized rate of improvement is smaller as the difference between target and current performance (performance gap) is also smaller, consistent with the law of diminishing returns as improvement initiatives approach their targets. Other specific benefits from the current system of quality performance measurement are listed below:

- *Time performance*. The Company has the shortest lead time in the industry for complete orders, 99 percent, with a 0.3 standard deviation. Customers interviewed coincided in that the lead time from the company is very reliable and short compared with the competition.
- *Current practices greatly facilitate internal integration*. The quality measurement system in place can be attributed in great part for achieving a high degree of internal integration in the Company, not least because it provides personnel with a common language and means to evaluate process performance and improvement.
- *There is no incoming material inspection for inter-plant shipments*. This saves the Company time and financial resources, and is possible by the use of effective internal quality control practices at each facility. Although these facilities operate under the same management, examples in other industries show that this practice is also possible between firms, when there is a high degree of external integration.
- Posting *quality performance information* and having quality control plans available at each work area provides real-time feedback to employees, allowing them to immediately know the status of the processes.
- Throughout the interviews, it was observed a consistent *commitment to quality goals among managers*, which is probably the most important component of any quality management system.

8.1.3 Investigate the impact of alternative practices on performance

This objective was addressed by the analysis of current practices and the simulations in Chapter 6 and Chapter 7, respectively. Some opportunities for improvement identified are listed below.

- The Company currently lacks *true measures of supply chain performance*. Performance information for each facility is reported in the corporate dashboard, which constitutes valuable feedback to managers and motivation for improvement, but lacks a supply chain perspective, running the risk of fostering local optimization (Beamon, 1999). External suppliers are not included in these reports. Ideally, a supply chain performance system should "capture performance across all supply chain members" and "encourage the cooperative behavior across firms" (Lambert and Pohlen, 2001). A system to measure supply chain quality performance was suggested and simulated.
- The current system of quality performance measurement *does not facilitate the rapid identification of defect causes* when these are originated upstream the supply chain. Designing or modifying measures to better reflect the true origin of defects could greatly benefit the company. An example of such measure was investigated in Chapter 7, and illustrates how it can be used to improve defect detection rate.
- *Information sharing seems limited to the immediate supply chain partners*, with very little sharing of information beyond that. A supply-wide system of quality information could provide timely feedback to internal and external supplier, and facilitate error correction before the impact becomes greater. Sharing information with suppliers could result in potential gains, since this would reduce uncertainty at both sides, and decrease significantly the delay between defect detection and improvement action. For example, if scheduling issues are the major cause for drying the majority of its own lumber input, the components plant could benefit from sharing production plans with suppliers, thus allowing them to provide kiln-dried lumber in a timely manner. No significant differences were found in drying defects between material dried at the plant and purchased kiln-dry, suggesting that suppliers are capable of providing consistent quality.
- *The flow of quality-related information between the components plant and lumber suppliers is unidirectional*, with the former specifying grade requirements and providing feedback through a grade bill, or in some cases, rejection of entire loads. Furthermore, suppliers are not involved in developing quality requirements for their product. It has been documented that the participation of customers and suppliers in

the development of product specifications fosters supplier responsibility and results in better new product design (Petersen, et al., 2005).

- *Supplier development efforts are almost inexistent*. This includes supplier evaluation, certification, and development of supplier capabilities. This practice could help reduce variability both in time performance and product quality. Incoming materials for inter-firm shipments are not inspected. This is different, however, for external suppliers; incoming lumber, for example, is re-graded and pre-surfaced at reception, which makes the Company responsible for the suppliers' quality. A capability index-based system for supplier evaluation was suggested in Section 5.1.4.
- *Alignment of performance measures with customer needs*. The results of this study show that there is a lack of alignment between lumber grades and customer needs. Lumber grades are designed to maximize parts yield, and not necessarily final customer's requirements of quality. Similarly, the company could benefit from including color, which is an extremely important quality attribute, among the major quality performance measures throughout the supply chain.

8.2 Study Limitations

As mentioned above, the methodological approach for this research was a single case study, with the main focus on learning about quality measurement practices in a supply chain. The purpose in using this approach was to obtain in-depth knowledge about an exemplary case, and hence the case selected needed not be representative, but rather chosen based on theoretical reasons. Therefore, although the principles on which the analysis and conclusions are based are common to most supply chains (e.g., need for integration, quality improvement, and need for effective performance measurement system design); specific results might not apply to all enterprises (e.g., the use of six-sigma measures of performance, the channels of distributions used, or the particular manufacturing strategy).

The focal company is an integrated kitchen cabinet manufacturer that purchases its raw materials externally, and then carries out the transformation process from lumber drying to installation at the construction site. This is not necessarily a common sourcing strategy in the industry, and brings both benefits and limitations to the study. Several facilities working under the same corporate umbrella are more likely to have a higher degree of internal integration, and adopt common quality management practices. As an example, there is practically no inspection of incoming materials for inter-plant shipments, which is less likely to occur in a non-integrated supply chain.

In this research, the case of study was analyzed as a static system, with no consideration for change. While this assumption was useful for the purposes of the study, it does not necessarily hold true in a continuous improvement environment. The effect of improvement events and changing customers' tastes, for example, were not considered among the variables. Also, certain quality attributes inspected could become irrelevant as improvement activities reduce defect rate related to those attributes to a very low level relative to other defects.

The numerical analysis in Chapter 5 and Chapter 7 are based on one-year's worth of data; this results in the following limitations: (1) seasonality was not included in the analysis of the time series, introducing a systematic source of variability; (2) during the year of analysis, the U.S. economy experienced a downturn, reflected in the fall of housing starts, on which the production volume at the facilities studied is highly dependent; and (3) partly due to the two previous points, the significant associations found between variables might not be valid in future periods.

Lastly, common to most research efforts, limited financial and time resources result in a need to make decisions about the scope, in order to have a manageable unit of study. In this dissertation, the system analyzed did not include all the components of the supply chain. While some of these suppliers might not play a crucial role in the overall quality performance (supplier of, for example, corner gussets or braces, fasteners, and cabinet frame parts), the importance of some supplier's quality may be comparable to lumber quality, for example suppliers of finishing products to the door plant (potentially contributing to a fifth of final defects at this facility), and suppliers of "custom parts" to the service center (source of more than a quarter of the variances at this point in the supply chain). Likewise, only one customer to the assembly plant (the service center) was included in the calculation of supply chain performance; but this customer purchases only a fraction of the total output. In order for the measures really reflect supply chain performance, a greater number of customer should be included. The same is true for lumber suppliers, the suppliers selected for the analysis only provide close to a fifth of the total lumber used by the components plant.

8.3 Recommendations for Future Research

Based on the previous sections, some recommendations for future research can be mentioned:

- Based on the findings described in the present document, an industry-wide survey could be conducted among wood products manufacturers, to assess quality measurement practices. Potential factors to analyze could be company size, industry subsector, and location. Specific practices could then be related to measures of market or financial performance.
- The issue of traceability of defects in the wood products supply chain could be investigated by selecting a number of attributes (e.g., color, wood defects, drying defect) and follow a production batch throughout the entire supply chain, in order to identify and quantify the impact of quality of inputs on the final product's quality.
- Future research could investigate the effects (positive and negative) of improvement efforts at a local and at the supply chain level. Sterman et al. (1997) pointed out that unanticipated effects of successful quality programs are caused by interactions between the quality improvement initiative and other subsystems in the organization.
- The process of implementing a supply chain performance system could be investigated, to identify potential roadblocks and facilitating factors. In this same topic, the cost-effectiveness of implementing a supply chain performance measurement system, especially for small companies could be investigated.
- Future research could focus on the benefits and costs associated with using a common system for performance measurement in a typical supply chain. Confidentiality issues, for example, may play a big role when a company decides whether to participate in an integrated system.

- The case-studied firm uses simultaneously more than one standard for its documentation practices. The interactions and effects of using measurement systems developed in-house along with other quality standards (such as ISO 9000 and quality awards criteria, such as the Baldrige National Quality Program's) could be investigated.

Literature Cited

Agin, N. (1966). Min-max inventory model. *Management Science, 12*(7), 517-529.

Akkermans, H. (2007). *Beyond rounding up the usual suspects: Towards effective quality management policies for production ramp-ups in high-tech supply chains.* Paper presented at the The 2007 International Conference of the System Dynamics Society, Boston, Massachusetts, USA.

Akkermans, H. A., & Oorschot, K. E. v. (2005). Relevance assumed: a case study of balanced scorecard development using system dynamics. *The Journal of the Operational Research Society, 56*(8), 931.

American Forest and Paper Association (2005). U.S. Forest Products Industry - Competitive Challenges in a Global Marketplace. Retrieved from http://www.growthevote.org

American Hardwood Export Council (Undated). An Illustrated Guide to American Hardwood Lumber Grades. 24. Retrieved from http://www.natlhardwood.org/illustrated_guide/IllustratedGradingGuide.pdf

American Lumber Standard Committee (2001-2006). American Lumber Standard Committee Incorporated Retrieved November 2, 2006, from http://alsc.org/

Anderson, R. C., Fell, D., Smith, R. L., Hansen, E. N., & Gomon, S. (2005). Current consumer behavior research in forest products. *Forest Products Journal, 55*(1), 21-27.

Anderson, R. C., & Hansen, E. N. (2004). The impact of environmental certification on preferences for wood furniture: a conjoint analysis approach. [Journal article]. *54*(3), 42-50.

Architectural Woodwork Institute (2006). AWI Quality Certification Program Retrieved November 4, 2006, from http://www.awiqcp.org

Aryee, G., Naim, M. M., & Lalwani, C. (2008). Supply chain integration using a maturity scale. *Journal of Manufacturing Technology Management, 19*(5), 559-575.

Baldrige National Quality Program (2009). *Baldrige Criteria for Performance Excellence*. from http://www.baldrige.nist.gov/Criteria.htm.

Barki, H., & Pinsonneault, A. (2005). A Model of Organizational Integration, Implementation Effort, and Performance. *Organization Science, 16*(2), 165.

Batson, R. G. (2008). A survey of best practices in automotive supplier development. *International Journal of Automotive Technology and Management, 8*(2), 129.

Batson, R. G., & McGough, K. D. (2006). Quality Planning for the Manufacturing Supply Chain. *The Quality Management Journal, 13*(1), 33.

Beamon, B. M. (1999). Measuring supply chain performance. [Article]. *International Journal of Operations & Production Management, 19*(3-4), 275-292.

Beamon, B. M., & Ware, T. M. (1998). A process quality model for the analysis, improvement and control of supply chain systems. *International Journal of Physical Distribution & Logistics Management, 28*(9/10), 704.

Behara, R. S., Fontenot, G. F., & Gresham, A. (1995). Customer satisfaction measurement and analysis using six sigma. *The International Journal of Quality & Reliability Management, 12*(3), 9.

Berry, D., & G.N. Evans, R. M.-J. a. D. R. T. (1999). The BPR SCOPE concept in leveraging improved supply chain performance. *Business Process Management Journal, 5*(3), 254.

Bishop, J. (1990, July/August). In value-added manufacturing, customer calls the shots. *Forest Industries, 117,* 29-31.

Blanchard, D. (2006). What's Working for U.S. Manufacturers. *Industry Week, 255*(10), 49.

Boone, R. S., Milota, M. R., Danielson, J. D., & Huber, D. W. (1992). Quality Drying of Hardwood Lumber: Guidebook-Checklist, *FPL-IMP-GTR-2* (pp. 56): U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Bourne, M., Neely, A., Platts, K., & Mills, J. (2002). The success and failure of performance measurement initiatives: Perceptions of participating managers. *International Journal of Operations & Production Management, 22*(11), 1288.

Brewer, P. C., & Speh, T. W. (2000). Using the balanced scorecard to measure supply chain performance. *Journal of Business Logistics, 21*(1), 75.

Breyfogle, F. W. (1999). *Implementing Six Sigma : Smarter solutions using statistical methods* (Vol. xxxvii, 791 p. :). New York :: John Wiley.

Broman, N. O. (1995). Visual Impressions of Features in Scots Pine Wood Surfaces - a Qualitative Study. *Forest Products Journal, 45*(3), 61-66.

