The development of inventory lot-sizing model and production and inventory planning simulation models for remanufacturing systems

By

Magdalene Andrew Munot

A Thesis Presented to

Monash University

In Partial Fulfilment of the Requirement for the

Degree of Doctor of Philosophy

Department of Mechanical and Aerospace Engineering

Faculty of Engineering

Monash University

January 2010

ERRATA

p 12 line 5 from top: “FujiXerox Australia (FujiXerox Australia, 2007a)” for “Fuji Xerox Australia (Fuji Xerox Australia, 2007a)”

p 12 line 14 from top: “(FujiXerox Australia, 2007b)” for “(Fuji Xerox Australia, 2007b)

p 12 line 12 from bottom: “(Dowlatshahi 2000, Giuntini and Gaudette 2003)” for “(Dowlatshahi, 2000; Giuntini and Gaudette, 2003)”

p 13 line 3 from bottom: “(Lund 1984a, Van der laan 1999)” for “(Lund, 1984a, van der Laan, 1999)”

p 14 line 11 from bottom: (Canon Global, 2008)” for “(Canon Global 2008)”

p 15 line 5 from bottom: “(Ferrer 1997, Ayres et al. 1997)” for “(Ferrer 1997; Ayres et al., 1997)”

p 16 line 2 from top: “(Debo et al. 2003, Linton 2008)” for “(Debo et al., 2003; Linton, 2008)”

p 17 line 4 from top: “(Guide and Wassenhove 2001, Jayaraman 2006)” for “(Guide and Wassenhove, 2001; Jayaraman, 2006)”

p 17 line 10 from top: “(Aras and Aksen 2008, Aras et al. 2008)” for “(Aras and Aksen, 2008; Aras et al., 2008)”

p 18 line 9 from top: “(Muckstadt and Isaac 1981, Van der laan et al. 1999, Van der laan 1997, Guide Jr and Srivastava 1997)” for “(Muckstadt and Isaac, 1981; van der Laan et al., 1999; van der Laan, 1997; Guide Jr, V.D.R. and Srivastava, 1997)”

p 18 line 12 from top: “(Guide Jr 2000, Ostlin et. al. 2009)” for “(Guide Jr, 2000; Ostlin, et. al., 2009)”

p 20 Figure 2.1: “1984a)” for “1984a).”

p 21 line 12 from top: “(Aras et al. 2004, Aras et al. 2006)” for “(Aras et al., 2004; Aras et al., 2006)”

p 28 line 8 from bottom: “(Guide Jr et al. 1997a, 1997b, Guide Jr and Srivastava 1997b, Fleischmann et al. 1997, Guide Jr et al. 1998, Guide Jr et al. 1999, Ferrer 2003)” for “(Guide Jr, et al., 1997a; 1997b; Guide Jr and Srivastava, 1997b; Fleischmann et al., 1997; Guide Jr et al., 1998; Guide Jr et al., 1999; Ferrer, 2003)”

p 33 line 14 from bottom: “(Souza et al. 2002, Denizel et al. 2007)” for “(Souza et al., 2002; Denizel et al., 2007)”

p 33 line 12 from bottom: “(Ketzenberg et al. 2003, Behret and Korugan 2005, Behret and Korugan 2009)” for “(Ketzenberg et al., 2003; Behret and Korugan, 2005; Behret and Korugan, 2009)”

p 38 line 1 from top: “(2001a, 2001b, 2005)” for “(2001a; 2001b; 2005)”

p 42 line 12 from bottom: “(FujiXerox Australia, 2007a)” for “(Fuji Xerox Australia, 2007a)” p 50 line 8 from bottom: “abovementioned” for “above mentioned”

p 52 line 12 from top: “(Musselman 1998, Law and Kelton 2000, Chung et al. 2004)” for “(Musselman, 1998; Law and Kelton, 2000; Chung et al. 2004)”

p 56 Figure 2.4: “2000)” for “2000).”

p 68 Figure 3.2: “lot-sizes” for “lot-sizes.”

p 84 line 2 from bottom: add a space between “4.2” and “Furthermore”

p 91 Figure 4.3: add a connecting line between blocks “Disassembly/Inspection” and “Reprocessing” for the GII processing

p 117 line 11 from top: “2x3x4” for “2^2x2^3x2^4”

p 117 line 12 from top: “2x3x3” for “2^2x2^3x2^3”

p 120 line 2 from top: “28800 hours” for “28900 hours”

p 123 Figure 5.1: “yields” for “yields.”

p 134 Figure 5.7: “configurations” for “configurations.”

p 139 Figure 5.8: “yields” for “yields.”

p 139 line 15 from top: add ($p < 0.05$) after “significant”

p 140 Figure 5.9: “configurations” for “configurations.”

p 151 Figure 5.11: “hours” for “hours.”

p 152 line two from top: add ($p < 0.05$) between “significant” and “comma”

p 153 Figure 5.12: “hours” for “hours.”

p 154: Figure 5.13: “hours” for “hours.”

p 154 line three from top: add ($p < 0.05$) between “significant” and “(figure 5.13)”

p 154 line six from bottom: add ($p < 0.05$) between “significant” and “comma”

p 155 line two from top: add ($p < 0.05$) between “significant” and “comma”

p 155 line thirteen from top: add ($p < 0.05$) after “significant”

p 156 Figure 5.14: “hours” for “hours.”

p 167 item 5: “Elsevier.” for “Elsevier”

p 177 item 6: “Product Recovery Management” for “*Product Recovery Management*”

p 178 items 6: “*Reverse Logistics Executive Council*” for “Reverse Logistics Council”

p 178 items 7: “M. W.,” for “M. W,”

p 178 item 8: “(2nd ed.)” for “(2nd ed.).

p 181 item 2: “push and pull” for “PUSH and PULL”

p 181 item 3: “Van der laan” for “van der Laan”

ADDENDUM

p 36 line 12 from bottom: add “process” and read “Few researchers have attempted to model remanufacturing systems with improved criteria of multiple-stages remanufacturing process and uncertain disassembly……”

p 84 line 7 from bottom: Add at the end of sentence:

“Further discussion on the mechanisms of the policies under the RMTS-strategy and their ranking are provided in sub-section 4.3.1. Similarly, sub-section 4.3.2 provides further discussion on the mechanisms of the policies under the RMTO-strategy and their rankings.

p 86 line 2 from bottom: add “a” and read “Figure 1: Architecture of a generic conceptual model of a remanufacturing system”

p 165 line 9 from bottom: Add at the end of sentence:

“Another future direction could focus on determining the exact values of the percentage savings (total cost) from implementing the model discussed in chapter 3”

p 166 line 12 from top: Add at the end of sentence:

“Finally, another future direction could focus on determining the exact values of the percentage of savings (average remanufacturing cycle-time) from implementing the models discussed in chapter 4”

Notice 1

Under the Copyright Act 1968, this thesis must be used only under the normal conditions of scholarly fair dealing. In particular no results or conclusions should be extracted from it, nor should it be copied or closely paraphrased in whole or in part without the written consent of the author. Proper written acknowledgement should be made for any assistance obtained from this thesis.

Notice 2

I certify that I have made all reasonable efforts to secure copyright permissions for third-party content included in this thesis and have not knowingly added copyright content to my work without the owner's permission.

Dedication

To my beloved husband Dominic for all his support, understanding, patience, sacrifice and love.

To my beautiful children, Emery and Ashley.

To my father, mother, brothers and sister for all your understanding and support.

Table of Contents

Abstract ………………………………………………………………………. i

Declaration ……………………………………………………………………… iv

Acknowledgments ……….……………………………………………………… v

List of Publications …..……………………………………………………….. vi

Nomenclatures…………………………………………………………………… vii

List of Figures …………………………………………………………………….. viii

List of Tables …………………………………………………………………..… xv

CHAPTER 1 ..…………………………………………………………………….. 1

Introduction

1.1 Motivation …..………………………………………………………………. 1

1.2 Research objectives and scope ………………………………………………. 4

1.3 Research contributions ..……………………………………………………… 7

1.4 Thesis overview.....……………………………………………………………… 8

CHAPTER 2 ..……………………………………………………………………… 10

Literature Survey

2.1 Introduction …………………………………………………………………… 10

2.2 An overview of remanufacturing operations………………………………… 10

2.2.1 Motivating factors and roles of remanufacturing ………………………… 10

2.2.2 Demand and market of remanufactured products………………………… 15

2.2.3 Sources, qualities and quantities of used products…………………… 16

2.2.4 Distinctive key stages and processes of remanufacturing……………… 19

2.2.5 Strategies and performance measures of remanufacturing systems ……………………………………………………………… 25

2.2.6 Unique characteristics of remanufacturing environment ……………. 28

2.3 A current survey of criteria for modelling and analysis of remanufacturing systems………………………………………………… 30

2.3.1 Inspection yields of used products ………………………………… 30

2.3.2 Disassembly yields of constituent components ……………………… 36

2.3.3 Reprocessing efforts of constituent components ………………….. 40

2.3.4 Key stages and processes of remanufacturing ……..………………… 41
2.3.5 Product structure of used products ………………………………….. 42
2.3.6 Analysis technique of remanufacturing systems ……..……………… 43
2.4 Principles of simulation of remanufacturing operations..…………………… 44
2.4.1 Fundamental of modelling techniques and simulation concepts ......……………………………………………………. 44
2.4.2 Vital roles of simulation in remanufacturing operations……..……… 49
2.4.3 Construction platform for simulation of remanufacturing operations ………………………………………………………... 53
2.4.4 Life-cycle of remanufacturing simulation projects ..………………... 55
2.5 Summary ……………………………………………………………….. 57

CHAPTER 3 ..……………………………………………………………... 59
An integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system considering variable remanufacturing lot-sizes
3.1 Introduction …………………………………………………………….. 59
3.2 Inventory lot-sizing model in a hybrid remanufacturing-manufacturing system ……………………………………………...…………………… 60
3.3 A new integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system …..……………….......................... 66
3.3.1 Model assumptions ……………………………………….….... 66
3.3.2 Model development ……………………………………….……… 67
3.3.3 Total cost per unit time …………………………………..……….. 73
3.3.4 Solution methodology ………………………..…………………… 74
3.4 A benchmark model for the benefit analysis ………………………………… 75
3.5 Case studies…………...……………………………………………..…….. 76
3.5.1 Examining the behaviour of manufacturing lot-size, number of remanufacturing lots, first remanufacturing lot-size with remanufacturing fraction ……………….…………… 77
3.5.2 Analysis of the benefits of the new model ………….……………… 78

3.5.3 Examining the behaviour of manufacturing lot-size and first remanufacturing lot-size with costs and demand parameters 79
3.5.4 Sensitivity analysis 81
3.6 Summary 82

CHAPTER 4 83
Integrated production and inventory planning simulation models
4.1 Introduction 83
4.2 Formulation of the problems 83
4.3 Definition, validation and architecture of the conceptual models 85
4.3.1 Architecture of the conceptual models of alternative remanufacture-to-stock system configurations 87
4.3.2 Architecture of the conceptual models of alternative remanufacture-to-order system configurations 94
4.4 Coding and verification of the computer programs and validation of the simulation models 98
4.4.1 Coding of the computer programs 98
4.4.2 Verification of the computer programs 99
4.4.3 Validation of the simulation models 100
4.5 Architecture of the major segments of simulation models 103
4.5.1 Inspection and remanufacturables management segment........ 103
4.5.2 Replacement components management segment........ 104
4.5.3 Customer demand management segment........ 105
4.5.4 Remanufacturing and finished products inventory control management segment of remanufacture-to-stock system 108
4.5.5 Remanufacturing and finished products inventory control management segment of remanufacture-to-order system 113
4.6 Design and execution of the simulation experiments 117
4.6.1 Designing the simulation experiments 117
4.6.2 Executing the simulation experiments 117
4.7 Summary 120

CHAPTER 5 ..…………………………………………………...…….…………... 121

The effects of system variables on the performance of remanufacturing systems and strategies

5.1 Introduction …………………………………………………………………….. 121

5.2 Case study 1: The effects of system variables on the performance of alternative remanufacture-to-stock system configurations …………...……... 121

5.2.1 The effect of inspection yields on remanufacturing cycle-time of alternative remanufacture-to-stock system configurations ....………… 122

5.2.2 The effect of alternative remanufacture-to-stock system configurations on finished products inventory profile………………. 126

5.2.3 The effect of used products quantities on customer service level of alternative remanufacture-to-stock system configurations …………………..…………………..……..……… 133

5.2.4 The sensitivity of alternative remanufacture-to-stock system configurations with respects to changes in system variables ………………………………………………….. 135

5.3 Case study 2: The effects of system variables on the performance of alternative remanufacture-to-order system configurations…..……………….… 138

5.3.1 The effect of inspection yields on remanufacturing cycle-time of alternative remanufacture-to-order system configurations ……………………………………...…………..... 139

5.3.2 The effect of used products quantities on customer service level of alternative remanufacture-to-order system configurations ……………………………………….……….. 143

5.3.3 The sensitivity of alternative remanufacture-to-order system configurations with respects to changes in system variables ……………………………………..…………………….. 146

5.4 Case study 3: The effects of system variables on the performance of remanufacturing strategies ……………………………..…………………. 150

5.4.1 The main and interactions effects of system variables on average remanufacturing cycle-time of a remanufacture-to-stock strategy……………………….…………….. 150

5.4.2 The main and interactions effects of system variables on average remanufacturing cycle-time of a remanufacture-to-order strategy ….. 153
5.4.3 The effect of alternative remanufacturing strategies on customer service-level ……………..……..……………………..…. 156
5.5 Summary ……………………………….…………………….…………... 159

CHAPTER 6 ..……………………………………...……………………….……... 161
Conclusion and future directions
6.1 Conclusion ……………………………….…………………………..…….. 161
6.2 Future directions ……………………………………..…………….……... 165

References ……………………………………….……………………………... 167

Appendix A ………………………………………………………………………... 184
Supplementary figures and tables for Chapter 2 ………………………………….. 184

Appendix B ………………………………………………………………………... 188
Supplementary figures and tables for Chapter 3…………………………………… 188

Appendix C ………………………………………………………………………... 194
Supplementary figures and tables for Chapter 4 …………………….……………. 194

Appendix D ……………………………………………………………………….. 205
Supplementary figures and tables for Chapter 5 …………………….……………. 205

Appendix E ………………………………………………………………………... 211
Results of the validation process of a generic model of remanufacturing system …………………………………………..………………………….. 211

Appendix F ………………………………………………………………………… 213
Computer program codes for the inspection and remanufacturables management segment ……………………………………………………………. 213

Appendix G ………………………………………………………………………... 215
Computer program codes for the replacement components management segment ………………………………………………………………………… 215

Appendix H …………………………………………………………………….. 217
Computer program codes for the customer demand management segment of RMTS-system ………………………………………………………… 217

Appendix I ……………………………………………………………………… 221
Computer program codes for the customer demand management segment of RMTO-system …….…………………………………………………... 221

Appendix J-a ……………………………………………………………………. 224
Computer program codes for the remanufacturing and finished products inventory control management segment of “*configA*” ………..………………….. 224

Appendix J-b ……………………………………………………………………. 230
Computer program codes for the remanufacturing and finished products inventory control management segment of “*configC*” …………………………… 230

Appendix J-c ……………………………………………………………………. 233
Computer program codes for the remanufacturing and finished products inventory control management segment of “*configD*” …………………………… 233

Appendix K-a …………………………………………………………………… 235
Computer program codes for the remanufacturing and finished products inventory control management segment of “*configE*” …….…………………… 235

Appendix K-b …………………………………………………………………… 238
Computer program codes for the remanufacturing and finished products inventory control management segment of “*configF*” …….…………………… 238

Appendix L ……………………………………………………………………... 240
Publications …………………………………………………………………….. 240

Abstract

Recently, remanufacturing has become an important production activity in many companies; a phenomenon that results from the increasingly strict environmental regulations, growing customer awareness of green environment and economical benefit. Nevertheless, remanufacturing systems remain uncertain and complex in nature due to the existence of several unique characteristics. In this context, this thesis provides a significant contribution to advancing the current knowledge on remanufacturing through the development and analysis of four valuable decision-making tools for remanufacturing.

The first decision-making tool is developed to address inventory lot-sizing problems in a hybrid remanufacturing-manufacturing system with varying remanufacturing fractions. The existing inventory lot-sizing models mainly implement a constant remanufacturing lot-size, which results in delay of remanufacturing process, carryover of remanufacturable stocks after each remanufacturing process and storage of remanufacturable items over the entire manufacturing interval. Accordingly, a new integrated inventory lot-sizing model is developed, which implements variable remanufacturing lot-sizes to address the problems of varying remanufacturing fractions in a hybrid remanufacturing-manufacturing system. The new integrated inventory lot-sizing model is utilised to concurrently determine the optimal lot-sizes for remanufacturing, number of remanufacturing lots and lot-sizes for manufacturing. Case studies show that the new integrated inventory lot-sizing model leads to a cost saving when compared to a benchmark model that implements a constant remanufacturing lot-size.

The second decision-making tool, an integrated production and inventory planning simulation model is developed to address a problem to determine the optimal remanufacturing policy for implementation in a remanufacture-to-stock system with varying inspection yields and availability of used products. Four-variants of the integrated production and inventory planning simulation models are developed and analysed, where different remanufacturing policies are examined for processing two different quality remanufacturable groups. Case studies show that for processing two different quality remanufacturable groups in a remanufacture-to-stock system with varying inspection yields and availability of used products, a policy which specifies simultaneous processing and utilising dedicated resources emerges as the optimal remanufacturing policy. By contrast, when resources are finite, a policy that specifies sequential processing and switching between the two quality remanufacturable groups to sustain production appears as the optimal remanufacturing policy.

Unlike the second tool, the third decision-making tool is developed to address a problem to determine the optimal remanufacturing policy for implementation in a remanufacture-to-order system with varying inspection yields and availability of used products. Three-variants of the integrated production and inventory planning simulation models are developed and analysed, in which different remanufacturing policies are assessed for processing two different quality remanufacturable groups. Case studies show that for processing two different quality remanufacturable groups in a remanufacture-to-order system with varying inspection yields and availability of used products, a policy that specifies sequential processing and switching between the two quality remanufacturable groups to sustain production emerges as the optimal remanufacturing policy.

Finally, the fourth decision-making tool is developed to address a problem to determine the optimal remanufacturing strategy for implementation in a remanufacturing system. Two-variants of the integrated production and inventory planning simulation models are developed and analysed, where different remanufacturing strategies are investigated for processing two different quality remanufacturable groups. Case studies show that for processing two different quality remanufacturable groups, a strategy that specifies carrying some finished products inventory at all times (i.e., a remanufacture-to-stock) emerges as the optimal remanufacturing strategy.

Declaration

This thesis contains no material which has been accepted for the award of any degree or diploma in any other university or institution and to the best of my knowledge contains no material previously published or written by another person, except where due references have been made in the text of the thesis.

[redacted]

Magdalene Andrew Munot

Acknowledgments

I would like to express my deepest and sincerest gratitude to my supervisor, Associate Professor Raafat N. Ibrahim for his continuous and invaluable guidance and support throughout my Ph.D. study. His understanding, encouragement and personal guidance have provided me with a very good foundation for this thesis. Also, his uncompromising high standard for quality research has significantly shaped my thesis.

I would like to express my deepest and sincere thankfulness to Associate Professor Paul B. Lochert for his constructive comments on my thesis. I would to thank Dr Hans Siajadi for his valuable assistance during the first year of my Ph.D. study.

I would like to thank Dr Dan Godamunne, Veera Chippada and Julius Dhanu from the Eco Manufacturing Centre, Fuji Xerox Australia, for their cooperation towards this research.

I would like to thank my employer, University Malaysia Sarawak (UNIMAS) for granting me a study leave to pursue my Ph.D. study at the Department of Mechanical and Aerospace Engineering, Monash University. I would like to thank the Ministry of Higher Education (MOHE), Government of Malaysia for awarding me a scholarship to pursue my Ph.D. study.

I would like to thank many new friends whom I have met while I am at Monash University, Dr Khadiza, Nurin, Dr Anna, Dr Wu, Sylvia, Sun, Sumaiya, Joe, Reza, Dan, Tim, Marini and others for their help and friendship.

Last but most importantly, I would to thank my beloved husband, Dominic for sharing my passion for life-long learning and being with our children and me, when we needed you most. Without your understanding and support none of this would have been possible.

List of Publications (*)

1. Andrew-Munot, M., Ibrahim, R.N. and Lochert, P.B., 2008. An inventory lot-sizing model for a manufacturing/remanufacturing environment with variable remanufacturing lot-sizes. Proceedings of the 15th International Conference on Life Cycle Engineering, The University of New South Wales: Sydney.

2. Andrew-Munot, M., Ibrahim, R.N. and Lochert, P.B., 2008. An Economic Lot-Sizing Model in a Manufacturing/Remanufacturing Environment. Proceedings of International Conference on Mechanical and Manufacturing Engineering 2008. Universiti Tun Hussein Onn Malaysia: Johor Bahru.

3. Andrew-Munot, M. and Ibrahim, R.N., 2009. Development and anaysis of mathematical and simulation models of decision-making tools for remanufacturing, Production Planning and Control, in review.

4. Andrew-Munot, M. and Ibrahim, R.N., 2009. An integrated inventory lot-sizing model for a hybrid remanufacturing-manufacturing system, The International Journal of Advanced Manufacturing Technology, in review.

5. Andrew-Munot, M. and Ibrahim, R.N., 2009. An integrated production and inventory planning simulation models for remanufacturing system, The International Journal of Advanced Manufacturing Technology, in review.

(*) Already published papers are in Appendix L.

Nomenclatures

Q_m	Manufacturing lot-size
Q_r	Remanufacturing lot-size
Q_{r1}	First remanufacturing lot-size
Q_{r2}	Second manufacturing lot-size
Q_n	Last remanufacturing lot-size
u	Remanufacturing fraction
K_m	Setup costs for manufacturing
K_r	Setup cost for remanufacturing
c_d	Disposal cost for scrap used products
c_m	Manufacturing cost for new products
c_r	Remanufacturing cost for used products
h_n	Holding costs per item per unit time for remanufacturable items
h_r	Holding costs per item per unit time for remanufactured items
h_m	Holding costs per item per unit time for newly manufactured products
UTC	Total cost per unit time
RMTS	Remanufacture-to-stock
RMTO	Remanufacture-to-order
RATO	Reassemble-to-order

List of Figures

Chapter 2

Figure 2.1: Key remanufacturing stages with corresponding process and material flows ……………………………………………………….………20

Figure 2.2: Examples of products with (a) a simple structure, and (b) a complex structure ……………………………………………….............22

Figure 2.3: Techniques for modelling and study of a system ……….……….44

Figure 2.4: The life-cycle of simulation projects on remanufacturing system ………………………………………………………….…………..56

Chapter 3

Figure 3.1: Remanufacturables and serviceables inventory profile in a hybrid remanufacturing-manufacturing system ……………….………………...65

Figure 3.2: Remanufacturables and servicebles inventory profile in a hybrid remanufacturing-manufacturing system considering variable remanufacturing lot-sizes ……………………………………………………..68

Figure 3.3: Material balance at the serviceables inventory ……………………...69

Chapter 4

Figure 4.1: Architecture of a generic conceptual model of remanufacturing system ………………………………………………………86

Figure 4.2: Architecture of conceptual model "*configA*" ……………………….90

Figure 4.3: Architecture of conceptual model "*configB*" ………..……….........91

Figure 4.4: Architecture of conceptual model "*configC*" ……………………….92

Figure 4.5: Architecture of conceptual model "*configD*" ……………………….93

Figure 4.6: Architecture of conceptual model "*configE*" …….…………………95

Figure 4.7: Architecture of conceptual model "*configF*" ……………………….96

Figure 4.8: Architecture of conceptual model "*configG*" ……………………….97

Figure 4.9: A typical finished products inventory profile over a period of time for: (a) manufacture-to-stock system, and (b) manufacture-to-order system ……………………………………………102
Figure 4.10: Architecture of the inspection and remanufacturables management segment ………………………………………………………..103
Figure 4.11: Architecture of the replacement components management segment for (a) component A, (b) component B ……………………………….104
Figure 4.12: Architecture of the customer demand management segment of RMTS-system ………………………………………………….....106
Figure 4.13: Architecture of the customer demand management segment of RMTO-system …………………………………………………..107
Figure 4.14: Architecture of the remanufacturing and finished products inventory control management segment of "*configA*" ……………..…………..110
Figure 4.15: Architecture of the remanufacturing and finished products inventory control management segment of "*configC*" …………………………111
Figure 4.16: Architecture of the remanufacturing and finished products inventory control management segment of "*configD*" ………...………………...112
Figure 4.17: Architecture of the remanufacturing and finished products inventory control management segment of "*configE*" …………………………114
Figure 4.18: Architecture of the remanufacturing and finished products inventory control management segment of "*configF*" ………..………………..115
Figure 4.19: Architecture of the remanufacturing and finished products inventory control management segment of "*configG*" …………………………116

Chapter 5

Figure 5.1: Average remanufacturing cycle-time of alternative RMTS -system configurations at different inspection yields ..…………………………123
Figure 5.2: SPSS Output of ANOVA – *Bonferroni* post-hoc test of remanufacturing cycle-time of alternative RMTS-system configurations ………………………………………………………………...124

Figure 5.3: A typical finished products inventory profile of “*configA*”
simulated over a period of 2 years ………………..…………………………….127
Figure 5.4: A typical finished products inventory profile of “*configB*”
simulated over a period of 2 years ………………………………………………128
Figure 5.5: A typical finished products inventory profile of “*configC*”
simulated over a period of 2 years ……………………..…………………….128
Figure 5.6: A typical finished products inventory profile of “*configD*”
simulated over a period of 2 years ………..…………………...……………...129
Figure 5.7: The effect of used products quantities on percentage of
satisfied customers of alternative RMTS-system configurations ………………134
Figure 5.8: Average remanufacturing cycle-time of alternative RMTO
-system configurations at different inspection yields …..………………………139
Figure 5.9: SPSS Output of ANOVA – *Bonferroni* post-hoc test of
remanufacturing cycle-time of alternative RMTO-system
configurations ...………………………………………………………………140
Figure 5.10: The effect of used products quantities on percentage of
satisfied customers of alternative RMTO-system configurations ..………..…...144
Figure 5.11: SPSS Output of a three-way ANOVA of a RMTS–strategy
considering customer demand arriving at every 40 hours ……...……………...151
Figure 5.12: SPSS Output of a three-way ANOVA of a RMTS-strategy
considering customer demand arriving at every 32 hours ……………………...153
Figure 5.13: SPSS Output of a three-way ANOVA of a RMTO-strategy
considering customer demand arriving at every 40 hours ……………………...154
Figure 5.14: SPSS Output of a three-way ANOVA of a RMTO-strategy
considering customer demand arriving every 28 hours ………………………...156
Figure 5.15: The effect of remanufacturing strategies on percentage of
satisfied customers …………………….……………..………………………157

Appendix A

Figure A1: Examples of remanufactured products ……………………………..184

Figure A2: The position of inventory in a RMTS system ……………………...185

Figure A3: The position of inventory in a RMTO system ……………………...186

Figure A4: The position of inventory in a RATO system ……………………...187

Appendix B

Figure B1: The effect of manufacturing setup cost, K_m on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u …………………………………………………188

Figure B2: The effect of manufacturing setup cost, K_m on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u …………………………………………………188

Figure B3: The effect of remanufacturing setup cost, K_r on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u …………………………..……………………..188

Figure B4: The effect of remanufacturing setup cost, K_r on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u …………………………….……………………189

Figure B5: The effect of remanufacturables holding cost, h_n on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u ……………………………….………………189

Figure B6: The effect of remanufacturables holding cost, h_n on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u ……………………………………………….189

Figure B7: The effect of new products holding cost, h_m on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u ……………………………………………….190

Figure B8: The effect of new products holding cost, h_m on
estimate of first remanufacturing lot-size, Q_{r1} at different values of
remanufacturing fraction, u ……………………..……………………………190
Figure B9: The effect of remanufactured products holding cost, h_r on
estimate of manufacturing lot-size, Q_m at different values of
remanufacturing fraction, u ………………………………..…………………190
Figure B10: The effect of remanufactured products holding cost, h_r on
estimate of first remanufacturing lot-size, Q_{r1} at different values of
remanufacturing fraction, u ……………………………………………………..191
Figure B11: The effect of demand quantity on estimate of manufacturing
lot-size, Q_m at different values of remanufacturing fraction, u …………………191
Figure B12: The effect of demand quantity on estimate of first
remanufacturing lot-size, Q_{r1} at different values of remanufacturing
fraction, u ……………………………………………………………………191

Appendix C

Figure C1: Verification of computer programs of the customer demand
segment ………………………………………………………………………194
Figure C2: A profile of finished products inventory generated from
simulation model "*configA*" ……………………………………………………195
Figure C3: A profile of finished products inventory generated from
simulation model "*configB*" …………………..………………………………..195
Figure C4: A profile of finished products inventory generated from
simulation model "*configC*" ………..…………………………………………..196
Figure C5: A profile of finished products inventory generated from
simulation model "*configD*" ……………..……………………………………..196
Figure C6: A profile of finished products inventory generated from
simulation model "*configE*" ……………………………………………………197
Figure C7: A profile of finished products inventory generated from
simulation model "*configF*" ……………………………………….…………...197

Figure C8: A profile of finished products inventory generated from simulation model “*configG*” ……….……………..…………………………....198
Figure C9: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model “*configA*” ….………………..…….………..201
Figure C10: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model “*configB*” ….……………………….……...202
Figure C11 Profiles of remanufacturing cycle-time over 5 replications generated from simulation model “*configC*” .………… ………..……………..203
Figure C12: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model “*configD*” ………………………………..204