Brown, T. D. (1979). Determining lumber target sizes and monitoring sawing accuracy (Vol. 29, pp. 48-54).

Brown, T. D. (1982). *Quality control in lumber manufacturing* (T. D. Brown, Trans. Vol. 288 p. :). San Francisco :: Miller Freeman Publications.

Bryan, G., & McDougall, D. (1998). Optimize your supply chain for best-possible operations. *Wood Technology, 125*(7), 35.

Buehlmann, U. (2004). What Does the Wood Industry Have to Gain by Leveraging the Supply Chain? On *Conference: Manufacturing Competitiveness of the Forest Products Industry: Competing in Today's Global Manufacturing and Consumer Marketplace* [PowerPoint presentation]. New Orleans, Lousiana: Forest Products Society.

Buehlmann, U., Bumgardner, M., Schuler, A., & Barford, M. (2007). Assessing the impacts of global competition on the Appalachian hardwood industry. *Forest Products Journal, 57*(3), 89.

Bumgardner, M., Buehlmann, U., Schuler, A., & Christianson, R. (2004). Domestic competitiveness in secondary wood industries. *Forest Products Journal, 54*(10), 21.

Buongiorno, J. (1996). Forest sector modeling: A synthesis of econometrics, mathematical programming, and system dynamics methods. *International Journal of Forecasting, 12*(3), 329.

Burgess, T. F. (1996). Modelling quality-cost dynamics. *The International Journal of Quality & Reliability Management, 13*(3), 8.

Bush, R. J., Sinclair, S. A., & Araman, P. A. (1991). Determinant Product and Supplier Attributes in Domestic Markets for Hardwood Lumber. [Article]. *Forest Products Journal, 41*(1), 33-40.

Calori, R., & Ardisson, J. M. (1988). Differentiation Strategies in Stalemate Industries. [Article]. *Strategic Management Journal, 9*(3), 255-269.

Carr, A. S., & Pearson, J. N. (1999). Strategically managed buyer-supplier relationships and performance outcomes. *Journal of Operations Management, 17*(5), 497.

Cassens, D. L., & Fischer, B. C. (1978). Hardwood Log Grades and Lumber Grades: Is There a Relationship? *Forestry & Natural Resources - Marketing and Utilization. Cooperative Extension Service Purdue University, FNR-84*. Retrieved from http://www.ces.purdue.edu/extmedia/FNR/FNR-84.html

Chan, F. T. S. (2003). Performance measurement in a supply chain. [Article]. *International Journal of Advanced Manufacturing Technology, 21*(7), 534-548.

Chandra, M. J. (2001). *Statistical quality control* (Vol. 284 p. :). Boca Raton, FL :: CRC Press.

Chen, C.-C., Yeh, T.-M., & Yang, C.-C. (2004). Customer-focused rating system of supplier quality performance. *Journal of Manufacturing Technology Management, 15*(7), 599.

Choi, T. Y., & Rungtusanatham, M. (1999). Comparison of quality management practices: Across the supply chain and industries. *Journal of Supply Chain Management, 35*(1), 20.

Closs, D. J., & Savitskie, K. (2003). Internal and external logistics information technology integration. *International Journal of Logistics Management, 14*(1), 63.

Company (2007). Tour Presentation [Electronic presentation document].

Cook, D. F. (1992). Statistical process control for continuous forest products manufacturing operations (Vol. 42, pp. 47-53).

Cumbo, D., Kline, D. E., & Bumgardner, M. (2006). Benchmarking performance measurement and lean manufacturing in the rough mill. *Forest Products Journal, 56*(6), 25-30.

Cuppett, D. G. (1966). Air-drying practices in the central Appalachians. *Research Papers. Northeastern Forest Experiment Station*(No. NE-56), 19.

D'Amours, S., Frayret, J.-M., & Rousseau, A. (2004). From the forest to the client- why have integrated management of the value creation network. *FOR@C - Forest to Customer. Université Laval. Quebec, Canada.* Retrieved from http://www.forac.ulaval.ca/fileadmin/docs/Publications/GestionIntegreeRCV.pdf

Dasgupta, T. (2003). Using the six-sigma metric to measure and improve the performance of a supply chain. *Total Quality Management & Business Excellence, 14*(3), 355.

De-Toni, A., Nassimbeni, G., & Tonchia, S. (1995). An Instrument for Quality Performance-Measurement. [Article]. *International Journal of Production Economics, 38*(2-3), 199-207.

De Vasconcellos, J. A. S. (1991). Key Success Factors in Marketing Mature Products. [Article]. *Industrial Marketing Management, 20*(4), 263-278.

Deming, W. E. (1986). *Out of the crisis* (Vol. xiii, 507 p. :). Cambridge, Mass. :: Massachusetts Institute of Technology, Center for Advanced Engineering Study.

Denig, J. (1993). *Small sawmill handbook : doing it right and making money* (Vol. ix, 182 p. :). San Francisco :: Miller Freeman.

Denig, J., Wengert, E. M., & Simpson, W. T. (2000). *Drying hardwood lumber. Gen. Tech. Rep. FPL–GTR–118.* (Vol. 138 p. :). Madison, WI:: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory.

Dong, M. (2001). *Process Modeling, Performance Analysis and Configuration Simulation in Integrated Supply Chain Network Design.* Unpublished Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Dunn, M. A., Shupe, T. F., & Vlosky, R. P. (2003). Homebuilder attitudes and preferences regarding southern yellow pine. *Forest Products Journal, 53*(4), 36-41.

Dupuy, C. A., & Vlosky, R. P. (2000). Status of electronic data interchange in the forest products industry. *Forest Products Journal, 50*(6), 32.

Earl, R. G. (1989). Quality & Supply Chain Logistics. *Management Services, 33*(6), 6.

Fabbe-Costes, N., & Jahre, M. (2008). Supply chain integration and performance: a review of the evidence. *International Journal of Logistics Management, 19*(2), 130-154.

Farris, J. A. (2006). *An empirical investigation of Kaizen event effectiveness outcomes and critical success factors.* Unpublished Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Va.

Ferdows, K., Lewis, M. A., & Machuca, J. A. D. (2004). Rapid-Fire Fulfillment. *Harvard Business Review, 82*(11), 104.

Few, S. (2006). *Information dashboard design : the effective visual communication of data* (1st ed. ed. Vol. viii, 211 p. :). Beijing ; Cambride [MA] :: O'Reilly.

Flynn, B. B., Schroeder, R. G., & Sakakibara, S. (1995). The impact of quality management practices on performance and competitive advantage. *Decision Sciences, 26*(5), 659.

Fontenot, G., Behara, R., & Gresham, A. (1994). Six sigma in customer satisfaction. *Quality Progress, 27*, 73.

Fontenot, R. J., Vlosky, R. P., Wilson, E. J., & Wilson, D. T. (1998). A model of buyer-seller relationship structure effects on firm performance. *American Marketing Association. Conference Proceedings, 9*, 206.

Forbes, C. L., Sinclair, S. A., Bush, R. J., & Araman, P. A. (1994). Influence of Product and Supplier Attributes on Hardwood Lumber Purchase Decisions in the Furniture Industry. [Article]. *Forest Products Journal, 44*(2), 51-56.

Ford, D. N., & Sterman, J. D. (2003). The Liar's Club: Concealing Rework in Concurrent Development. *Concurrent Engineering Research and Applications, 11*(3), 211-219.

Forest Products Laboratory (1999a). Air drying of lumber, *Gen. Tech. Rep. FPL-GTR-117* (pp. 62). Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Forest Products Laboratory (1999b). *Wood handbook - Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113*. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Forest Stewardship Council (2003). Forest Stewardship Council Retrieved November 17, 2006, from http://www.fsc.org/en/

Forker, L. B., Mendez, D., & Hershauer, J. C. (1997). Total quality management in the supply chain: what is its impact on performance? *International Journal of Production Research, 35*, 1681-1702.

Forker, L. B., Ruch, W. A., & Hershauer, J. C. (1999). Examining supplier improvement efforts from both sides. *Journal of Supply Chain Management, 35*(3), 40.

Forrester, J. W. (1961). *Industrial dynamics* (Vol. 464 p.). [Cambridge, Mass.]: M.I.T. Press.

Forrester, J. W. (1978). Industrial Dynamics: A Major Breakthrough for Decision Makers (E. B. Roberts, Trans.). In E. B. Roberts (Ed.), *Managerial applications of system dynamics* (Vol. xiii, 669 p. :, pp. 37-65). Cambridge :: MIT Press.

Forza, C., & Filippini, R. (1998). TQM impact on quality conformance and customer satisfaction: A causal model. *International Journal of Production Economics, 55*(1), 1.

Fram, E. H. (1995). Purchasing partnerships: The buyer's view. *Marketing Management, 4*(1), 49.

Freese, F. (1973). *A collection of log rules*: USDA Forest Service General Technical Report, Forest Products Laboratory, Madison.

Frohlich, M. T., & Westbrook, R. (2001). Arcs of integration: An international study of supply chain strategies. *Journal of Operations Management, 19*(2), 185.

Fynes, B., Voss, C., & Burca, S. d. (2005). The impact of supply chain relationship quality on quality performance. *International Journal of Production Economics, 96*(3), 339.

Garvin, D. A. (1984a). Product Quality - an Important Strategic Weapon. [Article]. *Business Horizons, 27*(3), 40-43.

Garvin, D. A. (1984b). What Does Product Quality Really Mean. [Article]. *Sloan Management Review, 26*(1), 25-43.

Gatchell, C. J., & Thomas, E. (1997). Within-grade quality differences for 1 and 2A common lumber affect processing and yields when gang-ripping red oak lumber. *Forest Products Journal, 47*(10), 85.

Germain, R., & Iyer, K. N. S. (2006). The Interaction of Internal and Downstream Integration and its Association with Performance. *Journal of Business Logistics, 27*(2), 29.

Graves, S. (2001). Six Sigma Rolled Throughput Yield. *Quality Engineering, 14*(2), 257.

Graves, S. (2008). Throughput Yield for Parallel Processes. In O. Espinoza (Ed.) (Electronic mail communication ed., pp. 1). Blacksburg.

Green, D. W., Ethington, R. L., King, E. G., Shelley, B. E., & Gromala, D. S. (2004). ASTM COMMITTEE D-7: WOOD: Promoting Safety and Standardization for 100 Years. *Forest Products Journal, 54*(9), 8.

Grushecky, S. T., Buehlmann, U., Schuler, A., Luppold, W., & Cesa, E. (2006). Decline in the US furniture industry: A case study of the impacts to the hardwood lumber supply chain. *Wood and Fiber Science, 38*(2), 365-376.

Gryna, F. M., De Feo, J. A., & Juran, J. M. (2007). *Juran's quality planning and analysis : for enterprise quality* (R. C. H. Chua, J. A. De Feo & J. M. Juran, Trans. 5th ed. ed. Vol. xxvi, 774 p. :). Boston :: McGraw-Hill.

Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. [Article]. *International Journal of Production Economics, 87*(3), 333-347.

Gunnarsson, H., Ronnqvist, M., & Lundgren, J. T. (2004). Supply chain modelling of forest fuel. *European Journal of Operational Research, 158*(1), 103.

Gunter, R., Rolf-Dieter, K., & Hans-Werner, K. (1994). Does quality pay? *The McKinsey Quarterly*(1), 51.

Gygi, C. (2005). *Six sigma for dummies* (N. DeCarlo & B. Williams, Trans. Vol. xvi, 344 p. :). Hoboken, NJ :: Wiley Pub.

Hahn, C. K., Watts, C. A., & Kim, K. Y. (1990). The Supplier Development Program: A Conceptual Model. *Journal of Purchasing and Materials Management, 26*(2), 2.

Hansen, E., & Bush, R. (1996). Consumer perceptions of softwood lumber quality. *Forest Products Journal, 46*(10), 29-34.

Hansen, E., & Bush, R. J. (1999). Understanding customer quality requirements - Model and application. [Article]. *Industrial Marketing Management, 28*(2), 119-130.

Hansen, E., & Punches, J. (1996). Perceptions often define softwood lumber quality. *Wood Technology, 123*(2), 30.

Hansen, E. N., Bush, R. J., & Fern, E. F. (1996). An empirical assessment of the dimensions of softwood lumber quality. *Forest Science, 42*(4), 407-414.