Appendix D

Figure D1: SPSS Output of a two-way ANOVA of “*configA*” …….……….205
Figure D2: SPSS Output of a two-way ANOVA of “*configB*” ………………..205
Figure D3: SPSS Output of a two-way ANOVA of “*configC*”…….…………..205
Figure D4: SPSS Output of a two-way ANOVA of “*configD*”……..…………206
Figure D5: A typical finished products inventory profile of “*configA*” simulated over a period of 2 years - customers demand arriving every 4 days ………………………………………..…………………...207
Figure D6: A typical finished products inventory profile of “*configB*” simulated over a period of 2 years - customers demand arriving every 4 days …………………………………..…...…………………………208
Figure D7 : A typical finished products inventory profile of “*configC*” simulated over a period of 2 years - customers demand arriving every 4 days …………………………………………….………………208
Figure D8: A typical finished products inventory profile of “*configD*” simulated over a period of 2 years - customers demand arriving every 4 days ………………………….…………………………………....209
Figure D9 : SPSS Output of a two-way ANOVA of “*configE*” ………………..209
Figure D10 : SPSS Output of a two-way ANOVA of “*configF*” …………...….209
Figure D11 : SPSS Output of a two-way ANOVA of “*configG*” ………..…….210

Appendix F

Figure F1: Architecture of the inspection and remanufacturables management segment ……………………………..…………………………213

Appendix G

Figure G1: Architecture of the replacement components management segment for (a) component A, (b) component B ……………………………….215

Appendix H

Figure H1: Architecture of the customer demand management segment of RMTS-system ……………………………………………………………..218

Appendix I

Figure I1: Architecture of the customer demand management segment of RMTO-system ……………………….……………………………………223

Appendix J

Figure J1: Architecture of the remanufacturing and inventory control management segment of "*configA*" ………………………………………….225
Figure J2: Architecture of the *submodel* called "*GI Remanufacturing Submodel*" ……………………………………………..……………….227
Figure J3: Architecture of the remanufacturing and inventory control management segment of "*configC*" ………………………………………….232
Figure J4: Architecture of the remanufacturing and inventory control management segment of "*configD*" ………………………………………….234

Appendix K

Figure K1: Architecture of the remanufacturing and inventory control management segment of "*configE*" ………………………………………….237
Figure K2: Architecture of the remanufacturing and inventory control management segment of "*configF*" ………………………………………….239

List of Tables

Chapter 2

Table 2.1: Summary of factors and corresponding features for selection of a production strategy ……………………………………………………….27

Chapter 3

Table 3.1: The solution for Q_r, $n*$ and Q_m^* resulting from the adjustment of a benchmark model …………………….….…………………...75

Table 3.2: The solution for Q_m, n and Q_{r1} for a given u …………..……………77

Table 3.3: Percentage of savings in total cost per unit time at different remanufacturing fractions ……………………………………………………..79

Chapter 4

Table 4.1: Remanufacturing policy of alternative RMTS-system configurations ……………………………………………………………….85

Table 4.2: Remanufacturing policy of alternative RMTO-system configurations ……………………………………………………………….85

Chapter 5

Table 5.1: Average remanufacturing cycle-time (hours) of "*configA*" under six combinations of yields and availability ...……….…………………………..125

Table 5.2: Average target-time, reorder-time and inventory cycle-time of alternative RMTS-system configurations ………...131

Table 5.3: The effect of changes in used products quantities on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand of every 40 hours …………….………….......................136

Table 5.4: The effect of changes in inspection yield on average remanufacturing cycle-time of alternative RMTS-system configurations -customer demand of every 32 hours ...…………...137

Table 5.5: Average remanufacturing cycle-time (hours) of “*configE”*
under six combinations of yields and availability …..……...............................142
Table 5.6: The effect of changes in used products quantities on average
remanufacturing cycle-time of alternative RMTO-system configurations
-customer demand of every 40 hours ………………..146
Table 5.7: The effect of changes in used products quantities on average
remanufacturing cycle-time of alternative RMTO-system configurations
-customer demand of every 28 hours …….………..148
Table 5.8: The effect of changes in inspection yields on average
remanufacturing cycle-time of alternative RMTO-system configurations
-customer demand of every 40 hours …….……………………………………..148

Appendix A

Table A1: Key stages for remanufacturing of toner cartridges,
automotive engines and washing machines …………..………………………..184

Appendix B

Table B1: The effect of changes in costs and demand parameters on
manufacturing lot-size at different remanufacturing fraction – case 1 …………192
Table B2: The effect of changes in costs and demand parameters on
manufacturing lot-size at different remanufacturing fraction – case 2 …………192
Table B3: The effect of changes in costs and demand parameters on first
remanufacturing lot-size at different remanufacturing fraction – case 1 ………193
Table B4: The effect of changes in costs and demand parameters on
remanufacturing lot-size at different remanufacturing fraction – case 2 ……….193

Appendix C

Table C1: Design of the simulation experiments for analyses of RMTS system and strategy …………………………………………………………..198

Table C2: Design of the simulation experiments for analyses of RMTO system and strategy …………………………………………………………..199

Table C3: Fixed system parameters for analyses of remanufacturing systems and strategies ………..………………………………………………200

Appendix D

Table D1. Average remanufacturing cycle-time (hours) of "*configB*" under six combinations of yields and availability……..………………………..206

Table D2. Average remanufacturing cycle-time (hours) of "*configC*" under six combinations of yields and availability ……..………………………..206

Table D3. Average remanufacturing cycle-time (hours) of "*configD*" under six combinations of yields and availability …….……………………...…206

Table D4: The effect of changes in used products quantities on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand of every 32 hours ……………………………………..…207

Table D5: The effect of changes in inspection yields on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand of every 40 hours …………………………………..……207

Table D6: Average remanufacturing cycle-time (hours) of "*configF*" under six combinations of yields and availability .……... ……………………..210

Table D7: Average remanufacturing cycle-time (hours) of "*configG*" under six combinations of yields and availability ………………………………210

Table D8: The effect of changes in inspection yields on average remanufacturing cycle-time of alternative RMTO-system configurations – customer demand of every 40 hours ……………………………………….210

Chapter 1
Introduction

1.1 Motivation

Recently remanufacturing of used products has become an important part of production activity in many companies (Guide et al., 1999; Guide, 2000; Aras et al., 2004; Ferrer and Swaminathan, 2006). This progress has been primarily motivated by three emerging factors; strict environmental regulations, increasing customer awareness of green environment and economical benefits. The automotive sector particularly has a strong history of remanufacturing (Seitz, 2007), where numerous auto parts such as starters, clutches, etc, have been remanufactured and resold as spare parts (Steinhilper, 1998). Remanufacturing is also gaining scientific significance in a variety of industries that include single use-devices for hospitals, such as wheelchairs and hearing aids (Srivastava, 2004; Rudi et al., 2000), cellular phones (Guide et al., 2003a) and truck tyres (Lebreton and Tuma, 2006).

Remanufacturing, which generally aims to transform used products or some of their components into a like-new condition, typically involves processes, such as inspection/grading, disassembly, component reprocessing/replacement and reassembly/testing. There are several unique characteristics that predominantly and naturally occur in the remanufacturing environment, which complicate production planning and control activities.

Firstly, used products exhibit highly uncertain quality conditions due to their different degree of usage. Used products that originate from a market-stream (e.g. retailers) exhibit relatively similar quality conditions than those that originate from a waste-stream (e.g. scrap brokers and collection centres). Secondly, the quantities of used products available for remanufacturing are also uncertain because it depends on a product's life-cycle stage and rate of technological changes. Thirdly, the uncertain quality conditions results in an inspection yield that varies from one batch to another. Fourthly, the uncertain quality conditions also lead to a disassembly yield that differs from one batch to another.

Furthermore, the uncertain quality conditions also result in a reprocessing effort of constituent components that varies from one unit to another and from one batch to another. Remanufacturing frequently involves multiple-types of constituent components, which presents a greater challenge in addressing the above mentioned characteristics. In a customer driven remanufacturing environment there are often requirements to match and reassemble the same set of constituent components into a final product. Finally, companies' often need to balance customer demand with availability of used products in order to prevent excess inventory build-up and maximise customer service level.

Clearly, the existence of the above mentioned eight unique characteristics, as well as their interactions would inevitably cause difficulties with regard to production planning and control activities in remanufacturing operations. For example, when remanufacturing coexists with normal manufacturing operations (i.e., a hybrid remanufacturing-manufacturing system), a problem to determine the optimal inventory lot-sizing for remanufacturing and manufacturing is complicated by the uncertain quality conditions and availability of used products (Van der laan et al., 1999; Inderfurth and Van der laan, 2001; Kiesmuller, 2003; Hedjar et al., 2005).

In such a hybrid environment, the economic order quantity lot-sizing model has been widely applied in managing and controlling the inventory of remanufacturable and serviceable items, where constant remanufacturing lot-sizes have been extensively implemented. However, such models with constant remanufacturing lot-sizes have a few factors that limit their performance, in particular under conditions of varying remanufacturing fractions.

Firstly, when the remanufacturing process is delayed, a loss of responsiveness to customer demand could occur, particularly when manufacturing of new products involve a long lead-time. Secondly, excess inventory could occur when remanufacturable stocks are carried over after each remanufacturing process. This could be costly when storage capacity is restricted. Thirdly, higher cost could be incurred when remanufacturable stocks are stored during the entire manufacturing interval. In this context, it is evident that a new inventory lot-sizing model in a hybrid remanufacturing-manufacturing system is necessary in order to address these problems. Consequently, the development of an integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system considering variable remanufacturing lot-sizes is the primary focus of this research.

Given the existence of eight unique characteristics in the remanufacturing environment, it is imperative that such unique characteristics are treated as a set of essential criteria in the modelling and analysis of remanufacturing systems. Nevertheless, scores of studies have failed to treat such unique characteristics as a set of essential criteria. This could probably be attributed to difficulties that are regularly associated with mathematical modelling of remanufacturing systems with unique characteristics. From this view, it is apparent that the modelling and analysis of remanufacturing systems with unique characteristics would greatly benefit from the application of simulation techniques.

Simulation techniques have been broadly and successfully applied in the development and analysis of countless decision-making models in areas that include the manufacturing industry, service industry and defence sector. Such broad applications of simulation techniques have been established mainly due to its superior analysis capability, which provides analysts with a system-wide view of the effect of changes in system parameters on the performance of a system. Consequently, the development of integrated production and inventory planning simulation models in a remanufacturing system with varying inspection yields and availability of used products is the secondary focus of this research.

1.2 Research objectives and scope

In light of the argument presented earlier, this research aims to develop models for decision-making tools for remanufacturing. Specifically, the research objectives are defined as follows:

1. Development of an integrated inventory lot-sizing model to concurrently determine the optimal lot-sizes for remanufacturing, number of remanufacturing lots and lot-sizes for manufacturing in a hybrid remanufacturing-manufacturing system with varying remanufacturing fractions.

2. Development of integrated production and inventory planning simulation models to determine the optimal remanufacturing policy for processing two different quality remanufacturable groups in a remanufacture-to-stock system with varying inspection yields and availability of used products.

3. Development of integrated production and inventory planning simulation models to determine the optimal remanufacturing policy for processing two different quality remanufacturable groups in a remanufacture-to-order system with varying inspection yields and availability of used products.

4. Development of integrated production and inventory planning simulation models to determine the optimal remanufacturing strategy for processing two different quality remanufacturable groups in a remanufacturing system.

For the first objective, the scope of work is specified as follows:

(a) To develop a conceptual model that illustrates the profiles of remanufacturable and serviceable items inventory considering variable remanufacturing lot-sizes.

(b) To develop a mathematical model that characterises the corresponding total cost per unit time.

(c) To examine the behaviour of major decision variables (lot-sizes for remanufacturing, number of remanufacturing lots and lot-sizes for manufacturing) with remanufacturing fractions and cost and demand parameters.

(d) To examine the benefit of the new model with variable remanufacturing lot-sizes when compared to a model with constant remanufacturing lot-sizes.

(e) To examine the robustness of the major decision variables (lot-sizes for remanufacturing and lot-sizes for manufacturing) with regards to changes in costs and demand parameters.

For the second and third objectives, the scope of work is specified as follows:

(a) To develop a generic conceptual model of a remanufacturing system.

(b) To develop conceptual models that represent the configurations of different remanufacturing policies in a remanufacture-to-stock and remanufacture-to-order remanufacturing systems.

(c) To code and verify the computer programs and validate the simulation models.

(d) To examine and compare the effects of system variables on the performance of four alternative remanufacture-to-stock system configurations and three alternative remanufacture-to-order system configurations.

(e) To examine and compare the robustness of four alternative remanufacture-to-stock system configurations and three alternative remanufacture-to-order system configurations with regards to changes in the system's variables.

(f) To examine (d) and (e) (above) at different levels of customer demand.

For the fourth objective, the scope of work is specified as follows:

(a) To examine the effects of system variables on the performance of remanufacture-to-stock and remanufacture-to-order remanufacturing strategies.

(b) To compare the performance of remanufacture-to-stock and remanufacture-to-order remanufacturing strategies with respect to customer service level.

1.3 Research Contributions

In particular, this thesis makes the following contributions:

(i) Development of an integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system considering variable remanufacturing lot-sizes.

(ii) Establishment of a set of essential criteria for modelling and analysis of remanufacturing systems with unique characteristics.

(iii) Application of simulation techniques in the modelling and analysis of remanufacturing systems with unique characteristics.

(iv) Development of integrated production and inventory planning simulation models for a remanufacture-to-stock system with varying inspection yields and availability of used products.

(v) Development of integrated production and inventory planning simulation models for a remanufacture-to-order system with varying inspection yields and availability of used products.

(vi) Development of integrated production and inventory planning simulation models for a remanufacturing system.

1.4 Thesis Overview

This thesis is organised into six chapters, which are Introduction, Literature Survey, An Integrated Inventory Lot-Sizing Model in a Hybrid Remanufacturing-Manufacturing System Considering Variable Remanufacturing Lot-Sizes, Integrated Production and Inventory Planning Simulation Models, The Effect of System Variables on The Performance of Remanufacturing Systems and Strategies, and Conclusion.

Chapter 1 presents the overall motivation, objectives and scope and contributions of the research work.

Chapter 2 provides an overview of literature that is pertinent to this research. The first part offers an overview of the remanufacturing operation, which concludes with establishing the existence of several unique characteristics in the remanufacturing environment. The second part presents a current survey of the criteria for modelling and analysis of remanufacturing systems, which aims to establish the research gaps that need to be addressed. The third part offers a review of the principles of simulation, which forms the research tool for the second research focus.

Chapter 3 introduces an integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system that implements variable remanufacturing lot-sizes to address the problem of varying remanufacturing fractions. A mathematical model that characterises the total cost per unit time associated with such a model is also presented, which is utilised to concurrently determine the optimal values for the major decision variables (lot-sizes for remanufacturing, number of remanufacturing lots and lot-sizes for manufacturing) under a given remanufacturing fraction. Case studies are also provided to demonstrate: (i) the behaviour of the major decision variables with regards to remanufacturing fractions and costs and demand parameters, (ii) the benefit of implementing the new model, and (iii) the robustness of the major decision variables with regards to changes in costs and demand parameters.

Chapter 4 describes the life-cycle that corresponds to the construction and analysis of the simulation models that are defined in research objectives 2, 3 and 4. This includes important stages such as: (i) formulation of the problems, (ii) definition, validation and architecture of conceptual models, (iii) coding and verification of computer programs and validation of simulation models, (iv) architecture of the major segments of simulation models, and (v) design and execution of simulation experiments. These stages are crucial in order to ensure successful construction and analysis of the simulation models that are specified in research objective 2, 3 and 4.

Chapter 5 discusses the effects of system variables on the performance of remanufacturing systems and strategies. The first case study examines: (i) the effects of inspection yields, alternative system configurations and quantities of used products on the performance of remanufacture-to-stock systems, and (ii) the robustness of remanufacture-to-stock systems' performance with regards to changes in inspection yields and availability of used products. The second case-study assess: (i) the effects of inspection yields and quantities of used products on the performance of remanufacture-to-order systems, and (ii) the sensitivity of remanufacture-to-order systems' performance with regards to changes in inspection yields and availability of used products. The third case study investigates: (i) the effects of inspection yields, alternative system configurations and availability of used products on the performance of remanufacture-to-stock and remanufacture-to-order strategies, and (ii) the effects of remanufacture-to-stock and remanufacture-to-order strategies on the customer service level.

Chapter 6 presents conclusions that arise from this research, as well as the future directions for this research.

Chapter 2
Literature Survey

2.1 Introduction

This chapter discusses literature that pertains to this research project. Section (2.2) discusses six fundamental aspects of remanufacturing operations. Section (2.3) provides a current survey of the criteria that have been adopted and implemented in modelling and analysis of remanufacturing systems. Section (2.4) discusses four major underlying principles of simulation that are pertinent to modelling and analysis of remanufacturing systems. Section (2.5) summarizes some critical points that have emerged and established from the materials that are presented and discussed in this chapter.

2.2 An overview of remanufacturing operations

2.2.1 Motivating factors and roles of remanufacturing

In many companies the main business objectives of providing excellent customer service level and maintaining low cost production have become more crucial with an increasingly volatile operating environment and uncertain customer demand. To date, three major factors have become very important and are responsible for motivating companies to engage in remanufacturing activity. These factors have been identified as strict environmental regulations imposed by governmental bodies, increasing customer awareness of green environment and economical benefit posed by remanufacturing.

(a) Strict environmental regulations

The emerging trend of strict environmental regulations imposed by governmental bodies has forced companies to extend their manufacturers' responsibility to include products that have been used and retired. This extended manufacturers' responsibility has further forced companies to devise products and production process that could make product recovery via remanufacturing feasible.

In Europe, for example, the introduction of directive on waste electrical and electronic equipment (*Directive/2002/96/EC*) states that "*Where appropriate, priority should be given to the reuse of waste electrical and electronic equipment (WEEE) and its components, subassemblies and consumables. Where reuse is not preferable, all WEEE collected separately should be sent for recovery, in the course of which a high level of recycling and recovery should be achieved. In addition, producers should be encouraged to integrate recycled material in new equipment*".

In another case, the introduction of a directive on legislation of end-of-life vehicle (*Directive 2000/53/EC*) has forced the European automobile manufacturers to assume full responsibility for disposal of their products (cars) that are manufactured from 2002 onwards with no cost to the final owners. In addition, the directive states that "*the requirements for dismantling, reuse and recycling of end-of life vehicles and their components should be integrated in the design and production of new vehicles*".

(b) Increasing customer awareness of green environment

Customers are becoming more sensitive and aware of the implication of disposing used products on the green environment. For instance, increasingly more customers are purchasing products from manufacturers who are responsible for taking back their products after the end of the products useful life (Gungor and Gupta, 1999). For the manufacturers, taking back and reprocessing their used products in an environmentally-friendly manner creates an opportunity to boost the value of their products, which subsequently, can serves as a marketing strategy to gain advantage by becoming an environmentally-friendly company.

In Australia, Fuji Xerox Australia (Fuji Xerox Australia, 2007a) has taken the initiative to be one of the pioneering companies that implements remanufacturing program for printers and copier parts; which began as early as 1990s. In the year 2006, for instance, such remanufacturing practice has saved the company approximately $13 million and created revenue of $5.4m in exports. The company has also been commended on numerous occasions for their effort on maintaining and reducing the environmental impact of the company’s activity. In 2001, for example, the company’s eco-manufacturing centre was commended for being environmentally responsible (Fuji Xerox Australia, 2007b)

(c) Economical benefit

Remanufacture of used products incurred cost that is typically 40% - 65% less that those incurred in the manufacture of new products (Dowlatshahi, 2000; Giuntini and Gaudette, 2003). This results from the availability of raw materials (recovered components), which are cheaper than newly manufactured components because recovered components do not have to be redesigned and ordered from new suppliers. Furthermore, it has also been well recognised that reuse of components in the production of subsequent product generations results in cost savings (Bhattacharya et al., 2006). In terms of energy consumption, remanufacture of used products only requires about 15% of the energy that is needed to manufacture new products. For example, in 1997, Xerox Europe has reported gaining over $80 million savings through the implementation of end-of-life equipment take-back and reprocessing program (Maslennikova and Foley, 2000).

> For the original equipment manufacturers (OEMs) such as General Electric, Boeing, Caterpillar, Deere, Navistar, and Pitney Bowes, remanufacturing operations has become an integral part of their business models, and amongst them, they currently lease, remanufacture, and remarket an estimated $130 billion of assets (Giuntini and Gaudette, 2003). OEMs that do not engage in remanufacturing activity might risk losing their competitiveness because third-party collectors or competitors could collect and remanufacture their used products. However, recently more OEMs are realising this risk and have begun to initiate remanufacturing program as a strategy to maintain companies' competitiveness (Rogers and Tibben-Lembke, 1999).

Until lately, companies have viewed the environmental regulations and customer awareness as an added operational cost rather than potential sources for generating alternative profit and boosting corporate image. However, with the increasing pressure to become environmentally responsible and sourcing for inexpensive raw materials, more companies are considering remanufacture of used products as a strategy to generate profit, boost company image and maintain competitiveness.

Remanufacture of used products (remanufacturing), generally refers to an industrial process in which used/worn-out/broken products (henceforth called used products) are transformed into "new products" (Lund, 1984a, van der Laan, 1999). Hereafter, these "new products" are referred to as remanufactured products to differentiate them from a completely new product.

The role of remanufacturing activity within any companies depends on the relationship between the companies and used products that are being remanufactured (Lund, 1984a).

(a) Remanufacturing of a company's own used products

When companies remanufacture their own used products (in the case of original equipment manufacturer, OEM), remanufacturing activity usually co-exist with the normal manufacturing activity (hereafter, called a hybrid environment), where resources can either be shared between the two activities or dedicated to individual activity. Firstly, in a hybrid environment remanufacturing serves as a production activity that generates extra profit through the production of remanufactured products.

Secondly, remanufacturing can provide an alternative source for raw materials for the production of new products at a lower cost. Finally, remanufacturing also creates an opportunity to produce spare-components, which can be sold to the spare-components market. Some examples of the OEM remanufacturers are Fuji Xerox Australia (Fuji Xerox Australia, 2007a), BMW (van der Laan, 1997), Volvo CE (Sandavall and Stelin, 2006) and Canon (Canon Global 2008).

(b) Remanufacturing of other companies used products

When a company remanufactures other companies' used products, the remanufacturing activity is mainly viewed as a source for generating profit. This is often the case when third-party remanufacturers, remanufacture OEMs used products (hereafter, called contract remanufacturers) when OEMs out-source remanufacturing activity (Lund, 1984b). For instance, Hewlett-Packard's used printers are remanufactured in a network of hardware recovery centres (Kumar et al., 2002). Once OEMs' used products are remanufactured they are shipped back to OEMs for redistribution.

In addition, there are third-party remanufacturers who realise the economical benefit of remanufacturing and hence would remanufacture any types of used products as long as there are markets for them. Examples of this type of remanufacturer can be found for ink cartridges (Krazit, 2003) and mobile phones (Guide Jr et al., 2003a). Some examples of the third party companies who are engage in remanufacturing operation are MRI (Aust) Pty Ltd (MRI Aust Pty Ltd, 2007) and 24 Hour Toner (Sundin, 2004).

2.2.2 Demand and market of remanufactured products

Demand for remanufactured products occurs in two types of market, a primary-products market and a secondary-products market. Within the primary-product market, demand for remanufactured products usually occurs when the remanufactured products are perfect substitute for new products (Souza and Ketzenberg, 2002). This is the situations when customers bring in OEMs used products for remanufacturing at an OEM's remanufacturing facility and get the same units back, which have been remanufactured to a quality standard that is as good as new ones. In this case, the cheaper price remanufactured products are sold in the same market as the new products (Ferrer and Swaminathan, 2009).

For a secondary-products market, demands for remanufactured products are more common among customers who may have financial restrictions. Remanufactured products are usually produced by third-party remanufacturers who harvest the economical benefits of remanufacturing. In this instance, remanufactured products (e.g. computer systems, auto components and office equipment) have a lower quality standard and price than newly manufactured products (Ferrer 1997; Ayres et al., 1997) or even remanufactured products sold in a primary-products market. Despite their cheaper price, remanufactured products that are produced by third-party remanufacturers are often considered as less attractive (and hence less demanded) than those that are produced by OEMs remanufacturers (Linton, 2008).

Demand for remanufactured products also depends on the classes of customers and their perceived quality of remanufactured products (Debo et. al., 2003; Linton, 2008). The upper class customers, for example, who do not have financial restrictions prefer to purchase a completely new product and are less willing to purchase a remanufactured product. By contrast, the lower class customers who usually have financial restrictions are more than willing to purchase a remanufactured product, because it would be the best choice for them.

For these lower class customers the main reason for buying a remanufactured product is the functionality of a product rather than the product's actual quality standard. However, in some situations the actual quality standard of a remanufactured product is not an issue for the upper and middle classes customers. For examples, in some countries, like Malaysia and Indonesia, customer desire to own a prestigious brand item such as luxury car, would influence them to purchase a remanufactured version of the prestigious brand item.

2.2.3 Sources, qualities and quantities of used products

Basically, any manufactured product, device or mechanical system can be remanufactured. The major requirements as highlighted by Lund (1984b) are discarded used products with lower costs in materials and reprocessing the components than the market value of remanufactured items. The types of products being remanufactured include automotive parts, industrial equipment, commercial products and residential products (Figure A1 in appendix A).

Furthermore, products that are considered for remanufacturing have to meet a certain remanufacturability aspects in order to ensure that they are successfully remanufactured and sold. These aspects are described in the literature (Hauser and Lund, 2003) as: (i) durable product, (ii) product that fails functionally, (iii) standardized product with interchangeable parts, (iv) product with high remaining value-added, (v) product with low acquisition cost, (vi) product with stable technology, and (vii) customer awareness of the remanufactured version.

In general, used products that are considered for remanufacturing, originate either from a waste-stream or market-stream (Guide and Wassenhove, 2001; Jayaraman, 2006). The waste-stream used products correspond to products that have been discarded because they are no longer useful. This includes cars that have been heavily damaged during accidents and sent to a wrecking facility or refrigerators that have malfunctioned and sent to a third party products recovery facility. Accordingly, the waste-stream generates a high proportion of used products with poor quality (Aras and Aksen, 2008; Aras et al., 2008). By contrast, used products that originate from the market-stream correspond to products that are still useful but are no longer needed by the owners, e.g., old model of cellular phones which are traded-in for new models, which have more and advanced features.

Despite their origins, used products exhibit uncertain quality conditions because they have been subjected to a different degree of utilization (Guide Jr et al., 1999). For example, considering the same type of used product, say cellular phones, the quality conditions can range from minor cosmetic blemishes due to light usage to significantly damaged surfaces because of heavy usage. The quality conditions also depend on the environment in which the products have been utilized. For instance, comparing a cellular phone and an automotive engine, the quality conditions might range from one worn-out component (for a cellular phone) to multiple worn-out components (for an automotive engine).

Furthermore, the extent to which the quality condition of used products varies from one unit to another unit (henceforth, known as variability of quality conditions) basically depends on their origins. As stated earlier, the waste-stream generates a high proportion of used products with a poor quality, thus, these used products would exhibit a high variability of quality conditions as compared to those that are obtained from a market stream.

In addition to the uncertain quality conditions, the quantities of used products available for remanufacturing are also uncertain, which is a reflection of the uncertain nature of a product's life (Muckstadt and Isaac, 1981; van der Laan et al., 1999; van der Laan, 1997; Guide Jr, V.D.R. and Srivastava, 1997). The quantities of used products available for remanufacturing depend on the product's life-cycle stage and the rate of technological changes (Guide Jr, 2000; Ostlin, et. al., 2009). Products that have just been introduced into the market generate less quantity of used products than those that have been in the market for a very long time (i.e. nearly at the end-of-life stage). Furthermore, the rate at which a product's technology changes also has an effect on the quantities of used products available for remanufacturing.

To illustrate, electronic products are normally associated with a rapid technology development and faster products innovation which are primarily driven by the customers desire to own the latest product generation. One particular example is the latest generation of Nintendo DS gaming consoles (DSi), which have a camera and voice recorder features (Nintendo DSi, 2009). On the other hand, for some product types such as washing machines or microwaves, the product technology development and innovation are relatively slow, which are probably due to low customer's desire to own the latest generation of washing machine or microwave.

Despite, the product's life-cycle stage and rate of technological changes, the quantities of used products available for remanufacturing could be increased in several ways. Firstly, in situations where remanufacturing is utilised to support a product upgrade, warranty and repair services, a seeding strategy can be implemented to increase the quantities of used products available for remanufacturing (Akcali and Morse, 2004). Basically, this strategy involves selling a certain number of new products in the first period of time and receiving these new products as used products during the subsequent period of time.

Secondly, the implementation of buy-back programs and financial incentives to product holders could also provide a way to influence the quantities of used products returned for remanufacturing (Klausner and Hendrickson, 2000). Finally, advanced information systems such as radio frequency identification (RFID) tags could be implemented to track the location and quality conditions of products currently utilised in the market (Klausner et al., 1998) .

2.2.4 Distinctive key stages and processes of remanufacturing

Remanufacturing, as already stated, refers to an industrial process in which used products are transformed into remanufactured products with a quality condition that is typically as good as new products (Lund, 1984a). This industrial process (remanufacturing process) generally consists of a number of key stages, where different process takes place at each stage (Figure 2.1). However, it is important to note that the number of actual key processes and their exact sequence are dependent upon a product type. Sundin (2004), for example, has characterised the key remanufacturing processes corresponding to several product types such as those tabulated in table A1 (Appendix A).