Harding, O. V., Steele, P. H., & Nordin, K. (1993). Description of defects by type for six grades of red oak lumber. *Forest Products Journal, 43*(6), 45.

Harry, M. J. (1998). Six sigma: A breakthrough strategy for profitability. *Quality Progress, 31*(5), 60.

Harry, M. J. (2000). Six sigma focuses on improvement rates. *Quality Progress, 33*(6), 76.

Healey, M., & Rawlinson, M. (1994). Interviewing Techniques in Business and Management Research (V. J. Wass & P. E. Wells, Trans.). In V. J. Wass & P. E. Wells (Eds.), *Principles and practice in business and management research* (Vol. xv, 306 p. :, pp. 123-145). Aldershot, Hants, England ; Brookfield, Vt. :: Dartmouth Pub. Co.

Hines, P., & Rich, N. (1997). The seven value stream mapping tools. *International Journal of Operations & Production Management, 17*(1), 46.

Hiziroglu, S. (2007). Practical Approaches to Wood Finishing. *Oklahoma Cooperative Extension Service,* (NREM-5016), 4. Retrieved from http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-2742/NREM-5016web.pdf

Houlihan, J. B. (1985). International Supply Chain Management. *International Journal of Physical Distribution & Materials Management, 15*(1), 22.

Hsieh, F. Y., Bloch, D. A., & Larsen, M. D. (1998). A simple method of sample size calculation for linear and logistic regression. *Statistics in Medicine, 17*(14), 1623-1634.

Hunter, S. L., Bullard, S., & Steele, P. H. (2004). Lean production in the furniture industry: The double D assembly cell. *Forest Products Journal, 54*(4), 32-38.

International Organization for Standardization (2004). ISO 9000 and ISO 14000 - in brief Retrieved November 17, 2006, from http://www.iso.org

Jambekar, A. B. (2000). A systems thinking perspective of maintenance, operations, and process quality. *Journal of Quality in Maintenance Engineering, 6*(2), 123.

Jankowski, D. (2006). What Can We Learn from Deming? *Mortgage Banking, 66*(11), 94.

Johnson, A. H. (2002). 35 years of IT leadership: A new supply chain forged. *Computerworld, 36*(40), 38.

Jones, A., Seville, D., & Meadows, D. (2002). Resource sustainability in commodity systems: the sawmill industry in the Northern Forest. *System Dynamics Review, 18*(2), 171.

Jones, D., & Womack, J. (2002a). *Seeing the Whole - Mapping the Extended Value Stream*. Brookline, MA.: The Lean Enterprise Inst.

Jones, D., & Womack, J. (2002b). Seeing the Whole - Mapping the Extended Value Stream. In T. L. E. I. Inc. (Ed.) (pp. 3-5). Brookline, MA.: The Lean Enterprise Inst.

Kannan, V. R., & Tan, K. C. (2007). The impact of operational quality: a supply chain view. *Supply Chain Management, 12*(1), 14.

Kao, C., & Yang, Y. C. (1991). Measuring the efficiency of forest management (Vol. 37, pp. 1239-1252).

Kelton, W. D. (2004). *Simulation with Arena* (R. P. Sadowski & D. T. Sturrock, Trans. 3rd ed. ed. Vol. xxiv). New York, NY :: McGraw-Hill Higher Education.

Khanna, V. K., Vrat, P., Shankar, R., & Sahay, B. S. (2004). Managing the transition phases in the TQM journey: A system dynamics approach. *The International Journal of Quality & Reliability Management, 21*(4/5), 518.

Kim, B., & Oh, H. (2005). The impact of decision-making sharing between supplier and manufacturer on their collaboration performance. *Supply Chain Management, 10*(3/4), 223.

Kocakülâh, M. C., Brown, J. F., & Thomson, J. W. (2008). Lean Manufacturing Principles and their Application. *Cost Management, 22*(3), 16.

Koulikoff-Souviron, M., & Harrison, A. (2005). Using Case Study Methods in Researching Supply Chains (H. Kotzab & M. Westhaus, Trans.). In H. Kotzab, S. Seuring, M. Muller, G. Reiner & M. Westhaus (Eds.), *Research methodologies in supply chain management* (Vol. xi, 619 p. :, pp. 267-282). Heidelberg ; New York :: Physica-Verlag.

Kozak, R. A., & Maness, T. C. (2003). A system for continuous process improvement in wood products manufacturing. *Holz Als Roh-Und Werkstoff, 61*(2), 95-102.

Kuei, C.-H., Madu, C. N., & Lin, C. (2001). The relationship between supply chain quality management practices and organizational performance. *The International Journal of Quality & Reliability Management, 18*(8/9), 864.

Lambert, D. M. (2006). *Supply Chain Management* (2nd ed.). Sarasota, FL: Supply Chain Management Institute.

Lambert, D. M., & Cooper, M. C. (2000). Issues in supply chain management. [Article]. *Industrial Marketing Management, 29*(1), 65-83.

Lambert, D. M., & Pohlen, T. L. (2001). Supply chain metrics. *International Journal of Logistics Management, 12*(1), 1.

Lapide, L. (2000). True measures of supply chain performance. *Supply Chain Management Review, July/August,* 25-28.

Lee, C. W., Kwon, I.-W. G., & Severance, D. (2007). Relationship between supply chain performance and degree of linkage among supplier, internal integration, and customer. *Supply Chain Management, 12*(6), 444.

Lee, J.-Y. (2005). Using DEA to measure efficiency in forest and paper companies. *Forest Products Journal, 55*(1), 58.

Lee, J., & Unnikrishnan, S. (1998). Planning quality inspection operations in multistage manufacturing systems with inspection errors. *International Journal of Production Research, 36*(1), 141-155.

Levy, P., Bessant, J., Sang, B., & Lamming, R. (1995). Developing integration through total quality supply chain management. *Integrated Manufacturing Systems, 6*(3), 4.

Li, S. H., Rao, S. S., Ragu-Nathan, T. S., & Ragu-Nathan, B. (2005). Development and validation of a measurement instrument for studying supply chain management practices. [Review]. *Journal of Operations Management, 23*(6), 618-641.

Lo, V. H. Y., & Yeung, A. (2006). Managing quality effectively in supply chain: a preliminary study. *Supply Chain Management, 11*(3), 208.

Lummus, R. R., Vokurka, R. J., & Krumwiede, D. (2008). Supply Chain Integration and Organizational Success. *S.A.M. Advanced Management Journal, 73*(1), 56.

Maki, R. G., & Milota, M. R. (1993). Statistical Quality-Control Applied to Lumber Drying. [Article]. *Quality Progress, 26*(12), 75-79.

Mandal, P., Howell, A., & Sohal, A. S. (1998). A systemic approach to quality improvements: The interactions between the technical, human and quality systems. *Total Quality Management, 9*(1), 79.

Mandal, P., Love, P. E. D., & Gunasekaran, A. (2002). Towards a system dynamics modelling framework for quality in manufacturing. *International Journal of Manufacturing Technology and Management, 4*(3,4), 333.

Mason-Jones, R., & Towill, D. R. (1997). Information enrichment: designing the supply chain for competitive advantage. *Supply Chain Management, 2*(4), 137.

Mason-Jones, R., & Towill, D. R. (1999). Total cycle time compression and the agile supply chain. *International Journal of Production Economics, 62*(1,2), 61.

McPherson, G. (1990). *Statistics in scientific investigation : its basis, application, and interpretation* (Vol. xxvi, 666 p. :). New York :: Springer-Verlag.

Minahan, T. A. (2005). 5 Strategies for High Performance Procurement. *Supply Chain Management Review, 9*(6), 46.

Mitchell, P. H., Wiedenbeck, J., & Ammerman, B. (2005). *Rough mill improvement guide for managers and supervisors*.

Montgomery, D. C., Peck, E. A., & Vining, G. G. (2001). *Introduction to linear regression analysis* (3rd ed. ed. Vol. xvi). New York :: Wiley.

Moriarty, R. T., & Reibstein, D. J. (1986). Benefit Segmentation in Industrial Markets. *Journal of Business Research, 14*(6), 463.

Muralidharan, C., Anantharaman, N., & Deshmukh, S. G. (2002). A multi-criteria group decisionmaking model for supplier rating. *Journal of Supply Chain Management, 38*(4), 22.

National Hardwood Lumber Association (2003). Rules for the measurement and inspection of hardwood and cypress. In N. H. L. Association (Eds.) Available from http://www.natlhardwood.org/pdf/Rulebook.pdf

Naylor, J. B., Naim, M. M., & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of Production Economics, 62*(1,2), 107.

Neely, A. (1999). The performance measurement revolution: why now and what next? *International Journal of Operations & Production Management, 19*(2), 205.

Neely, A., Gregory, M., & Platts, K. (2005). Performance measurement system design - A literature review and research agenda. [Review]. *International Journal of Operations & Production Management, 25*(12), 1228-1263.

New, C. (1993). The Use of Throughput Efficiency as a Key Performance Measure for the New Manufacturing Era. *The International Journal of Logistics Management, 4*(2), 95-104.

NIST/SEMATECH (2006, 7/18/2006). e-Handbook of Statistical Methods, Retrieved October 27, 2008, from http://www.itl.nist.gov/div898/handbook/

Novack, R. A., & Thomas, D. J. (2004). The Challenges of Implementing the Perfect Order Concept. *Transportation Journal, 43*(1), 5.

Nyrud, A. Q., & Baardsen, S. (2003). Production efficiency and productivity growth in Norwegian sawmilling (Vol. 49, pp. 89-97).

Olah, D., Smith, R., & Hansen, B. (2003). Wood material use in the U.S. cabinet industry 1999 to 2001. *Forest Products Journal, 53*(1), 25.

Oliva, R., & Sterman, J. D. (2001). Cutting corners and working overtime: Quality erosion in the service industry. *Management Science, 47*(7), 21.

Ott, L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis* (5th ed. ed. Vol. xvii). Australia ; Pacific Grove, CA :: Duxbury/Thomson Learning.

Ozanne, L. K., & Vlosky, R. P. (2003). Certification from the U.S. consumer perspective: a comparison from 1995 and 2000. [Journal article]. *53*(3), 13-21.

Pagell, M. (2004). Understanding the factors that enable and inhibit the integration of operations, purchasing and logistics. *Journal of Operations Management, 22*(5), 459.

Pakarinen, T. (1999). Success factors of wood as a furniture material. *Forest Products Journal, 49*(9), 79-85.

Parasuraman, A. (1985). A Conceptual Model of Service Quality and Its Implications for Future Research. *Journal of Marketing (pre-1986), 49*(000004), 41.

Parasuraman, A., Zeithaml, V. A., & Berry, L. L. (1988). Servqual - a Multiple-Item Scale for Measuring Consumer Perceptions of Service Quality. [Article]. *Journal of Retailing, 64*(1), 12-40.

Patterson, D. W., & Anderson, R. B. (1996). Use of statistical process control in the furniture and cabinet industries. *Forest Products Journal, 46*(1), 36-38.

Persson, F., & Olhager, J. (2002). Performance simulation of supply chain designs. *International Journal of Production Economics, 77*(3), 231.

Petersen, K. J., Handfield, R. B., & Ragatz, G. L. (2005). Supplier integration into new product development: coordinating product, process and supply chain design. *Journal of Operations Management, 23*(3,4), 371.

Pitcher, M. (2006). How to combat push inventory systems. *Official Board Markets, 82*(50), 10-11.

Punches, J., & Vlosky, R. (1998). Share data quickly, widely to boost business efficiency. *Wood Technology, 125*(4), 22.

Pyzdek, T. (2000). Yield the Right Way. *Quality Digest*. Retrieved from http://www.qualitydigest.com/mar00/html/sixsigma.html

Pyzdek, T. (2003). *The Six Sigma handbook a complete guide for green belts, black belts, and managers at all levels* (Rev. and expanded ed. ed.). New York :: McGraw-Hill.

Rahman, S.-u. (2006). Quality management in logistics: an examination of industry practices. *Supply Chain Management, 11*(3), 233.

Raisinghani, M. S., Ette, H., Pierce, R., Cannon, G., & Daripaly, P. (2005). Six Sigma: concepts, tools, and applications. *Industrial Management & Data Systems, 105*(3/4), 491.

Rast, E. D., Sonderman, D. L., & Gammon, G. L. (1973). *A guide to hardwood log grading*: USDA Forest Service General Technical Report, Northeastern Forest Experiment Station.

Ravichandran, J. (2006). Six-Sigma Milestone: An Overall Sigma Level of an Organization. *17*, 973.

Ravichandran, J. (2007). Cost-based process weights for DPMO and the overall performance of an organization. *The TQM Magazine, 19*(5), 442.

Reeb, J. E., & Massey, J. G. (1996). Using customer-driven information to add value to lumber. *Forest Products Journal, 46*(10), 41-44.

Repenning, N. P. (2001). Understanding fire fighting in new product development. *Journal of Product Innovation Management, 18*(5), 285-300.

Roberts, E. B. (1978). *Managerial applications of system dynamics* (E. B. Roberts, Trans. Vol. xiii, 669 p. :). Cambridge :: MIT Press.

Roberts, E. B. (1978). System Dynamics - An Introduction (E. B. Roberts, Trans.). In E. B. Roberts (Ed.), *Managerial applications of system dynamics* (Vol. xiii, 669 p. :, pp. 3-35). Cambridge :: MIT Press.

Robinson, C. J., & Malhotra, M. K. (2005). Defining the concept of supply chain quality management and its relevance to academic and industrial practice. *International Journal of Production Economics, 96*(3), 315.

Rodrigues, A. M., Stank, T. P., & Lynch, D. F. (2004). Linking Strategy, Structure, Process, and Performance in Integrated Logistics. *Journal of Business Logistics, 25*(2), 65.

Roethlein, C. J. (2000). *Quality and strategy within United States based manufacturing supply chains.* Unpublished Dissertation, University of Rhode Island, United States -- Rhode Island.

Rogers, K. W., Purdy, L., Safayeni, F., & Duimering, P. R. (2007). A supplier development program: Rational process or institutional image construction? *Journal of Operations Management, 25*(2), 556.

Rosenzweig, E. D., Roth, A. V., & Dean, J. W. (2003). The influence of an integration strategy on competitive capabilities and business performance: An exploratory study of consumer products manufacturers. *Journal of Operations Management, 21*(4), 437.

Ross, D. F. (1998). *Competing through supply chain management : creating market-winning strategies through supply chain partnerships* (Vol. xv, 365 p. :). New York :: Chapman & Hall.

Ruddell, S., & Stevens, J. A. (1998). The adoption of ISO 9000, ISO 14001, and the demand for certified wood products in the business and institutional furniture industry. *Forest Products Journal, 48*(3), 19-26.

Salvador, F., Forza, C., Rungtusanatham, M., & Choi, T. Y. (2001). Supply chain interactions and time-related performances An operations management perspective. *International Journal of Operations & Production Management, 21*(4), 461.

Sanders, N. R., & Premus, R. (2005). Modeling the Relationship Betwee Firm IT Capability, Collaboration, and Performance. *Journal of Business Logistics, 26*(1), 1.

Saraph, J. V., Benson, P. G., & Schroeder, R. G. (1989). An Instrument For Measuring The Critical Factors Of Quality Management. *Decision Sciences, 20*(4), 810.

Schlager, K. J. (1978). How Managers Use Industrial Dynamics (E. B. Roberts, Trans.). In E. B. Roberts (Ed.), *Managerial applications of system dynamics* (Vol. xiii, 669 p. :, pp. 145-153). Cambridge :: MIT Press.

Seuring, S. (2005). Case Study Research in Supply Chains - An Outline and Three Examples (H. Kotzab & M. Westhaus, Trans.). In H. Kotzab, S. Seuring, M. Muller, G. Reiner & M. Westhaus (Eds.), *Research methodologies in supply chain management* (Vol. xi, 619 p. :, pp. 235-250). Heidelberg ; New York :: Physica-Verlag.

Shepherd, C., & Günter, H. (2006). Measuring supply chain performance: current research and future directions. *International Journal of Productivity and Performance Management, 55*(3/4), 242.

Shiba, M. (1997). Measuring the efficiency of managerial and technical performances in forestry activities by means of Data Envelopment Analysis (DEA) (Vol. 8, pp. 7-19).

Sila, I., Ebrahimpour, M., & Birkholz, C. (2006). Quality in supply chains: an empirical analysis. *Supply Chain Management, 11*(6), 491.

Simatupang, T. M., & Sridharan, R. (2008). Design for supply chain collaboration. *Business Process Management, 14*(3), 401-418.

Sinclair, S. A., Hansen, B. G., & Fern, E. F. (1993). Industrial Forest Product Quality - an Empirical-Test of Garvin-8 Quality Dimensions. [Article]. *Wood and Fiber Science, 25*(1), 66-76.

Smith, R. L., Pohle, W., Araman, P., & Cumbo, D. (2004). Characterizing the adoption of low-grade hardwood lumber by the secondary wood processing industry. *Forest Products Journal, 54*(12), 15.

Sowlati, T. (2005). Efficiency studies in forestry using data envelopment analysis. *Forest Products Journal, 55*(1), 49.

Stank, T. P., Keller, S. B., & Daugherty, P. J. (2001). Supply chain collaboration and logistical service performance. *Journal of Business Logistics, 22*(1), 29.

Steele, P. H. (1984). *Factors determining lumber recovery in sawmilling*.

Steele, P. H., Wiedenbeck, J., Shmulsky, R., & Perera, A. (1999). The influence of lumber grade on machine productivity in the rough mill. *Forest Products Journal, 49*(9), 48.

Sterman, J. D., Repenning, N. P., & Kofman, F. (1997). Unanticipated side effects of successful quality programs: Exploring a paradox of organizational improvement. *Management Science, 43*(4), 503.

Stevens, G. C. (1989). Integrating the Supply Chain. *International Journal of Physical Distribution & Materials Management, 19*(8), 3.

Stevens, J., Mubariq, A., & Ruddell, S. (1998). Forest products certification: a survey of manufacturers (Vol. 48, pp. 43-49).

Stevenson, W. J. (2000). Supercharging your Pareto analysis. *Quality Progress, 33*(10), 51.

Stuart, I., McCutcheon, D., Handfield, R., McLachlin, R., & Samson, D. (2002). Effective case research in operations management: A process perspective. *Journal of Operations Management, 20*(5), 419.

Supply-Chain Council (2008). Supply-Chain Operations Reference-model version 9.0. 28. Retrieved from www.supply-chain.org

Tan, K.-C., Kannan, V. R., Handfield, R. B., & Ghosh, S. (1999). Supply chain management: an empirical study of its impact on performance. *International Journal of Operations & Production Management, 19*(10), 1034.

Tapping, D., Luyster, T., & Shuker, T. (2002). *Value stream management : eight steps to planning, mapping, and sustaining lean improvements* (T. Luyster & T. Shuker, Trans. Vol. vi, 169 p. :). New York, N.Y. :: Productivity.

Taylor, N. H. (1989). Marketing alder with "user friendly" grades. *Proceedings ... Annual Hardwood Symposium of the Hardwood Research Council*(17th), 127-132.

Teigen, K. H. (1994). Yerkes-Dodson: A Law for all Seasons. *Theory Psychology, 4*, 23.

Thakur, D. (2002). 9 reasons to switch to a single supplier system. *Quality Progress, 35*(3), 61.

The Economist (2007). Special Report: In the shadow of prosperity - Trade's victims; Trade's victims. *The Economist, 382,* 29.

Towill, D. R. (1996). Time compression and supply chain management - a guided tour. *Supply Chain Management, 1*(1), 15.

Towill, D. R., Naim, M. M., & Wikner, J. (1992). Industrial Dynamics Simulation Models in the Design of Supply Chains. *International Journal of Physical Distribution & Logistics Management, 22*(5), 3.

U.S. Census Bureau (2005). *Annual Survey of Manufactures- Statistics for Industry Groups and Industries: 2004*. from http://www.census.gov/prod/2005pubs/am0431gs1.pdf.

U.S. Commerce Department's Technology Administration (2006). Baldrige National Quality Award Retrieved November 18, 2006, from http://www.quality.nist.gov

U.S. Department of Commerce (2004a). *Nonupholstered Wood Household Furniture Manufacturing: 2002*.

U.S. Department of Commerce (2004b). *Wood Kitchen Cabinet and Countertop Manufacturing: 2002*.

Vahid, S., & Sowlati, T. (2007). Efficiency analysis of the Canadian wood-product manufacturing subsectors: A DEA approach. *Forest Products Journal, 57*(1/2), 71.

Van-Aken, E. M. (2004). The Quality Paradox: Aligning Performance Measurements to Decision Making. On *Conference: Manufacturing Competitiveness of the Forest Products Industry: Competing in Today's Global Manufacturing and Consumer Marketplace* [PowerPoint presentation]. New Orleans, Lousiana: Forest Products Society.

Van-Aken, E. M., & Coleman, G. D. (2002). Building better measurement. *Industrial Management, 44*(4), 28.

Van-Donk, D. P. (2001). Make to stock or make to order; The decoupling point in the food processing industries. *International Journal of Production Economics, 69*(3), 297.

Van-Donk, D. P., & Van-der-Vaart, T. (2005). A case of shared resources, uncertainty and supply chain integration in the process industry. *International Journal of Production Economics, 96*(1), 97.

Vickery, S. K., Jayaram, J., Droge, C., & Calantone, R. (2003). The effects of an integrative supply chain strategy on customer service and financial performance: an analysis of direct versus indirect relationships. *Journal of Operations Management, 21*(5), 523.

Viitala, E. J., & Hänninen, H. (1998). Measuring the efficiency of public forestry organizations (Vol. 44, pp. 298-307).

Visawan, D., & Tannock, J. (2004). Simulation of the economics of quality improvement in manufacturing: A case study from the Thai automotive industry. *The International Journal of Quality & Reliability Management, 21*(6/7), 638.

Vlosky, R. P., Wilson, E. J., Cohen, D. H., Fontenot, R., & et al. (1998). Partnerships versus typical relationships between wood products distributors and their manufacturer suppliers. *Forest Products Journal, 48*(3), 27.

Walker, B., Bovet, D., & Martha, J. (2000). Unlocking the supply chain to build competitive advantage. *International Journal of Logistics Management, 11*(2), 1.

Walker, W. T. (2005). Emerging trends in supply chain architecture. *International Journal of Production Research, 43*(16), 3517.

Wang, F.-K., Du, T. C., & Li, E. Y. (2004). Applying Six-Sigma to Supplier Development. *Total Quality Management & Business Excellence, 15*(9,10), 1217.

Wang, S. J. (1988). A new dimension sawmill performance measure. *Forest Products Journal, 38*(10), 64-68.

Wang, T., Chen, Y., & Feng, Y. (2005). On the time-window fulfillment rate in a single-item min-max inventory control system. *IIE Transactions (Institute of Industrial Engineers), 37*(7), 667-680.

Wankhade, L., & Dabade, B. M. (2006). TQM with quality perception: a system dynamics approach. *The TQM Magazine, 18*(4), 341.

Weinfurter, S., & Hansen, E. N. (1999). Softwood lumber quality requirements: Examining the supplier/buyer perception gap. [Article]. *Wood and Fiber Science, 31*(1), 83-94.

Wikner, J., Towill, D. R., & Naim, M. (1991). Smoothing Supply Chain Dynamics. *International Journal of Production Economics, 22*(3), 231.

Winistorfer, P. M. (2005). Competitiveness, manufacturing, and the role of education in the supply chain for the forest industry. *Forest Products Journal, 55*(6), 6.

Witell, L., & Löfgren, M. (2007). Classification of quality attributes. *Managing Service Quality, 17*(1), 54.

Womack, J. P. (2006). Value Stream Mapping. *Manufacturing Engineering, 136*(5), 145.

Wood, N. (2004). Learning to see: How does your supply chain function? *Management Services, 48*(4), 16.

Wood Products Quality Council (2006). Wood Products Quality Council Retrieved November, 1st, 2006, from http://www.wpqc.com/

Yin, R. K. (1984). *Case study research : design and methods* (Vol. 160 p. ;). Beverly Hills, Calif. :: Sage Publications.