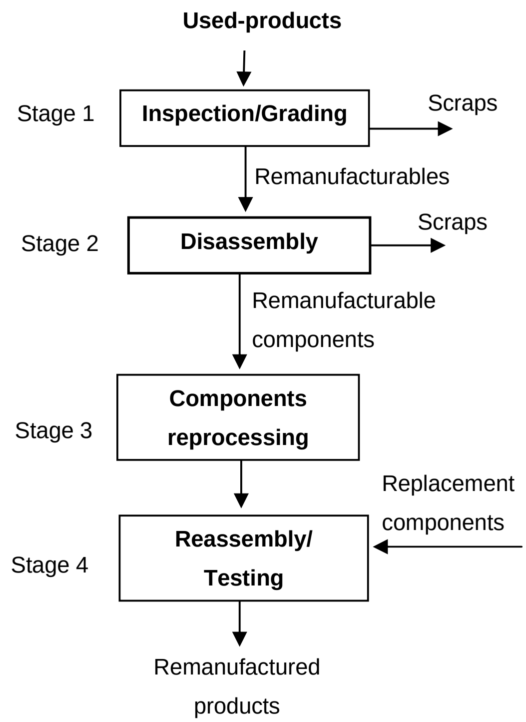


Figure 2.1: Key remanufacturing stages with corresponding processes and material flows (constructed based on remanufacturing process described in Lund, 1984a).

As can be seen from figure 2.1, remanufacture of used products typically consists of four key stages, where the input to one stage extensively depends upon the output from the preceding stages (with the exception of the first stage).

(a) Stage 1 - Inspection process

During the first stage of remanufacturing, used products are inspected for their quality conditions in order to assess their remanufacturability status. This process normally involves complete visual inspection, where inspection times are identical for the same type of used products that originate from the same source (e.g. used cellular phones from the market stream). However, as discussed, between the waste and market streams, the waste-stream would generate used products with a high variability of quality conditions, therefore would result in a different inspection times for each unit of used product. Moreover, used products that originate from the waste-stream would probably require a longer inspection time and special inspection tools.

During the inspection process, used products can be considered either as scrap or remanufacturable. Scraps are either disposed off or sold to scrap brokers, whereas remanufacturables are sent for disassembly/inspection process at the second stage. The proportion of used products that are graded as remanufacturables (inspection yield) might vary from one batch to another due to the uncertain quality conditions of used products.

In spite of their origins, remanufacturables have to be further classified into multiple different quality groups, where the best quality remanufacturable group should be given the highest priority for remanufacturing (Aras et al., 2004; Aras et al., 2006). Furthermore, the waste-stream as already stated, generates remanufacturables with a high variability of quality conditions, therefore, it is more likely that there would be more quality groups than the market stream.

(b) Stage 2 – Disassembly/inspection process

During this process, remanufacturables are disassembled into their modules which are further disassembled into their constituent components. This process usually involves general purpose tools such as power drill, although occasionally robot arms might be necessary for disassembly of complex products (Steinhilpher, 1998) or hazardous parts (Zussman and Seliger, 1999).

Despite their quality groups and origins, disassembly times for the same type of remanufacturables would be identical. The disassembly times largely depends upon the complexity of a product structure, where remanufacturables with a simple product structure (Figure 2.2(a)), would require shorter a disassembly time than remanufacturables with a complex product structure (Figure 2.2(b)). One more factor that influences the disassembly time is the labour skill that is assigned for the disassembly process, where a highly skilled labour (e.g. robot arms) could reduce and hence improve the disassembly times.

H and K are end products.
I and J are constituent components of product H.
M is a sub-assembly of product K.
L, N, O and P are constituent components of

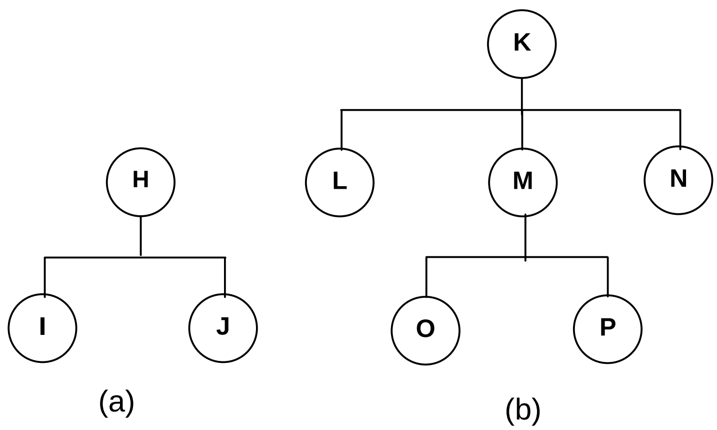


Figure 2.2: Examples of products with (a) a simple structure and (b) a complex structure

Depending on the product structure and volume, disassembly of remanufacturables and inspection of the constituent components can either take place simultaneously or sequentially. For high volume remanufacturables with a simple product structure, disassembly and inspection process can takes place simultaneously. Similarly, for low volume remanufacturables with a complex product structure, disassembly and inspection process can takes plane simultaneously. By contrast, for high volume remanufacturables with a complex product structure, disassembly and inspection process usually take place sequentially in a two-stage disassembly line (Steinhilper, 1998).

Similar to the inspection process of used products in the first stage, the inspection of constituent components can also results in two possible outcomes, where constituent components are either considered as scraps or remanufacturables. For scrap components they have to be replaced and replacements can be ordered either from the internal production lines (in the case of OEMs remanufacturers) or external sources (third-party remanufacturers). The issue of replacement components is very critical, particularly for a RMTO-strategy, where customers send their used products (e.g. aircraft engines) for remanufacture and request the same items back.

Because of the uncertain quality conditions of remanufacturables, the proportion of constituent components (e.g. component J in Figure 2.2(a)) that are classified as remanufacturables, may well varies from one batch to another (hereafter, this proportion is termed as disassembly yield). Reconsidering component J, its disassembly yield would be higher for the best remanufacturable quality group compared with the worst quality group. Furthermore, for the same quality remanufacturable group, the disassembly yield of a constituent component would be probably higher for components that have been derived from the market-stream remanufacturables.

The uncertain quality conditions of remanufacturables would also result in a different sets of remanufacturable constituent components. To illustrate, consider two units of remanufacturable with a product structure as shown in Figure 2.2(b). Disassembly and inspection of the first unit of remanufacturable might result in a set of remanufacturable constituent components that include components L, N, & O, whereas disassembly and inspection of a second unit of remanufacturable can result in a set of remanufacturable constituent components that include components N, O & P.

Irrespective of the product structure, the product design would also affect the disassembly yield of constituent components (Ferrer, 2001). Products that are originally designed for disassembly would generate a higher disassembly yields than those that are not originally designed for disassembly because of the damaged during disassembly.

Similar to remanufacturables that are discussed in stage 1 (Inspection/Grading), remanufacturable constituent components are also probably in different quality conditions. As such, they need to be further classified into multiple different quality groups, where the best quality component group is given the highest priority to remanufacture. Furthermore, remanufacturables that originate from the waste-stream would result in more quality component groups than the market-stream.

(c) Stage 3 - Reprocessing of remanufacturable constituent components

This stage typically involves processes that include cleaning, repairing (e.g. machining worn-out holes) and surface finishing with the aim to restore the remanufacturable constituent components to their original condition. The exact number of processes and time required to reprocess each constituent component to its original condition mainly depends upon the quality component group. For instance, the best quality component group could probably require cleaning and surface finishing, therefore leading to a simple process and short reprocessing time. By contrast, the worst quality component group probably require cleaning, repairing and surface finishing, thus resulting in a complex procedure and longer reprocessing time.

For a complex component design, multiple repair steps, such as welding and trimming might be necessary in order to restore the components to their original condition. Conversely, for some components like bulb, electrical wire or cellular phone casing, there is no repair process required because these components are merely replaced with new ones. The case of no repair process could also be the scenario for third-party remanufacturers, who are not equipped with the appropriate technology to repair components, particularly when the used products are OEMs products.

(d) Reassembly

Similar to the disassembly process that is described in stage 2, the reassembly process typically involves general purpose tools for reassembly of product with a simple structure and robot arms for reassembly of product with a complex structure. The commencement of a reassembly process is principally affected by the completion of the preceding processes, i.e., reassembly process is only initiated when all the relevant components (remanufactured & new) are available. Similar to the disassembly process, the reassembly time can be improved by employing a highly skilled labour for the reassembly process.

2.2.5 Strategies and performance measures of remanufacturing systems

Remanufacturing process, as discussed previously, consists of four stages with uncertain natures of input, processes and output. These uncertain natures of output from each stage and the inter-dependency between stages further lead to uncertain and complex nature of remanufacturing systems. In this thesis, remanufacturing systems refer to an integrated collection of processes, people, machines and procedures, whose primary function is to transform used products into remanufactured products. In other words, remanufacturing systems typically consist of four highly inter-dependent key stages (with corresponding process, people and procedures) with uncertain characteristics of the input, processes and output.

For any remanufacturing system, the production activity might be carried out according to a remanufacture-to-stock (RMTS) strategy, remanufacture-to-order (RMTO) strategy or re-assemble-to-order (RATO) strategy. Typically, for the RMTS strategy, remanufacturing activity proceeds until a target-level of the finished products inventory is achieved, unless there is insufficient stock of remanufacturable items. For this strategy, the main focus is to position most of the inventory towards the end of system in terms of finished products (indicated by a solid line triangle in figure A2 in appendix A).

By contrast, for the RMTO strategy, remanufacturing activity is initiated once a customer's demand has occurred and is immediately suspended after that demand is satisfied. Therefore, the primary focus is to position most of the inventory at the beginning of the system in terms of raw materials (indicated by a solid line triangle in figure A3 in appendix A). In between these two extreme strategies (RMTS and RMTO) is the RATO strategy, where the RMTS strategy is applied in the first half of the remanufacturing system and the RMTO strategy is applied in the second half of the remanufacturing system. For the RATO strategy, the primary focus is to position most of the inventory in the middle part of the remanufacturing system in terms of disassembled components (indicated by a solid line triangle in figure A4 in appendix A).

The selection and implementation of a specific production strategy mainly depends on several factors such as given in table 2.1. As given in table 2.1, the selection of a specific production strategy has to consider the following factors: (i) volume of used products available for remanufacturing, (ii) time regarding the availability of used products, (iii) testing of the quality conditions of used products, (iv) complexities of the product structure, (v) complexities of the testing and evaluation processes, and (vi) complexities of the remanufacturing process.

To illustrate, the RMTS strategy can be implemented under conditions of: (i) high volume of used products available for remanufacturing, (ii) uncertain time with respects to the availability of used products, (iii) limited testing of the quality conditions of used products, (iv) low to moderate complexities of the product structure, (v) low to moderate complexities of the testing and evaluation processes, and (v) low to moderate complexities of the remanufacturing processes.

Table 2.1:
Summary of factors and corresponding features for selection of a production strategy (adapted from Guide et. al., 2003b)

Key factors	RMTS	RMTO	RATO
Volume	High	Moderate	Low
Timing of availability	Uncertain	Forecast with some certainty	Forecast with some certainty
Testing of quality	Limited	Uncertain	Highly uncertain
Complexity of product	Low to moderate	Moderate to high	High
Complexity of test and evaluation	Low to moderate	Moderate to high	High
Complexity of remanufacturing	Low to moderate	Moderate to high	High

The selection of a production strategy would further dictate the choice of key performance measures of remanufacturing systems (hence remanufacturing companies), which are either based on cost or remanufacturing-related activity. For the remanufacturing-related activity, the performance measures typically include remanufacturing rate and capacity, utilization and availability of remanufacturing facility and work-in-process. In most situations the remanufacturing-related performance measures are normally tied up with cost, e.g., a high remanufacturing rate at a low production cost.

For the traditional manufacturing systems that operate based on a manufacture-to-stock strategy, the key performance measure is primarily based on the percentage of actual customer demands that are met or service level (Tersine, 1994). Similarly, for remanufacturing systems that operate based on a remanufacture-to-stock strategy, the key performance measure might also be based on the percentage of actual customer demands that are met. By contrast, for remanufacturing systems that operate according to a remanufacture-to-order strategy, the key performance measure is mainly based on the remanufacturing lead time or delivery lead time (Souza et al., 2002).

2.2.6 Unique characteristics of remanufacturing environment

Up to this point, it can be argued and established that there are several unique characteristics that naturally and predominantly present within a remanufacturing environment, which affect the behaviour (performance) of a remanufacturing system. It has been identified that these unique characteristics are:

(i) uncertain quality conditions of used products,
(ii) uncertain quantities of used products available for remanufacturing,
(iii) varying inspection yields of used products,
(iv) varying disassembly yields of constituent components,
(v) varying reprocessing efforts of constituent components,
(vi) multiple-key remanufacturing stages with inter-dependency between stages,
(vii) multiple-types of constituent components,
(viii) matching and reassembly the same set of constituent components into final products in customer driven environment,
(ix) balancing customer demand with availability of used products in order to prevent excess inventory build-up and maximise customer service level.

Such unique characteristics have also been observed by a number of researchers (Guide Jr, et al., 1997a; 1997b; Guide Jr and Srivastava, 1997b; Fleischmann et al., 1997; Guide Jr et al., 1998; Guide Jr et al., 1999; Ferrer, 2003) who have discuss the implications of these unique characteristics on the performance of remanufacturing systems. Furthermore, there has been agreement that the presence and interactions of these unique characteristics have lead to remanufacturing systems that are uncertain and complex in nature. This subsequently leads to planning and management of remanufacturing operations to be more difficult than the traditional manufacturing operations.

Similar to the traditional manufacturing systems, the production and inventory planning activities of remanufacturing systems usually consists of determining the quantity of: (i) raw materials (used products) to acquire from suppliers, (ii) remanufacturables to stock, (iii) remanufacturables for remanufacturing, and (iv) serviceable items to stock, so as to provide excellent customer service level. However, unlike the traditional manufacturing systems, production and inventory planning activities of remanufacturing systems are much more complex due to the existence of several unique characteristics.

For example, given the uncertain quantities of used products that are available for remanufacturing, as well as their uncertain quality conditions, the main questions would be: (i) when to order used products from suppliers, and (ii) what are the quantities of used products to order, such that customer demand are met without carrying excessive inventory of remanufacturable and serviceable items.

The above example shows that the production planning activity of remanufacturing systems can become quite complicated in the presence of several unique characteristics. Therefore, such unique characteristics have to be properly taken into account in order to achieve effective planning and management of remanufacturing systems. Moreover, the wide recognition of these unique characteristics suggests the need for their proper treatment in remanufacturing studies. Accordingly, it is imperative that these unique characteristics are treated as a set of essential criteria in modelling and analysis of remanufacturing systems.

2.3 A current survey of criteria for modelling and analysis of remanufacturing systems

As already established in subsection (2.2.6), remanufacturing systems are uncertain and complex in nature due to the presence of several unique characteristics, which further complicate planning and management of such systems. It has also been argued and established that these unique characteristics have to be regarded as a set of essential criteria in modelling and analysis of remanufacturing systems. Nonetheless, as presented and argued in the following subsections (2.3.1 to 2.3.5), the majority of existing research on remanufacturing have failed to treat such unique characteristics as a set of essential criteria in modelling and analysis of remanufacturing systems. For these existing research, the commonly assumed criteria in modelling and analysis of remanufacturing systems have been mostly incomplete and simplified, when compared to the set of essential criteria that are stated in subsection 2.2.6.