Yin, R. S. (1998). DEA: A new methodology for evaluating the performance of forest products producers. *Forest Products Journal, 48*(1), 29-34.

Young, T. M., & Winistorfer, P. M. (1999). Spc. [Article]. *Forest Products Journal, 49*(3), 10-17.

Zinkhan, F. C. (1988). Evaluating the performance of a forest products firm. *Forest Products Journal, 38*(9), 33-36.

Zokaei, A. K., & Simons, D. W. (2006). Value chain analysis in consumer focus improvement. *International Journal of Logistics Management, 17*(2), 141.

Zu, X. (2009). Infrastructure and core quality management practices: how do they affect quality? *The International Journal of Quality & Reliability Management, 26*(2), 129.

Appendix A: Lumber Supplier Questionnaire

LUMBER SUPPLIER QUESTIONNAIRE

Company ______________________ Location: ______________________

Name: ______________________ Position: ______________ Date: __________

----- General Information -----

1. Type of facility (mark more than one option if applies)
   - ☐ Sawmilll
   - ☐ Air drying yard
   - ☐ Pre- and/or kiln-drying operation
   - ☐ Dimension operation
   - ☐ Concentration yard

2. What is the annual lumber output at this facility?

   ______________ bf per year

3. How many employees work at this facility?

   ______________ employees

4. What is the sawmill processing capacity?

   ______________ bf per hour

5. What is your average inventory at:
   - Log yard ______________ bf
   - Air-drying yard ______________ bf
   - Finish product ______________ bf

6. What is the installed capacity at your:
   - Predryers ______________ bf
   - Kilns ______________ bf

----- Value-added Processes -----

7. Please, mark those process that apply to your company

☐ End-coating	☐ Custom grading	☐ Color sorting
☐ End-trimming	☐ Custom sorts	
☐ Pre-surfacing	☐ Custom dimensioning	

----- Technology -----

8. Please, mark the items that apply to your sawmill technology

☐ Headrig optimizer	☐ Trimmer optimizer	☐ Drop/bin sorter
☐ Edger optimizer	☐ Grade mark reader	☐ Resaw optimizer

----- Quality Control System -----

9. Number of employees who spend 50% or more of their time in activities related to Quality Control and/or Improvement: ________ employees

10. What are the main activities of the quality personnel?

    ____

    ____

11. When do you monitor thickness variation?
    - ☐ Thickness variation is not monitored
    - ☐ Only when there are complains
    - ☐ According to a program
    - ☐ Other method (explain)

    ____

12. When do you monitor grading accuracy?
    - ☐ Grading accuracy is not monitored
    - ☐ Only when there are complains
    - ☐ According to a program
    - ☐ Other method (explain)

    ____

13. What controls/checks do you normally conduct at **log reception** and at the **log yard**?

Description ______
Method used ______
Specification ______
Responsible ______
Frequency ______
Reaction plan ______
Reporting ______

14. What controls/checks do you normally conduct during **lumber manufacturing process**?

Description ______
Method used ______
Specification ______
Responsible ______
Frequency ______
Reaction plan ______
Reporting ______

15. What controls/checks do you normally conduct **during and after kiln-drying**?

Description ______
Method used ______
Specification ______
Responsible ______
Frequency ______
Reaction plan ______
Reporting ______

16. What controls/checks do you normally conduct at the **green chain**?

Description ______
Method used ______
Specification ______
Responsible ______
Frequency ______
Reaction plan ______
Reporting ______

17. What controls/checks do you normally conduct on the **lumber sorting** process?

Description ______
Method used ______
Specification ______
Responsible ______
Frequency ______
Reaction plan ______
Reporting ______

18. What controls/checks do you normally conduct on your **lumber shipment process**?

Description ______________________________

Method used ______________________________

Specification ______________________________

Responsible ______________________________

Frequency ______________________________

Reaction plan ______________________________

Reporting ______________________________

19. Do you currently have a program for quality improvement (e.g. program to reduce thickness variation or improve grading accuracy)?

Description ______________________________

____

Results ______________________________

____

----- Performance Metrics -----

20. What performance data do you currently collect/measure?

- ☐ Overrun/underrun
- ☐ Log cost per MBF lumber
- ☐ Lumber recovery factor
- ☐ Lumber grade yield
- ☐ Conversion cost (per log or MBF or minute)
- ☐ Lumber thickness variation
- ☐ Breakeven sawlog price
- ☐ Headrig downtime/uptime
- ☐ Tape-measure checks
- ☐ Sawing times (per log or MBF)

21. What metrics related to quality do you use, if any?

Metric	Description

----- About the Customer-----

22. Species sold to the Company's plant

- ☐ Red/white Oak
- ☐ Soft Maple
- ☐ Hickory
- ☐ Hard maple
- ☐ Cherry
- ☐ Yellow-poplar

23. How does the Company communicate its lumber quality requirements (e.g. grade-mix, 6-8 feet lumber allowance, mineral content)?

____

____

24. Does your company participates in developing these quality requirements? How?

____

____

25. How would you categorize the Company compared with your average customer?

In terms of quality requirements	In terms of sales volume
☐ Below average	☐ Below average
☐ Average	☐ Average
☐ Higher than average	☐ More than average

26. How often does the Company reject a truckload

- ☐ 1% or less of total shipments are rejected
- ☐ 2 to 5% of total shipments are rejected
- ☐ More than 5% of total shipments are rejected

27. How often does the Company have claims/observations on your shipments

- ☐ 1% or less of total shipments have quality claims
- ☐ 2 to 5% of total shipments have quality claims
- ☐ More than 5% of total shipments have quality claims

28. Whenever there is a quality issue with one of your lumber shipments, how does the Company communicate it to you?

____

____

29. How do you deal with quality claims from the Company (e.g. on a case by case basis, a formal process)?

____

____

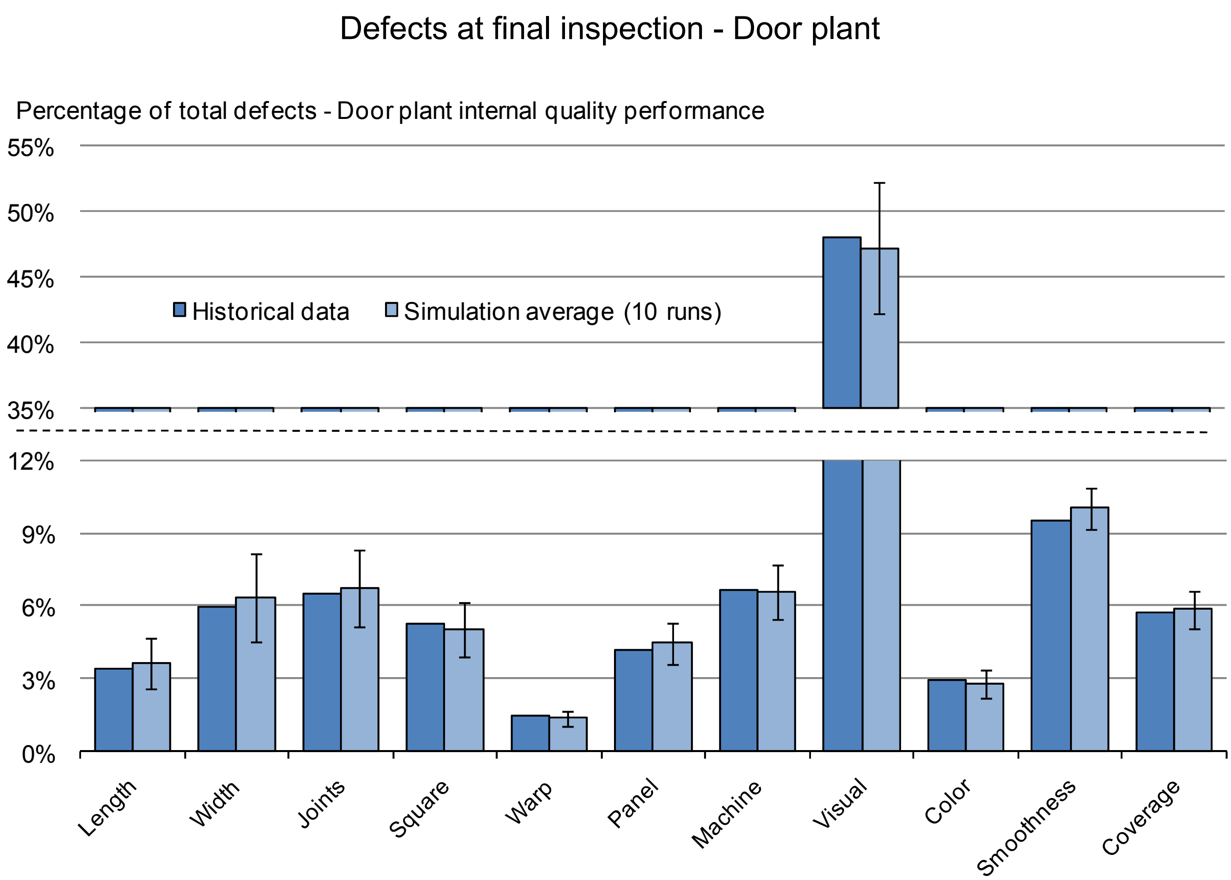
----- Quality Attributes - Importance Scale -----						
30. For each question below, please check the box to the left of the number that best fits your opinion on the importance of the issue. Use the scale above to match your opinion.						
Attribute	**Scale of Importance**					
	Not at all important	**Not very important**	**Average importance**	**Somewhat important**	**Extremely important**	**No opinion**
How do you think the customer rates the importance of the following lumber characteristics:						
Accuracy of grading	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Consistency of grading	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Accuracy of board footage	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Consistency of lumber thickness	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Consistency of lumber overall quality	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Adequacy and consistency of color	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Presence of wane	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Presence of stain	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Packaging (appearance, stacking)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Overall lumber appearance	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Only for kiln-dry lumber:						
Straightness of lumber	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Presence of surface checks, end splits	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Accuracy of moisture content	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Consistency of moisture content	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
How do you think the customer rates the importance of the following lumber supplier attributes?						
Competitive pricing	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Order mix filled correctly	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
On-schedule delivery	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Having previous business with supplier	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Supplier's reputation	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Personal relationship with supplier	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Adequacy of your physical facilities	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide kiln-dry lumber	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide end-coated lumber	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to deliver rapidly on short notice	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide desirable length mix	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide desirable width mix	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide end-trimmed lumber	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to deliver large orders	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to deliver mixed loads	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide custom grades	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to provide a variety of species	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to arrange credit	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐
Ability to arrange shipping	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐

Appendix B: Example of a Quality Control Plan

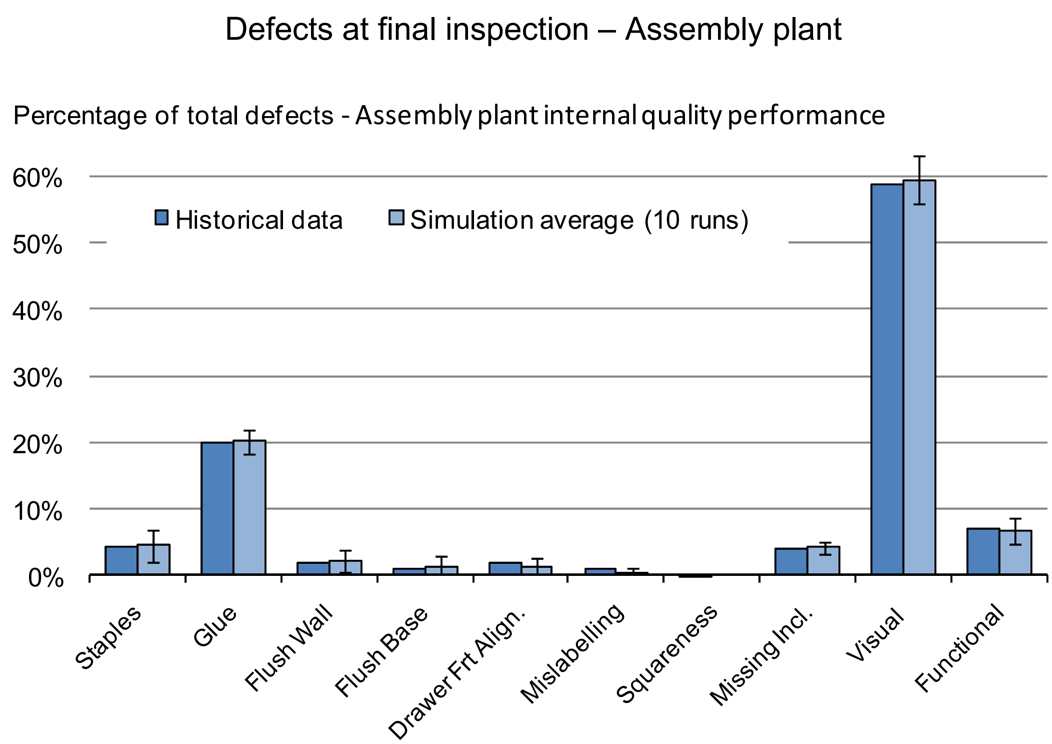
		Product Identification	Work Area		QA Approval			
		Moulder Strip Stock	Rough Mill Dept.					
Document Number		Process Identification	Date	Control plan revision	Supervisor Approval			
		Moulder 1 and 2						
Characteristics					Sample			
No.	Control item	Specification/Tolerance	Method of control	Data Collection Form	#	Frequency	Reaction Plan	Person Responsible
1	Groove Width (Refer to fig. 1 for moulder groove check)	.189" ± .003" P. Overlay Profile .177 ± .003 Std., Woodward,Sundale and Portrait Profile	Optical Comparator	Control Chart, In Process Audit Form	3	Hour	Once the average drops lower than the control limit; check sample ever 15 Min.	Operator
2	Groove Depth	.505" ± .005"	Depth Gauge	None	1	15 Minutes	Measure 3 additional samples if unacceptable, reset moulder	Operator
3	Strip Stock Thickness	.805" ± .005"	Caliper	None	1	15 Minutes	Measure 3 additional samples if unacceptable, reset moulder	Operator
4	Strip Stock Width	2.312" ± .010" Std. Profile 2.450" ± .010" P. Overlay Profile 2.125" ± .010" Woodward Profile 1.880 ± .010" Sundale 2.313 ± .010" Portrait	Caliper	None	1	15 Minutes	Measure 3 additional samples if unacceptable, reset moulder	Operator
5	Profile Fit	Must fit steel block in all critical areas	Steel Profile Block	None	1	15 Minutes	Measure 3 additional samples if unacceptable, reset moulder	Operator
6	Quality of Cut	Chatter- Slightly visible-Not detected by touch. Pulled Grain- Slight allowed in cross grain only. Tear out-Slight in angular grain only. Burnishing-None allowed	Visual	None	1	15 Minutes	Inspect 3 additional sample if unacceptable, reset moulder	Operator
7	Profile Alignment	0" offset ± .005"	Steel Profile Block	None	1	15 Minutes	Measure 3 additional samples if unacceptable, reset moulder	Operator
8	Profile Squareness	.000" out of square, .000" upward tilt, .015" downward tilt	Steel Profile Block & Square	None	1	15 Minutes	Measure 3 additional samples if unacceptable, reset moulder	Operator
9	Amount of Joint	Maximum allowable joint land width .032" or Maximum allowable OD reduction -.020"	Visual, Calipers, Comparator	Tooling Log	1	Once per change of profile	Notify Supervisor and Grinding Room Technician	Operator
10	Feed Rate	STD Oak Single Bead - Max. 300 fpm STD Maple & Cherry - Max. 280 fpm WWD Oak - Max. 265 fpm	Digital Read Out	In-Process Audit Form	1	Hour	Notify Moulder Operator, Supervisor, and Quality Assurance Supv	Quality Technician
11	SPC (Control Chart) Moulder Grove	Get on piece of moulding stock and check for quality of cut, strip stock thickness, width, and check with gage block, sut three pieces out of strip stock, lightly sand inside grove with 180 grit sandpaper, put pieces on Opticial Compareter and measure the groove width and depth, average the groove depth and record on chart, record the groove width on chart, average, and range, plot results on chart	Visual / Manual	SPC Chart		5 samples per hour	Stop the process, determine root cause, perform corrective actions, circle out of control plots, briefly note root cause and corrective action on chart	Operator
12	SPC (Control Chart) Moulder Thickness	Get on piece of moulding stock and check for quality of cut, width, and check with gage block, use calipers to mease strip stock thickness, record five readings on chart, add all five together to get the sum, divide the sum by five to get the average, subtract the highest value to get the range	Visual / Manual	SPC Chart		5 samples per hour	Stop the process, determine root cause, perform corrective actions, circle out of control plots, briefly note root cause and corrective action on chart	Operator

Appendix C: Validation Run Results

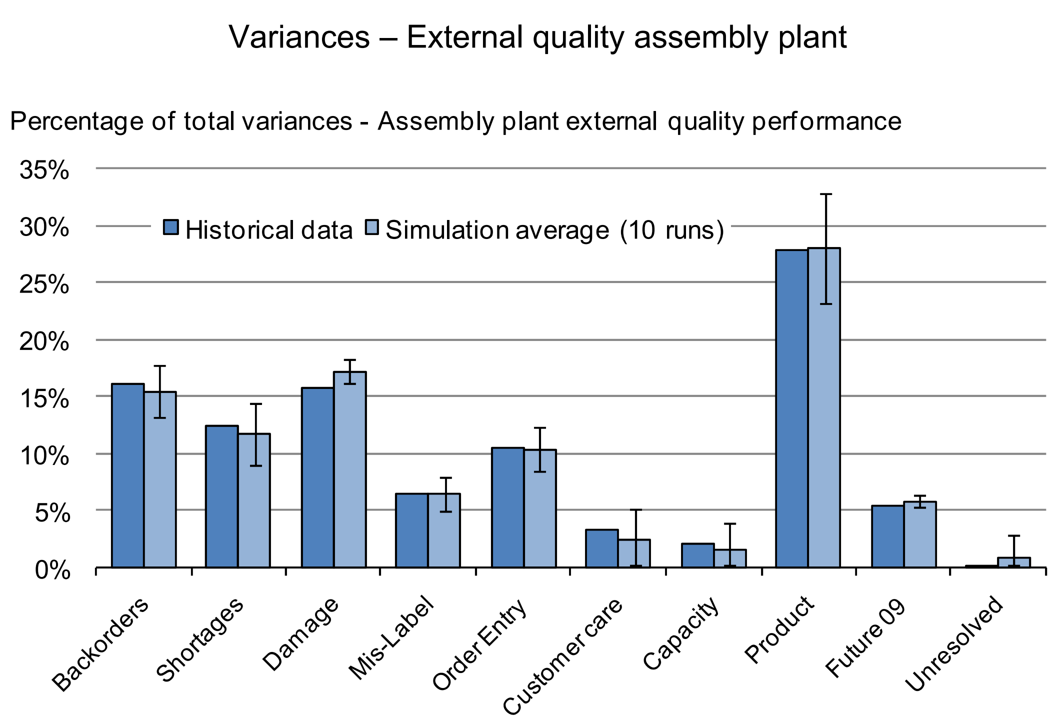
Defect Generators Results



* Error bars represent one standard deviation plus and minus from the simulation averag

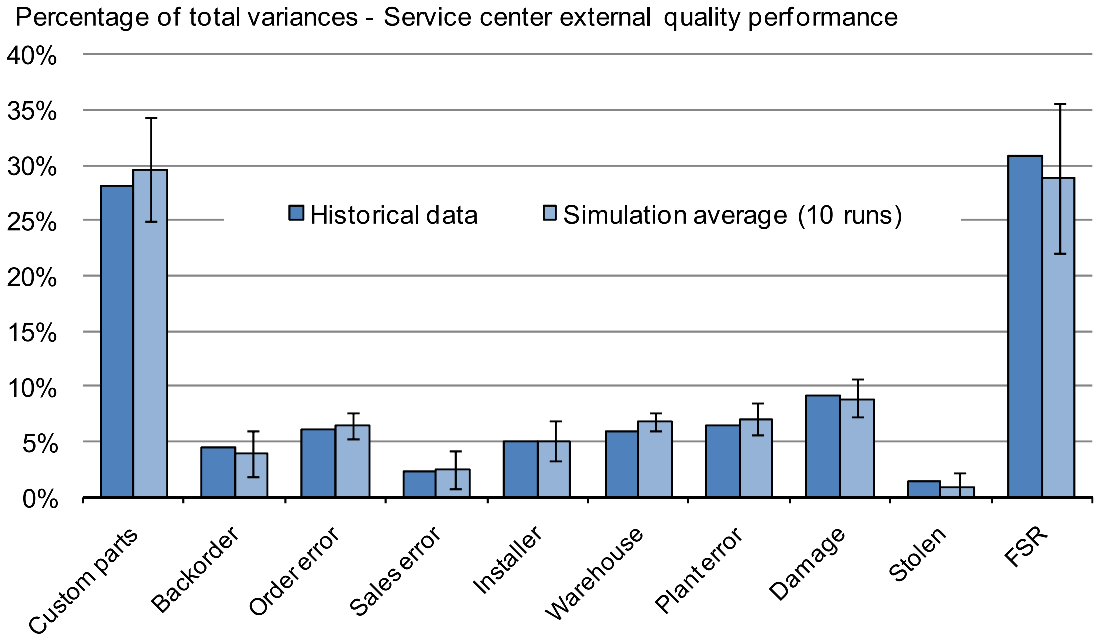


* Error bars represent one standard deviation plus and minus from the simulation average



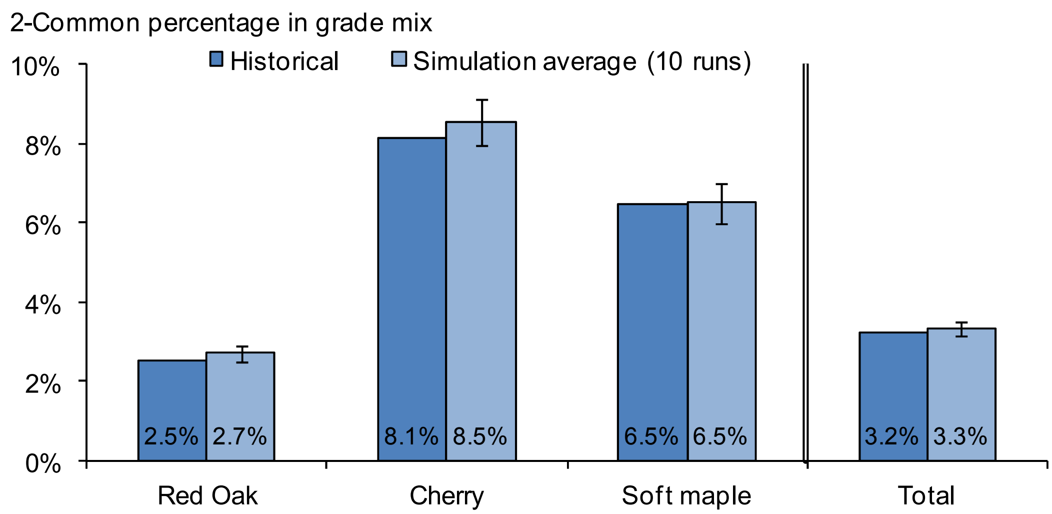
* Error bars represent one standard deviation plus and minus from the simulation average