2.3.1 Inspection yields of used products

By far, the most commonly assumed criterion for modelling and analysis of remanufacturing systems has been uncertain quality conditions of used products. These uncertain quality conditions of used products have been reflected by the necessity to dispose used products that are deemed unfit for remanufacturing, i.e., scraps. Used products that are deemed fit for remanufacturing (i.e. remanufacturables) have been treated either as: (i) remanufacturables with a single quality group or (ii) remanufacturables with multiple different quality groups. Furthermore, for both cases (i) and (ii), the uncertain quality condition of used products has also been reflected by the uncertain yields of inspection.

(i) Uncertain inspection yields of a single quality remanufacturable group

This modelling and analysis criterion has been assumed in models of remanufacturing systems, where the key remanufacturing stages have been aggregated into one remanufacturing stage. Within the purely remanufacturing environment, this criterion has been assumed by Galbreth and Blackburn (2006), Zikopoulos and Tagaras (2007) and Zikopoulos and Tagaras (2008). Specifically, Galbreth and Blackburn (2006) considered a problem to determine the quantity of used products to acquire and their inspection and sorting policy under situations of uncertain inspection yields, as well as stochastic demand of remanufactured products.

Zikopoulus and Tagaras (2007) examined the profitability of a remanufacturing facility subject to uncertain inspection yield of used products which have been supplied from two collection sites. Building on this work, Zikopoulus and Tagaras (2008), considered another criterion which corresponds to the presence of errors during the classification process of remanufacturables, i.e. some scraps are misclassified as remanufacturables and vice-versa. The main objective of this work has been to determine the optimum quantity of used products to acquire from the collection centre and the amount required (after inspection process) for the subsequent remanufacturing process.

By contrast, within a hybrid remanufacturing-manufacturing environment, the criterion of uncertain inspection yields has been assumed by Souza and Ketzenberg (2002), Inderfurth (2005), Rubio and Corominas (2008) and Ketzenberg et. al. (2003). In particular, Souza and Ketzenberg (2002) assumed uncertain inspection yields in a model of hybrid remanufacturing-manufacturing system, in which customer demand for new products can be satisfied either by new products, remanufactured products or both. Moreover, both remanufacturing and manufacturing processes have been assumed to occur in two-stages, where the resources for the second-stage (assembly) has been shared between the two processes.

The main focus was to determine the optimal long-run production mix for the two product types (new and remanufactured) that maximises the profit while subject to a constraint on average order lead time. Their findings show that determining the optimal production mix for the new and remanufactured products is important and also requires careful consideration of the operating environment and production characteristics.

Similar to Souza and Ketzenberg (2002), Inderfurth (2005) has also assumed uncertain yields of inspection in a model of hybrid remanufacturing-manufacturing. However, in this case, the key stages of remanufacturing process have been aggregated into a single-stage. Like Souza and Ketzenberg (2002), the decision-making problem was to determine the product mix (remanufactured and new), as well as the inventory of remanufacturable items, remanufactured items and new products.

Rubio and Corominas (2008) have also assumed uncertain inspection yields in a single-stage model of remanufacturing system that coexists with normal manufacturing system. However, unlike any other work reported in this thesis, remanufacturing of used products was assumed to occur in a lean remanufacturing environment. For this lean remanufacturing production, the primary problem was to determine the remanufacturing and manufacturing capacities, quantity of used products to acquire from suppliers and quantity of remanufacturables required for the subsequent remanufacturing process.

Ketzenberg et al. (2003) considered a special model of a hybrid remanufacturing-manufacturing system, where disassembly has been assumed to take place in a disassembly line. Disassembled constituent components are utilized either for the reassembly of remanufactured products or reassembly of new products (which has also been assumed to occur in a production line). The central objective was evaluating two design configurations (combined-production line or parallel-production line) for a hybrid disassembly-assembly production line under conditions of uncertain inspection yields. For the combined-production line configuration, disassembly-assembly process takes place in the same station.

By contrast, for the parallel-production line configuration, disassembly-assembly process occurs in two separate production lines. Their general findings show that implementation the of parallel-production line configuration would be beneficial when the: (i) inter-arrival time of components to the reassembly process is low, (ii) reassembly times are low, (iii) variability of disassembly and remanufacturing time is high, (iv) percentage of demand that is satisfied with remanufactured components is high, and v) utilization of disassembly line is high.

(ii) Uncertain inspection yields of multiple different quality remanufacturable groups

Similar to the criterion discussed in (i), a criterion of uncertain inspection yields of multiple different quality remanufacturable groups has also been assumed in a pure remanufacturing environment (Souza et al., 2002; Denizel et al., 2007), as well as in a hybrid remanufacturing-manufacturing environment (Ketzenberg et al., 2003; Behret and Korugan, 2005; Behret and Korugan, 2009).

Souza et al. (2002) assumed uncertain inspection yields in a model of remanufacturing system, where used products are graded into four different quality remanufacturable groups. One of the quality group refers to remanufacturables that are sold directly to customers without being remanufactured, while the other three quality groups refer to remanufacturables that are remanufactured at their respective stations. The critical decision-making issue was determining the optimal product mix for the three different quality groups, which maximises the profit while maintaining a desired average order lead time over the long-run production. Among others, their findings show that: (i) companies could maximize profits by remanufacturing a mix of used products that does not include 100% of products with the highest margin, and (ii) reducing the error of grading remanufacturables would markedly decrease the average lead times.

Denizel et al., (2007) has also assumed uncertain inspection yields in a model of remanufacturing system, where used products have been graded into three different quality remanufacturable groups. In this model the primary planning problem was determining the quantity of: (i) remanufacturables for processing for each quality group, (ii) remanufacturables to carry for future period for each quality group, and (iii) remanufactured products to carry for future period, under the conditions of uncertain inspection yields (for each quality group) and uncertain customer demand. The results of their study show that remanufacturing of the exact demanded quantity is preferred, when the holding cost of remanufactured products is higher than the holding cost of used products. Furthermore, they show the value of implementing an established grading policy, where used products are graded appropriately and the best quality group is given the highest priority to remanufacture (when compared to no grading policy where used-products are remanufactured on a first-come and first-serve basis).

Unlike Souza et al. (2002) and Denizel et al. (2007), who assumed uncertain inspection yields of multiple different quality remanufacturable groups in a pure remanufacturing environment, Behret and Korugan (2005) assumed uncertain inspection yields of multiple different quality groups in a model of a hybrid remanufacturing-manufacturing system. Specifically, the uncertain inspection yields has been assumed for three different quality groups, which has been considered being remanufactured in a single-stage remanufacturing facility.

The central focus was assessing the advantages of classifying remanufacturables into three different quality groups (good, average and bad), where each quality group requires minimal, average and major remanufacturing effort, respectively and also subjected to uncertain inspection yields of each quality group. The results of their study show that multiple classification of remanufacturables is advantageous because it: (i) allows realistic estimation of manufacturing quantities of the new products, (ii) enables salvage values of excess remanufacturables to be determined according to their quality groups, and (iii) favours giving priority to high quality group, when remanufacturable rates is high and the holding cost is significant.

In their subsequent work, Behret and Korugan (2009) improved their model by assuming remanufacturing process to occur in two-stages (disassembly/reprocessing and reassembly), where the reassembly stage is shared between the remanufacturing and manufacturing processes. Under the scenario of uncertain inspection yields of three different quality remanufacturable groups, the focus was balancing the remanufacturing and manufacturing throughput with customer demand by controlling inventory at the various stages of remanufacturing and manufacturing. Their findings show that: (i) even under different cost scenarios, the quality based classification of remanufacturables presented a significant cost savings when remanufacturables rate is high, and (ii) classification of remanufacturables gives the opportunity to produce more of the higher quality group and dispose the lower quality group which would minimises cost.

2.3.2 Disassembly yields of constituent components

In addition to uncertain inspection yields, the uncertain quality conditions of used products also results in uncertain disassembly yields of constituent components. Similarly, uncertain disassembly yields of constituent components are also vital criteria for modelling and analysis of remanufacturing system. Nevertheless, as established from the discussion presented in subsection 2.3.1, the criteria of uncertain inspection yields and disassembly yields of constituent components has not been considered in any of the remanufacturing models. This probably results from the widely assumed and simplified criterion of used products with a simple product structure, where one-type of constituent component is considered for remanufacturing. This has lead to another regularly assumed and simplified criterion of a single-stage remanufacturing process, where the uncertain yields of disassembly has not been taken into account.

Few researchers have attempted to model remanufacturing systems with improved criteria of multiple-stages of remanufacturing and uncertain disassembly yields of a single-type constituent component. To exemplify, Aksoy and Gupta (2001a) have considered uncertain disassembly yields of a single-type constituent component in a three-stage remanufacturing system, where the main focus was to examine the effects of variable disassembly yields and other system parameters on the economic performance of a remanufacturing system.

In their later work, Aksoy and Gupta (2005) analysed a problem to distribute a given number of available inventory buffers amongst the various stations within a three-stage remanufacturing cell, which is subjected to uncertain disassembly yields of a single-type constituent component.

In contrast to their work in 2001a and 2005, Aksoy and Gupta (2001b) considered uncertain disassembly yields of a single-type constituent component in a two-stage remanufacturing system. The focus was to examine the trade-offs between increasing the number of inventory buffers and increasing the capacity of remanufacturing stations.

Similarly, Ferrer (2003) has also assumed uncertain disassembly yields of a single-type constituent component in a two-stage (disassembly/reprocessing and reassembly) remanufacturing system, where disassembly and reprocessing yields has been aggregated and assumed as the remanufacturing yields. The general aim was to examine the trade-off between the availability of information on remanufacturing yields and the supplier lead times for delivering the replacement components. Specifically, the focus was to determine the optimal lot-sizes for disassembling remanufacturable items and purchasing replacement components, subjected to uncertain remanufacturing yields and supplier lead times.

Their results show that when the variance of remanufacturing yields increases, it is more beneficial to possess information on disassembly yields (prior to the disassembly process) than to organise short delivery lead times with the suppliers. This assumption of aggregated remanufacturing yields might have been adequate for their simplified remanufacturing model. However, this assumption of aggregated remanufacturing yields would probably be limiting for models with multiple-type constituent components, predominantly when the constituent components have a significantly different disassembly yields and remanufacturing efforts.

In contrast to Aksoy and Gupta (2001a; 2001b; 2005) and Ferrer (2003), Ferrer and Ketzenberg (2004) have assumed uncertain disassembly yields of multiple-type constituent components. Comparable to their earlier work, Ferrer and Ketzenberg (2004) evaluated the trade-off case between the limited information on remanufacturing yields and potentially long supplier delivery lead times for the replacement components. Nonetheless, their current study considered two-types of constituent components, where remanufacturing yields of these two-types of constituent components are significantly different. Even though the criterion of product structure has been improved, the criterion of uncertain disassembly yields of each type constituent component is not completely improved because the actual disassembly yields of each constituent component are not modelled.

On the contrary, Tang et al. (2007) has assumed a better criterion of uncertain disassembly yields of multiple-type constituent components than that implemented by Ferrer and Ketzenberg (2004). Specifically, Tang et al. (2007) assumed uncertain disassembly yields of two-type constituent components in a three-stage system for remanufacturing high value automotive engines. In this three-stage remanufacturing system, the reprocessing stage of constituent components is substituted by outside procurement for the replacement components. The decision-making issue was planning for disassembly process and outside procurement activity, when remanufacturing process is subjected to uncertain disassembly yields of constituent components and stochastic supplier delivery lead times. Their results show that in spite of increasing the probability of a component being good, the planned disassembly and procurement lead times, as well as the operational cost remain unchanged.

In the preceding work (Aksoy and Gupta, 2001a; 2001b; 2005; Ferrer, 2003; Ferrer and Ketzenberg, 2004; and Tang et al., 2007) the criterion of uncertain disassembly yields of multiple-type constituent components have been assumed in remanufacturing systems with multiple-stages. In most cases, such remanufacturing systems with multiple-stages are mainly operated by OEMs or contract-remanufacturers, where the operational objective is to produce remanufactured products or components. To this end, it can be established that there has been limited assumption of uncertain disassembly yields of constituent components as essential criterion in the field of remanufacturing.

Surprisingly, there has been extensive assumption of uncertain disassembly yields of constituent components in the field of product recovery. Similar to remanufacturing systems, product recovery systems involve receiving used products that originate either from the waste or market streams, which are then disassembled into their respective constituent components. However, unlike remanufacturing systems, product recovery systems mainly involve recovering constituent components that are graded as good and recycling constituent components that are graded as bad; therefore components reprocessing are not required.

To date, the criterion of uncertain disassembly yields of constituent components has been widely assumed in models of product recovery systems. In such product recovery system the production planning issue is determining the optimal procurement quantity of used products and disassembly quantity of remanufacturable items, in order to obtain the desired quantity of good constituent components. This planning issue has been addressed in numerous works, some of which are found in Gupta and Taleb, 1994; Taleb and Gupta, 1997; Lambert and Gupta, 2002; Lee and Xirouchakis, 2004; Inderfurth and Langella, 2006; Jayaraman, 2006; Kim et al., 2006a; Kim et. al., 2006b; Kongar and Gupta, 2006; Langella, 2007 and Barba-Gutierrez et al., 2008.

2.3.3 Reprocessing efforts of constituent components

As established in subsection (2.2.3), regardless of their origins, used products exhibit uncertain quality conditions, therefore it cannot be neglected that each constituent component would require a different set of reprocessing process (hence different reprocessing time), even for the same type of constituent components. It has also been established in subsection (2.2.4), that for each constituent component the actual number of reprocessing processes and times that are necessary to restore the component to its original condition, depends on the quality of each constituent component (even for the same type of components).

Furthermore, as established, the start of a reassembly process, particularly for the RMTO strategy, mainly depends on the availability of relevant constituent components (remanufactured and replacement components). For these reasons, modelling and analysis of remanufacturing systems have to incorporate the criterion of different and uncertain reprocessing efforts (processes and times) of each constituent component.

For the majority of studies reviewed so far, the criterion of uncertain and different reprocessing efforts of constituent components has been predominantly neglected. Nevertheless, this criterion has been extensively assumed in studies that concentrate on remanufacturing activity at the shop-floor level. In particular, these studies have evaluated the performances of shop-floor control mechanisms under conditions of uncertain and different reprocessing efforts of constituent components.

It is important to note that this thesis excludes remanufacturing activity at the shop-floor control level, however, it is crucial to acknowledge that a criterion of uncertain and different reprocessing efforts of constituent components has been widely assumed in studies that can be found in Guide Jr (1995); Guide Jr (1996); Guide Jr (1997); Guide Jr and Srivastava (1997a); Guide Jr and Srivastava (1997b); Guide Jr and Spencer (1997); Guide Jr et al. (1997a), (1997b), (1997c); Guide Jr and Srivastava (1998); Guide et al. (1998); Guide et al. (2005) and Hou and Zhang (2005).

2.3.4 Key stages and processes of remanufacturing

As discussed and established in subsection 2.2.4, remanufacturing process typically consists of four key stages, namely, inspection, disassembly/inspection, components reprocessing/replacement and reassembly. Moreover, it has also been established that the output from one stage becomes an input to the next stage. To demonstrate, disassembled constituent components, the output from the disassembly stage becomes an input to the reprocessing/replacement stage, which then provides an input to the reassembly stage.