Variances – Service center



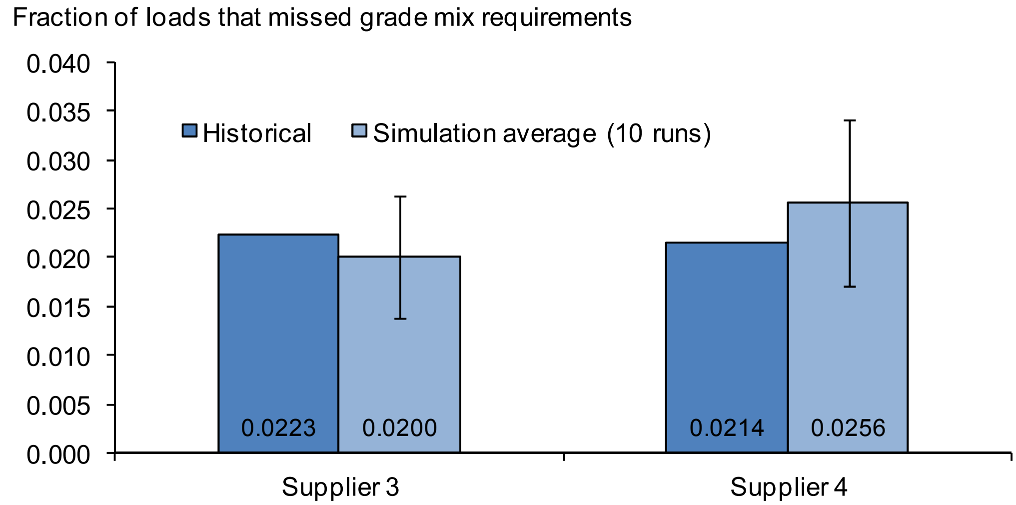
* Error bars represent one standard deviation plus and minus from the simulation average

2-Common Lumber Percentage in Lumber Mix



* Error bars represent one standard deviation above and below simulation average

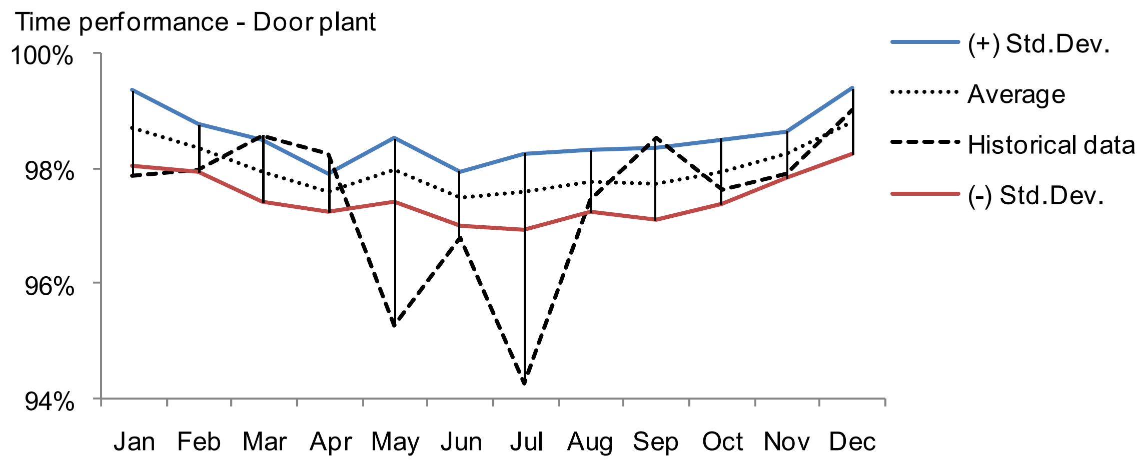
Missed-Grade Lumber Deliveries



* Error bars represent one standard deviation above and below simulation average

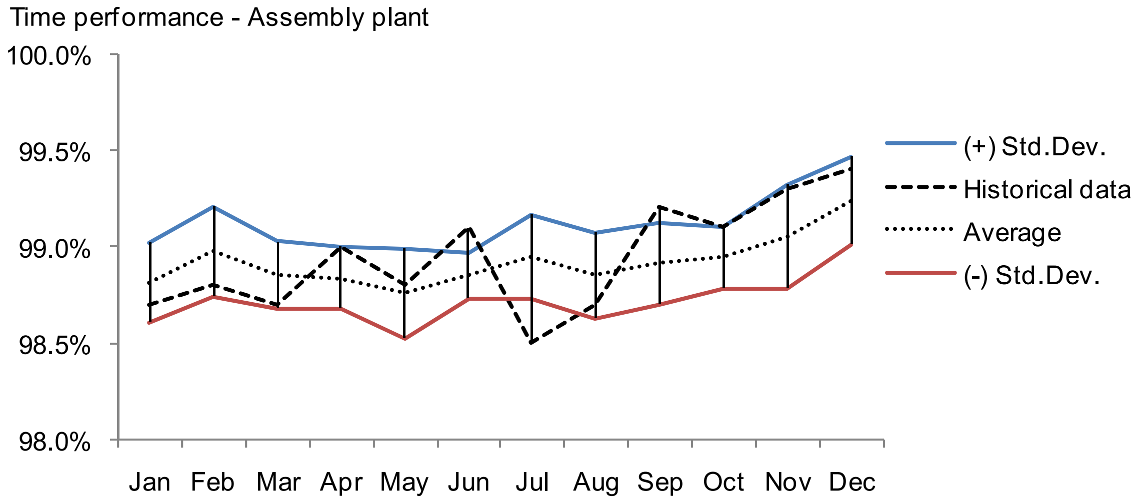
Time Performance

Door Plant



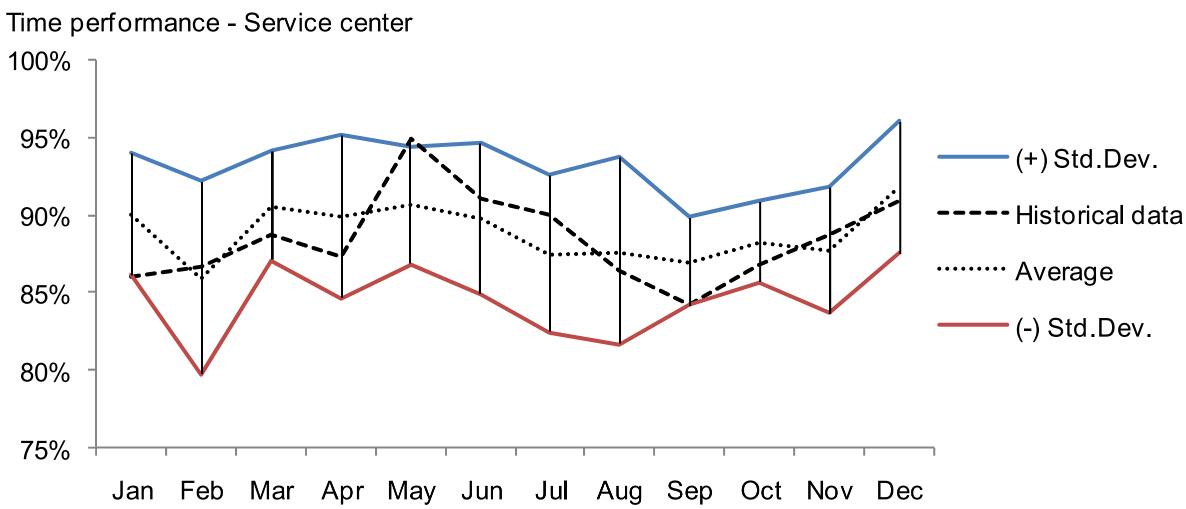
* Scale altered to show variations
** Average of historical and simulated values not significantly different at 0.05 (p=0.22)

Assembly Plant



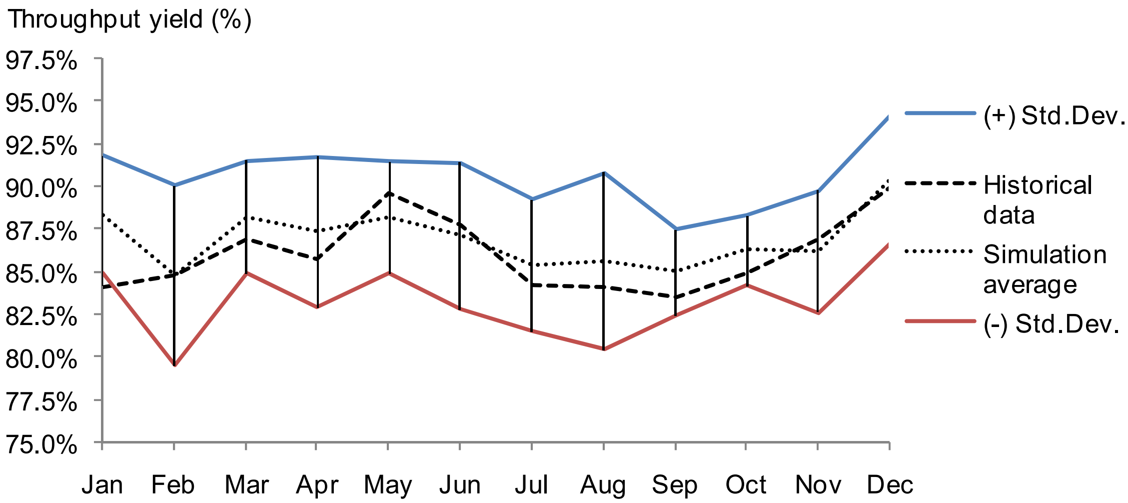
* Scale altered to show variations
** Average of historical and simulated values not significantly different at 0.05 (p=0.83)

Service Center



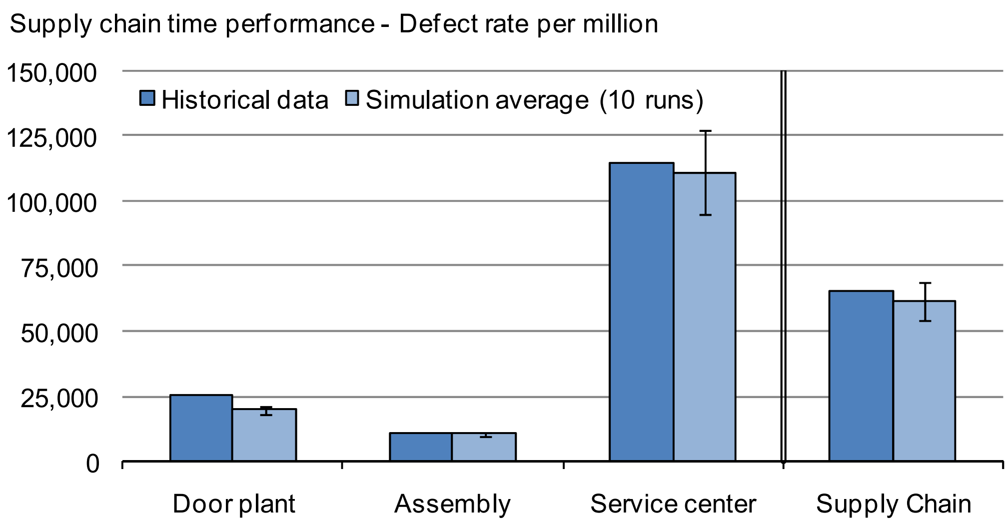
* Scale altered to show variations
** Average of historical and simulated values are significantly different at 0.05 (p=0.71)

Supply Chain Throughput Yield



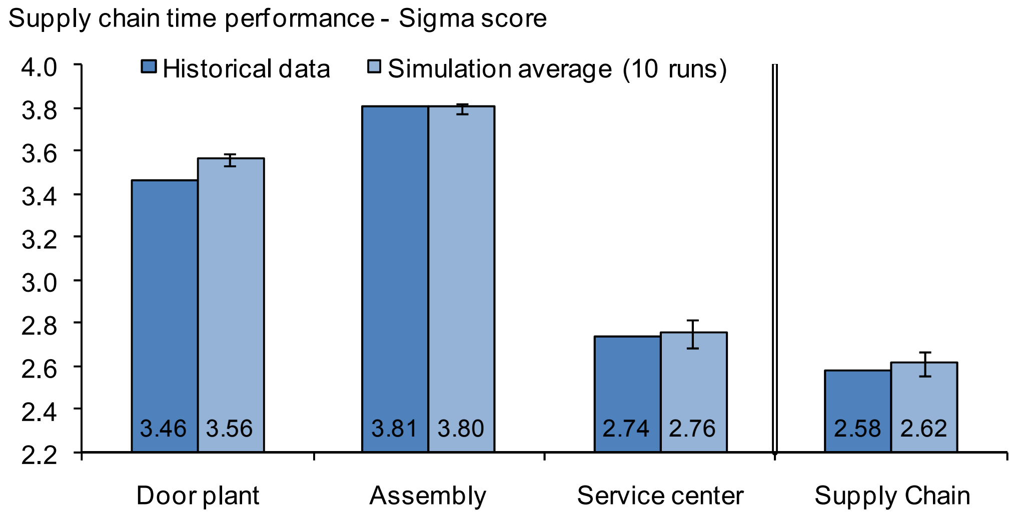
* Scale altered to show variations
** Average of historical and simulated values not significantly different at 0.05 (p=0.30)