Given the uncertain quality conditions of used products and the highly inter-dependent nature of the key remanufacturing stages, it is important that modelling and analysis of remanufacturing systems has to incorporate the criterion of multiple-key remanufacturing stages and their inter-dependency. However, as shown by the review of existing studies in subsections (2.3.1 to 2.3.3), a criterion of multiple-key remanufacturing stages and their inter-dependency has been broadly neglected by most of these studies, with the exception of Aksoy and Gupta (20001a), Aksoy and Gupta (2005) and Tang et al. (2007).

As discussed, Aksoy and Gupta (2001a) and Aksoy and Gupta (2005) have assumed multiple-key remanufacturing stages and their inter-dependency in models of a three-stage remanufacturing system. However, these models of remanufacturing systems were still inadequate because the criterion of multiple-type constituent components (see subsection 2.3.5) has been mistreated. Similarly, in a study by Tang et al. (2007), their model of remanufacturing system is still inadequate because the criterion of uncertain and different reprocessing efforts of constituent components has not been explicitly assumed.

2.3.5 Product structure of used products

Often, in the real-world, remanufacturing processes involve reprocessing multiple-type of constituent components, which is typical in the RMTO strategy, where customers sent their used products for remanufacturing and request the same unit back. In this situation, remanufacturing has to preserve the identity of used products by reprocessing as many as possible of the multiple-type constituent components; in this case, replacements of the constituent components are executed as the last option. To give an example, remanufactured printer & photocopiers that are produced by Fuji Xerox Australia, contain up to 97% of remanufactured components (Fuji Xerox Australia, 2007a). In a different example, Steinhilpher (1998) reported that remanufacturing of used automotive parts, such as alternators, frequently involve reprocessing multiple-type of constituent components.

Consequently, it is important that modelling and analysis of remanufacturing systems have to incorporate the criterion of reprocessing multiple-type of constituent components, particularly for customer driven remanufacturing process. However, as can be established from the previous subsections (2.3.1 to 2.3.3), the criterion of reprocessing multiple-type of constituent components has been mostly ignored. This probably results from a common assumption that remanufacturing systems are operated according to a remanufacture-to-stock strategy, with the exception of Tang et al., 2007.

2.3.6 Analysis technique of remanufacturing systems

The majority of studies discussed in the previous subsections (2.3.1 to 2.3.3) have treated remanufacturing activities as a set of logical and quantitative relationships. In this case, mathematical equations have been applied to represent the operation of remanufacturing systems (i.e., mathematical models of remanufacturing systems). For such mathematical models, the behaviours of remanufacturing systems of interest are studied and evaluated through manipulation of the mathematical equations.

This technique, which involves mathematical equations might has been sufficient and effective when the activities within a system of interest are relatively simple. For instance, the inventory lot-sizing problem in a hybrid remanufacturing-manufacturing system has been mainly modelled and analysed via a mathematical model, where the remanufacturing/manufacturing activities have been predominantly aggregated into a single stage and characterised by either deterministic or stochastic costs and lead times.

Nevertheless, remanufacturing systems are uncertain and complex in nature due to the presence of several unique characteristics, which have to be considered and properly incorporated into models of remanufacturing systems. For these reasons, a more powerful technique than mathematical modelling is necessary in order to effectively model and analyse remanufacturing systems with unique characteristics. In this context, the application of simulation techniques has presented an alternative method to analyse the uncertain and complex natures of remanufacturing systems. Simulation techniques have proven to be useful for analysis of different system configurations and/or alternative operating procedures for complex manufacturing systems under uncertainty (Li et al., 2009).

2.4 Principles of simulation of remanufacturing operations

2.4.1 Fundamental of modelling techniques and simulation concepts

In general, the study of a system can be achieved through the application of one or a combination of modelling techniques, as illustrated in Figure 2.3. For some situations, e.g., the evaluation of inventory control policies of a supermarket can be achieved by conducting experiments directly with the actual system. However, for many situations it is too difficult, costly or even impossible to conduct experiments with the remanufacturing lines. Thus, the remanufacturing lines can only be studied through experimentation with a model of the remanufacturing lines, which serves as a substitute for studying the actual remanufacturing lines.

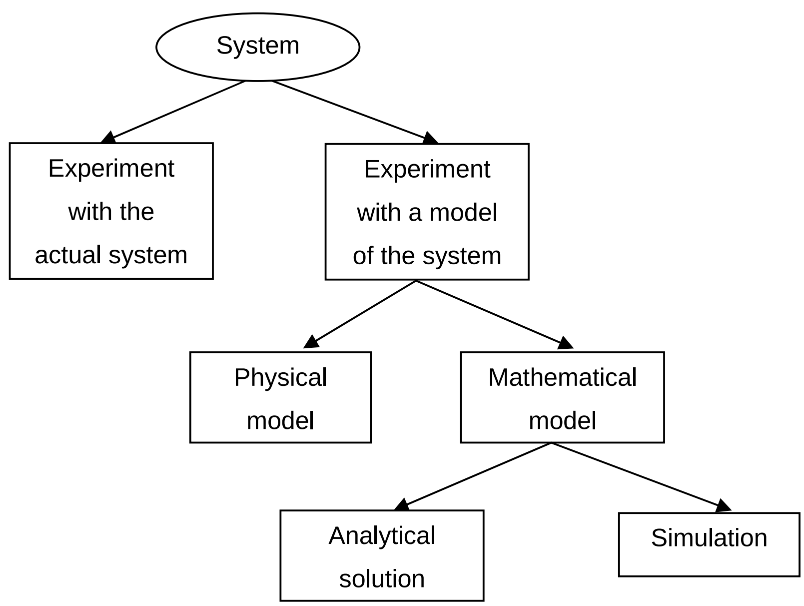


Figure 2.3. Techniques for modelling and study of a system (adapted from Law and Kelton, 2000)

For most engineering systems, their corresponding models are principally built based on some logical and quantitative relationships (i.e. mathematical equations), in which the models of systems are represented by some mathematical equations. This technique, which is universally known as mathematical modelling, typically involves manipulating the mathematical equations with the purpose of studying the behaviour of the mathematical model and hence the system that it is representing. Some mathematical models are quite simple, therefore, it is possible to use the equations and quantities to obtain an exact, analytical solution. Yet, for many complex engineering systems, their valid mathematical models are themselves complex, which would prevent any possibility of an analytical solution.

For complex engineering systems, their models have to be studied by means of simulation. Simulation as defined in this thesis refers to *"the imitation of the operation of a real-world processes or systems over time, usually on a computer with appropriate software"* (adapted from Banks (1998a) and Kelton et al., (2007)). This technique generally involves generating an artificial history of the systems and observing the process over time in order to infer the operating characteristics of the real-systems that are represented.

Simulation models of real-systems mainly consist of nine major facets (Law and Kelton, 2000): (a) entities, (b) global variables, (c) resources, (d) queues, (e) statistical accumulators, (f) events, (g) simulation clock, and (h) starting and stopping rule.

(a) Entities-Entities are “players” that move around, change status, affect and they themselves are affected by other entities and the state of the system, and affect the output performance measures. Entities are created, moved around for a while, and then are disposed of as they leave. Some entities never leave but just keep circulating in the system. In this thesis, entities are created to represent used products to be remanufactured, customers with demand for remanufactured products, replacement components for scrap components and personnel to monitor and control the production activity.

(b) Attributes–An attribute defines a characteristic that is employed to individualize entities, group several entities or select a specific entity. For an attribute that is employed to group several entities, a specific value is attached to all the group members. Some examples of attributes that have been defined in this thesis are *Demand*, *Arrival time*, and *Tolerance*.

(c) (Global) Variable-Variables refer to pieces of information that reflect some characteristic of a system, regardless of the number and kinds of entities present. There can be many different variables in a model, but each one is unique. Unlike attributes, variables are not tied to any particular entity, but rather pertain to the system at large. Variable are accessible by all entities, and many can be changed by any entity. Some examples of variables that have been defined in this thesis are *UPT1*, *Inventory* and *Scrap*.

(d) Resources-Resources correspond to personnel, equipment or space in a storage area. For certain situations entities might compete with each other for service from resources, where an entity seizes unit of available resources and releases the resources once it has finished using the resources. In this thesis, some of the resources names that have been defined are *UPsInspection*, *DisassemblyT1* and *DisassemblyT2*.

(e) Queues-A queue defines a place for an entity to wait, when it could not move forward, perhaps because it needs to seize a unit of a resource that is tied up by another entity. Some examples of queue names that have been defined in this thesis are *HoldH.Queue*, *Remanufacture?.Queue* and *HoldA. Queue*.

(f) Statistical accumulators-Statistical accumulators, which are initially set to zero, serve to keep track of certain variables when the simulation proceeds. In this thesis, statistical accumulators have been defined to keep track the total number of: (i) incoming used products, (ii) incoming customers, and (iii) total numbers of scrap component.

(g) Events-An event defines something that happens at an instant of simulated time which might change attributes, variables or statistical accumulators. Some examples of events that are encounter in this thesis are the arrival of a used product, arrival of a customer and departure of a satisfied customer.

(h) Simulation clock–Unlike real time, the simulation clock lurches from the time of one event to the time of the next event that is scheduled to happen. The current value of time in the simulation model is held in the variable called *simulation clock.*

(i) Starting and stopping rules–The starting and stopping rules determine how the simulation starts and stops and are determined and set by the modeller. In this thesis simulation is specified to stop once the simulation clock has reached a prescribed time.

Another important concept of simulation that relates to modelling and analysis of remanufacturing systems is the classification of simulation models. Simulation models of real systems (hereafter called simulation models) have been mainly classified along four different dimensions (Law and Kelton, 2000), namely, (a) static/dynamic models, (b) deterministic/stochastic models, (c) discrete/continuous models, and (d) terminating/non-terminating models.

(a) Static/dynamic simulation models-Static simulation models represent systems at a particular time, or represent systems in which time is not considered. Monte Carlo model, as an example, employs random numbers to evaluate complex equations and is typically implemented for military application (Hakala, 1995). Dynamic simulation models, on the contrary, represent systems which evolve over time, such as the conveyor systems in a factory.

(b) Deterministic/stochastic simulation models-Deterministic simulation models do not contain any random component and the output is "determined" once the set of input quantities and relationships in the models have been specified, although a great deal of computer time is involved. Nevertheless, for many systems, the models have at least some random input components, thus resulting in stochastic models (e.g. queuing and inventory systems). The output from stochastic simulations model is itself random, thus, it has to be treated as an estimate of the true characteristics of the models.

(c) Discrete/continuous simulation models-Discrete-event simulation models represent systems, where the variables change instantaneously at separate points in time. Continuous simulation models, on the contrary, represent systems where the variables change continuously with respect to time. Depending on the specific aims of the study, a discrete or continuous simulation model can be applied. In this thesis, discrete event simulation models have been assumed and constructed because the variables (e.g. *Inventory*, *UPT1*, etc) have been treated as changing instantaneously at separate points in time.

(d) Terminating/non-terminating simulation models-Terminating simulation models refer to models where there is a "natural" event that specifies the length of each replication. The event often occurs at a time point when the system is "cleared out" or at a time point after which no useful information is obtained. This is normally specified before executing any runs and the time of occurrence of an event for a run may be random variable. For non-terminating simulations there is no natural event to specify the length of run. This frequently happens when designing a new system or changing an existing system and the interest is the behaviour of the system at a steady-state, when it is operating "normally".

For such simulation models, the measure of performance is said to be a steady-state parameter of some output stochastic process. In this thesis, the simulation models are treated as non-terminating because these models have not represented or resembled any current real-world remanufacturing systems.

2.4.2 Vital roles of simulation in remanufacturing operations

It has been broadly recognised that the greatest role of simulation (within the field of manufacturing) is creating the opportunity for managers/engineers to attain a system-wide view of the effect of changes in the system parameters on the performance of manufacturing system (Carrie, 1988; Ross, 1997; Banks, 1998a; Law and Kelton, 2000; Chung, 2004; Werner, 2006; Kelton et al., 2007; Altiok and Melamed, 2007). Unquestionably, this role would be also applicable to study of remanufacturing systems. Remanufacturing systems, as argued and established, are uncertain and complex in nature due to the inherently occurring unique characteristics. Consequently, the application of simulation techniques would present an opportunity to assess a system-wide view of the effect of uncertain process variables, such as inspection yields of used products on a system's performances (e.g. throughput, processing time or finished products inventory).

Within the operations of manufacturing systems, simulation plays a vital role in three major areas (Law and Kelton, 2000), which are also relevant within the operation of remanufacturing systems. Firstly, simulation is vital for evaluating the requirement and quantity of equipment and personnel necessary when companies are planning to: (i) change the product volume or mix, (ii) evaluate the effect of new equipments on existing manufacturing line, (iii) evaluate the location and size of inventory buffers, or (iv) evaluate the number of operating shifts.

Secondly, simulation is vital for evaluating companies' performance, for instance, analysis of throughput and flow-time through the system. Finally, simulation is vital for evaluating a range of operational procedures, which might include proposed policies for: (i) dispatching orders to the shop floor, (ii) choosing the batch sizes, (iii) loading parts at a work station, or (iv) sequencing parts through the work stations.

Wide recognition of the above mentioned vital roles have lead to numerous successful applications of simulation techniques in various aspects of manufacturing, particularly in the design and operation of manufacturing systems. Rohrer (1998), for instance, has described and documented three successfully implemented simulation-based manufacturing projects for: (i) reconfiguration of manufacturing lines for refrigerators, (ii) introduction of new semiconductor wafer fabrication facility, and (iii) evaluation of manufacturing process for a new 777 Boeing aircraft.

In another case, Ulgen and Gunal (1998), has discussed the application of simulation in the design and operation of cars and trucks assembly plants and automotive components manufacturing plants. Gupta and Arasakesari (1991), Graehl (1992), and Evans and Biles (1992) have documented more cases of successfully implemented simulation-based manufacturing projects.

In addition to manufacturing, simulation techniques have been widely applied in management and improvement of the service industry. In the healthcare industry for example, a simulation model has been developed and implemented as a tool for health professionals to understand the process for conducting a randomized clinical trial (Eldabi et al., 2008). Specifically, the simulation model has enabled health professionals to establish some crucial variables that might affect the cost-effectiveness behaviour of a particular drug therapy. In other situations, simulation techniques has been applied as a tool to assess and improve the performance of the Japanese banking industry (Lauhery, et al., 1998).

In addition to manufacturing and service industries, simulation techniques have been widely applied as a decision-making tool in the defence sector. This typically involves simulation models as an aid to decision-making in military problems, such as war-game, acquisition, logistics, maintenance and communications. For instance, a simulation model has been developed and utilized as a tool to plan and evaluate the maintenance program and policies for the U.S. coast guard helicopters that are involved in search and rescue operations (Vigus, 2003).

In another case, a simulation model has been developed and implemented as a tool to plan and evaluate a combat mission strategy for a naval special warfare scenario (Hakala, 1995). Even though the literature have indicated that simulation techniques have been widely applied within the defence sector, a limited existence of published reports are associated with issues regarding confidentiality. Still, research by Shyong (2002), Kang and Roland (1998) provide more examples of the application of simulation techniques within the defence sector.