Supply Chain Time Performance Defect Rate per Million



*Error bars represent one standard deviation plus and minus the simulation average

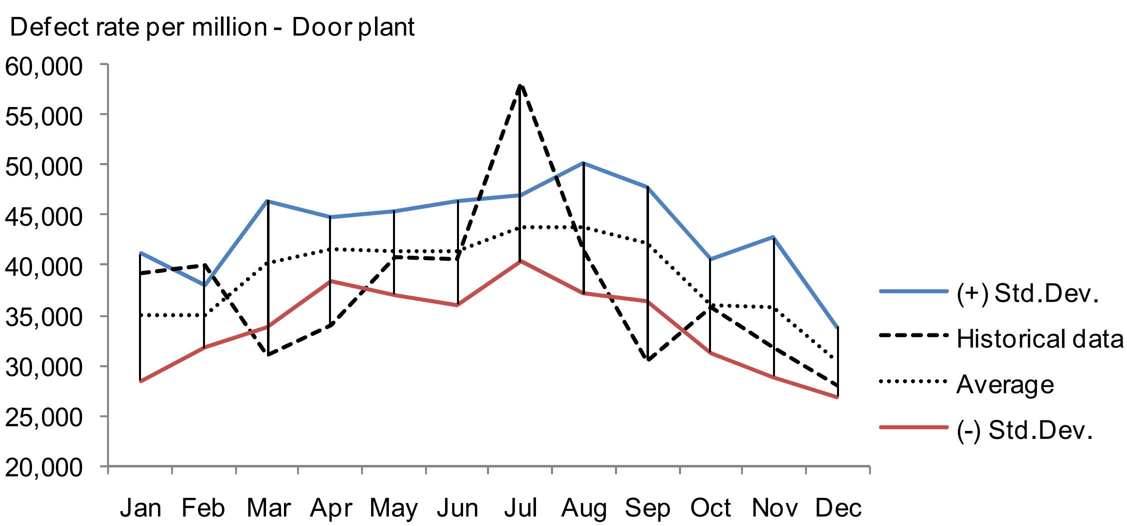
Supply Chain Time Performance Sigma Score



*Error bars represent one standard deviation plus and minus the simulation average

Product Quality Performance

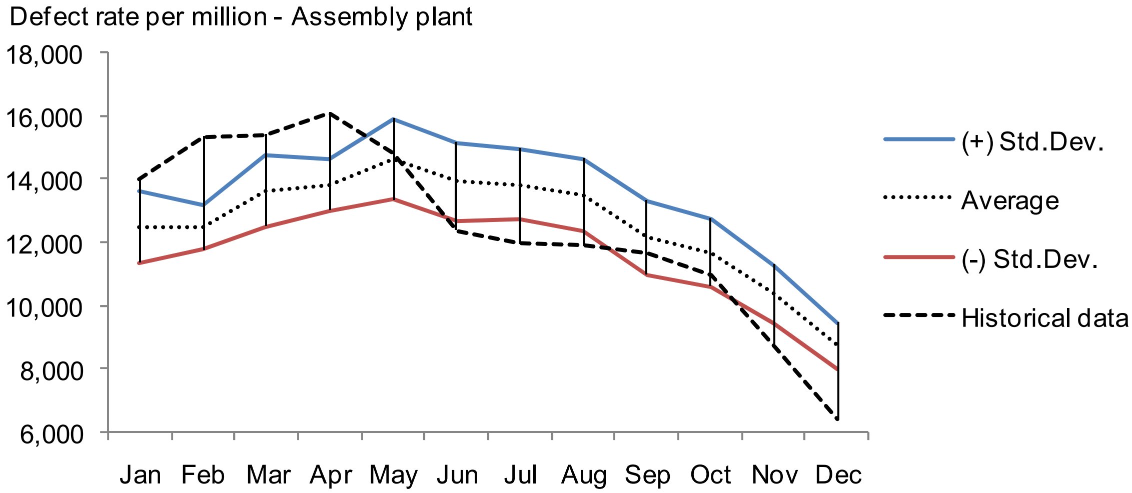
Door Plant



* Scale altered to show variations

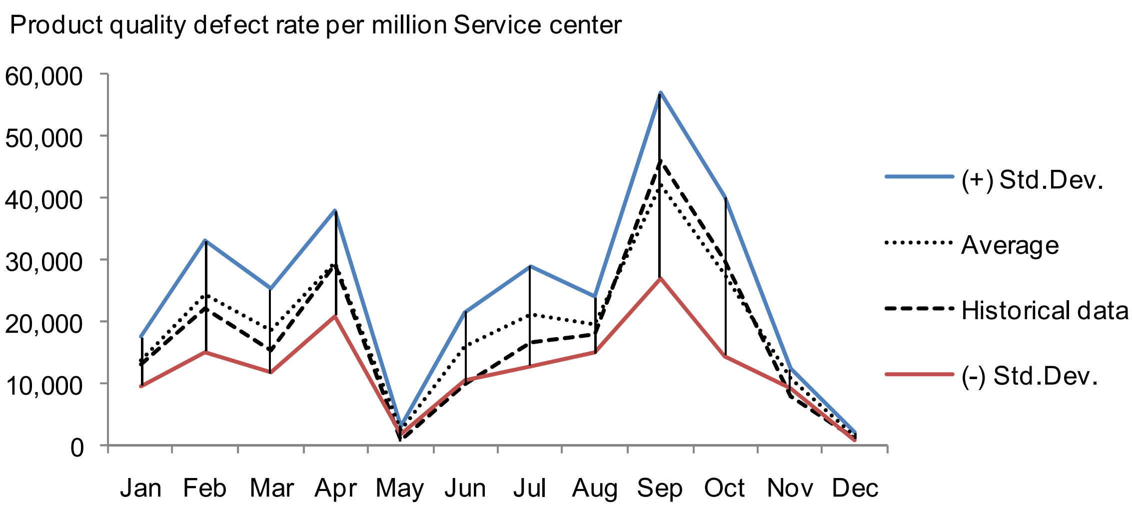
** Average of historical and simulated values not significantly different at 0.05 (p=0.66)

Assembly Plant



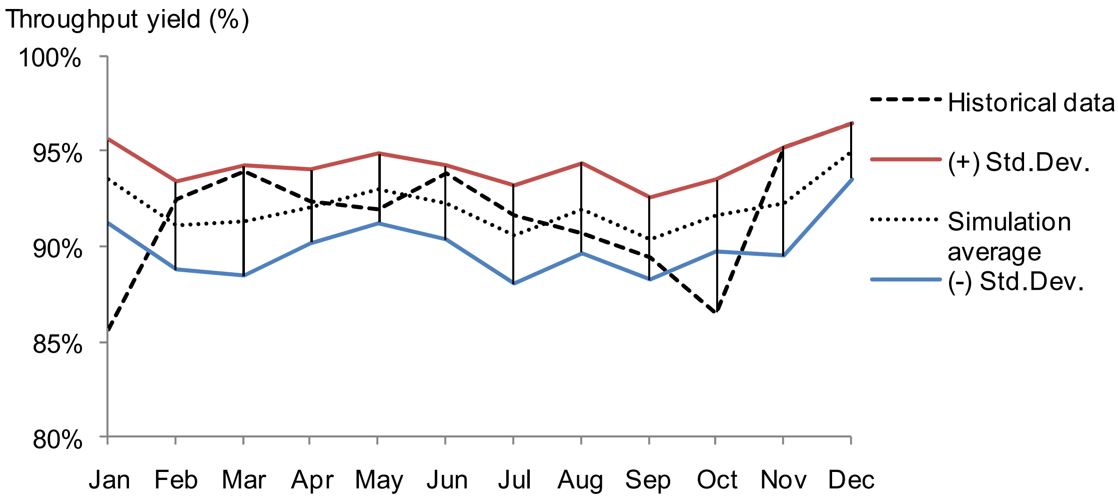
* Scale altered to show variations
** Average of historical and simulated values not significantly different at 0.05 (p=0.90)

Service Center



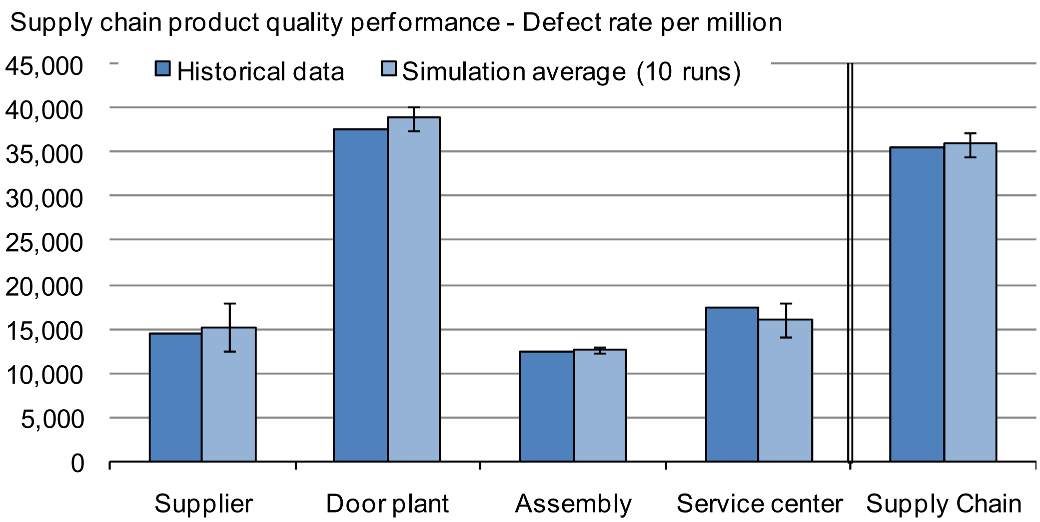
* Average of historical and simualted values not significantly different at 0.05 (p=0.8)

Supply Chain Throughput Yield



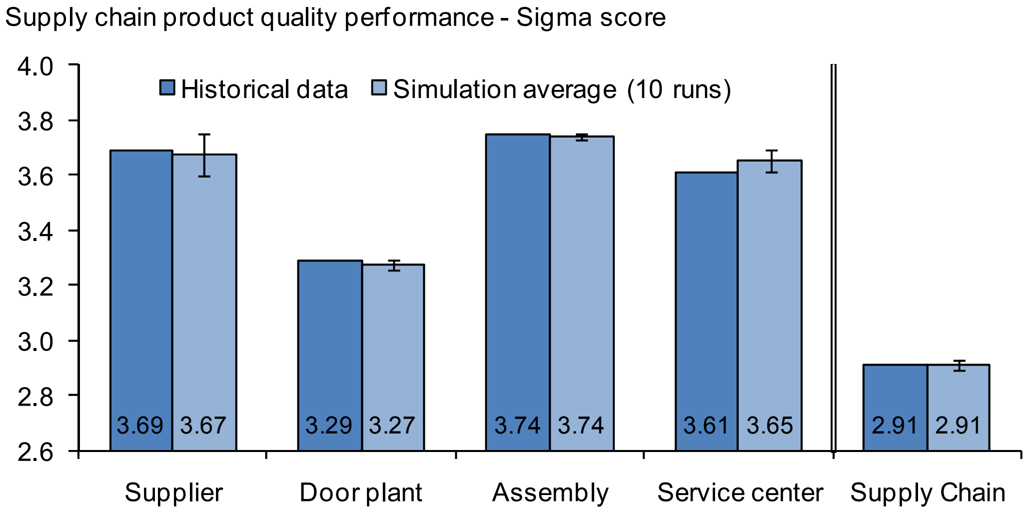
* Scale slatered to show variations
** Average of historical and simulated values not significantly different at 0.05 (p=0.73)

Supply Chain Defect Rate



*Error bars represent one standard deviation plus and minus the simulation average

Supply Chain Sigma Score



*Error bars represent one standard deviation plus and minus the simulation average