It is imperative to distinguish that the successful applications of simulation techniques for studying real-world systems or processes depends on two critical issues: (i) the modeller's skill and time, and (ii) the model's input and output (Musselman, 1998; Law and Kelton, 2000; Chung et al. 2004). Firstly, skills that are indispensable for constructing simulation models have to be acquired through special trainings and subsequent practical experience, which accumulates over a period of time. Consequently, if two competent individuals are to construct models of the same system, the resulting simulation models would be similar, but it is unlikely that these models would be the same. Furthermore, simulation modelling and analysis tasks are often expensive and time consuming.

Secondly, good collection of data are necessary for constructing simulation models, otherwise, the simulation models would be ineffective for the purpose of the study. Similarly, careful interpretations of the output data from the simulation models are crucial because these outputs are only an estimate of a model's true characteristics. For these reasons, recognition and appropriate treatment of the above mentioned issues are important to ensure successful simulation-based remanufacturing projects.

2.4.3 Construction platform for simulation of remanufacturing operations

Simulation, as defined earlier, is the "*imitation of the operation of a real-world processes or systems over time, usually on a computer with appropriate software*". This definition introduces another important underlying principle of simulation techniques, namely the usage of a computer with appropriate software, as the platform for constructing the simulation models.

In the early phase of digital computer, simulation models have been constructed based on the general-purpose procedural languages, such as FORTRAN (Kelton, et al., 2007). This technique was highly customizable and flexible with respect to the types of models and possible manipulations, but also tedious and susceptible to mistake because models have to be coded from scratch over time. Then with the advent of cheap and high-powered computers, special-purpose simulation languages, such as, GPSS, Simscript, SLAM, and SIMAN emerged and presented a much better technique for constructing various types of simulation models. However, these languages are still time consuming to learn and apply effectively (Kelton, et al., 2007).

At present, there are numerous high-level simulation language products that can be employed as a platform for constructing the simulation models. These platforms which are typically operated by intuitive graphical user interfaces, menus, and dialogs, can be further classified either as a general-purpose simulation platform or a manufacturing-oriented simulation platform (Banks, 1998b). General-purpose simulation platforms are utilized to construct simulation models which are targeted to solve nearly any discrete simulation problem, which include GPSS/H, SLX, SIMSCRIPTII.5, AweSim, SIMPLE++ and Extend.

By contrast, manufacturing-oriented simulation platforms, are utilized to construct simulation models of manufacturing and material handling systems, which include ProModel, AutoMod, Taylor II, WITNESS, FACTOR/AIM, Arena, and Extend+Manufacturing. In this thesis, the application of a high-level simulation language product, Arena 10.0, (Rockwell Automation, 2005) as the principal platform for constructing the simulation models (of remanufacturing systems) has been primarily due to its suitability and availability to the research project.

In spite of the types of simulation platform, there are some desirable features that are associated with a good platform for constructing simulation models. In general, these features can be categorized into six aspects, namely input, processing, output, environment, and cost (Banks, 1998b). The input aspect relates to a set of features that allow easy interaction between the user and the platform, as well as between the platform with other software like CAD. For example, a good feature includes the capability to allow a user to pick-and-click on the modelling features. The processing aspect refers to a set of features that are associated with executing or running the simulation model, e.g. for a steady-state analysis, the simulation platform must have a feature that includes the ability to reset the collected statistics to zero.

Regarding the output aspect, desirable features include the capability to allow data, events or system variables to be written to files, which are then imported into a spreadsheet or database program. Features that include an animation capability in terms of the quality of pictures, smoothness of movement and probability of remote viewing are some examples of the desired environment aspects. Finally, the cost aspect is also very important because some simulation platform could be really expensive to purchase.

2.4.4 Life-cycle of remanufacturing simulation projects

As discussed, successful constructions of simulation models and their applications in remanufacturing operations are very challenging task because there are many crucial issues to consider. Consequently, construction of simulation models has to follow a model/system development life-cycle concept to ensure that such simulations models are good representations of the real-systems and their successful applications. The model/system development life-cycle concept has been widely applied in the development and application of models that are other than simulation. For instance, the application of model/system development life-cycle concept for the development of information system can be found in Stefanou (2003).

Figure 2.4 illustrates the model/system development life-cycle concept that has been applied to construct and analyse the simulation models defined in research objectives 2, 3 and 4. As shown in figure 2.4, the life-cycle concept consists of nine major phases, where the output from phase 3 and phase 5 might result in repeating the previous phases. A complete discussions of activities that are involve in phase 1 to phase 8 are provided in chapter 4, while discussions on the output from phase 9 are provided in chapter 5.

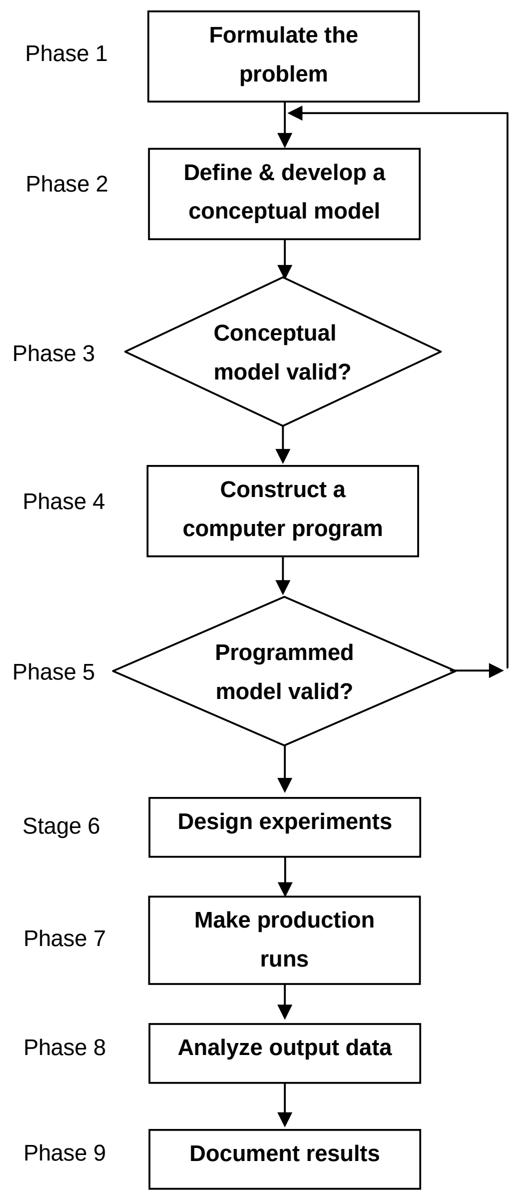


Figure 2.4: The life-cycle of simulation projects on remanufacturing system (adapted and modified from Law and Kelton, 2000).

2.5 Summary

This chapter has discussed literature that is important for this research project. Based on the preceding discussions it is apparent that:

(a) Remanufacturing has become an important production alternative to many companies, which are currently operating in a volatile environment.

(b) Remanufacturing systems are uncertain and complex in nature due to the occurrence of several unique characteristics, which has been identified as follows:

   (i) Uncertain quality conditions of used products,
   (ii) Uncertain quantities of used products available for remanufacturing,
   (iii) Varying inspection yields of used products,
   (iv) Varying disassembly yields of constituent components,
   (v) Varying reprocessing efforts of constituent components,
   (vi) Multiple-key remanufacturing stages with inter-dependency between stages,
   (vii) Multiple-types of constituent components,
   (viii) Matching and reassembly the same set of constituent components into final products in customer driven environment,
   (ix) Balancing customers demand with availability of used products to prevent excess inventory build-up and maximise customer service level.

(c) The above mentioned unique characteristics (b) have to be treated as a set of essential criteria in modelling and analysis of remanufacturing systems.

(d) Numerous existing studies on remanufacturing systems have failed to treat the above mentioned unique characteristics as a set of essential criteria in modelling and analysis of remanufacturing systems.

(e) A more powerful technique is necessary for modelling and analysis of remanufacturing systems considering the criteria stated in (b) above.

(f) The application of simulation techniques would become an enabling tool in modelling and analysis of remanufacturing systems considering the criteria stated in (b) above.

Chapter 3

An Integrated Inventory Lot-Sizing Model in a Hybrid Remanufacturing-Manufacturing System Considering Variable Remanufacturing Lot-Sizes

3.1 Introduction

This chapter discusses the development and analysis of a mathematical model that addresses inventory lot-sizing problems in a hybrid remanufacturing-manufacturing system with varying remanufacturing fractions. Section 3.2 provides a literature review of the existing inventory lot-sizing models in a hybrid remanufacturing-manufacturing system. Then section 3.3 discusses the development of a new integrated inventory lot-sizing model with variable remanufacturing lot-sizes.

Section 3.4, discusses a benchmark model that has been selected for the purpose of a comparison study. Section 3.5 discusses some case studies that examine: (i) behaviour of the major decision variables, (ii) benefits of the new inventory lot-sizing model, and (iii) sensitivity of the major decision variables with regards to changes in system parameters. Finally section 3.6 reiterates the purpose and content of this chapter.

3.2 Inventory lot-sizing model in a hybrid remanufacturing-manufacturing system

As discussed in chapter 2, the emerging trend of strict environmental regulations, increasing customer awareness of green environment and economical benefits have put more pressure on manufacturers to remanufacture their own used products. This has resulted in more manufacturers having to integrate remanufacturing activity into the normal manufacturing operation (hence a hybrid remanufacturing-manufacturing system). In such a hybrid remanufacturing-manufacturing system, used products provide another input resource for the production of new products.

However, given that the quantities and quality conditions of used products are uncertain, a major problem would be to balance the quantities of remanufactured and newly manufactured products in order to meet customer demand and minimise total cost. This problem essentially involves determining the optimal remanufacturing lot-size (Q_r) of used products and manufacturing lot-size (Q_m) of new products that minimises the total cost per unit time.

The economic order quantity model has been widely applied in managing and controlling the inventory of remanufacturables and serviceables in a hybrid remanufacturing-manufacturing system. The earliest work on inventory systems with remanufacturing, in which economic order quantity concept was applied could be found in Schrady (1967). As argued in Schrady (1967), it is better to hold inventory of remanufacturable items rather than serviceable items. This is primarily because the cost of remanufacturable items after being remanufactured is still cheaper than the cost of newly manufactured products. Therefore, in Schrady (1967) it was assumed that a control policy supplying 100% of demand from remanufactured products until the supplies of remanufacturable items drops to zero. It has also been assumed that there is one manufacturing lot that alternates with several remanufacturing lots, n; i.e., a policy of $P(1,n)$.

In Mabini et al. (1992), the model proposed in Schrady (1967) was extended in two ways. Firstly, it considered that for a single item model, a shortage or stock-out of the serviceable items inventory could be allowed. Secondly, the single item model with no shortage was modified to take into account multiple items competing for a common remanufacturing capacity. For both models, a numerical solution was proposed for obtaining the optimal value.

A different model from Schrady (1967) was analysed in Richter (1996a) and Richter (1996b). It was assumed that there was no continuous flow of used products to the manufacturer. Used products are collected in a 'second shop' and brought back to the 'first shop' (manufacturer) at the end of each 'collection interval'. This collection interval coincides with the production cycle in the first shop. Remanufacturing of used products was postponed until the end of the collection interval. In addition, a constant disposal rate of used products was allowed. The formula for the total average cost was determined, however, simple expressions for calculating the optimal lot-sizes were not attained.

The model developed in Schrady (1967) was also generalised in two directions in Teunter (2001). Firstly, it considered that several manufacturing lots (m) alternate with several remanufacturing lots (n); i.e., a policy of $P(m,n)$. It also considered that a variable disposal rate for used products takes place after the nth remanufacturing lot and over a certain period of time. Secondly, it assumed that different holding cost rate apply for remanufactured and newly manufactured products. The closed form expressions for optimal manufacturing and remanufacturing lots was obtained for a given remanufacturing fraction for two types of policies, $P(1,n)$ and $P(m,1)$.

Furthermore, it was shown in Teunter (2001) that having a policy of $P(m > 1, n > 1)$ would not always lead to an optimal solution, thus it was suggested that a policy of $P(1, n)$ or $P(m,1)$ might be selected. Recently, a policy of $P(m, n)$ developed in Teunter (2001) was generalised in Choi et al. (2007) in which the sequence of setups for the remanufacturing process and orders for newly manufactured products within one cycle were treated as decision variables.

The models reviewed so far have assumed a planning situation where remanufacturing process is carried out without being time consuming. This assumption is justified whenever the time needed to process a remanufacturing lot is only a very small fraction of the time period during which demand can be satisfied from this lot. The first study to consider a finite remanufacturing rate is that by Nahmias and Riveria (1979). They assume a finite remanufacturing rate greater than the demand rate, a situation where expensive items are being remanufactured.

Similar to Schrady (1967), Nahmias and Riveria (1979) derive an optimal order quantity for the manufacturing and remanufacturing for a set of policy that alternates one manufacturing lot and a variable number of remanufacturing lots. They conclude that incorporating a finite remanufacturing rate leads to a reduction in the average inventory level of both remanufacturable and serviceable items, thus resulting in a reduction of the corresponding holding cost for both inventories. Their results also imply that individual unit should be conveyed between the remanufacturing department and serviceables warehouse.

Koh et al. (2002) also assume limited remanufacturing capacity and remanufacturable items are gradually transformed into serviceable items. Their study is more general than that of Nahmias and Riveria (1979), as they allow remanufacturing rate to be both smaller and larger than the demand rate. They propose a numerical search procedure to simultaneously determine the optimal number of lot n for remanufacturing and m for manufacturing.

Teunter (2004) considers a more general model than those of Nahmias and Riveria (1979) and Koh et al. (2002). In their model, Teunter (2004) assume a finite remanufacturing rate as well as finite manufacturing rate. Finally, he proposes a heuristic method for ensuring the number of manufacturing/remanufacturing lots and manufacturing/remanufacturing lot-sizes are discrete. However, as argued by Konstantaras and Papachristos (2007), this approach is partly heuristic and therefore there is no guarantee for the quality of the so obtained solution, although numerical test indicates that it behaves very well in most cases. Therefore, Konstantaras and Papachristos (2007) present an exact method which leads to the optimal policy, i.e., leads to integer values for n and m.

In previous models, it was assumed that there are no shortages in serviceable items. The practice of permitting shortages in serviceable items is usually implemented by original equipment manufacture involved with used product remanufacturing. Konstantaras and Papachristos (2006), in their study: (i) allow a complete backordering of shortages, and (ii) consider a finite manufacturing and remanufacturing rate, both being greater than the demand rate, which in turn is greater than the return rate. They work within two set of policies: (i) one set-up in the remanufacturing shop alternates with a variable manufacturing lots for new products, $P(m,1)$, and (ii) one manufacturing lot for new products alternates with a variable remanufacturing lots, $P(1,n)$. The result of their numerical analysis shows that for both policies, a model with backordering is superior than a model that does not allows backordering (introduced in Teunter, 2004).

Similar to Konstantaras and Papachristos (2006), Wee et al. (2006) also consider shortages in serviceable items. In this work, their objective was to determine the optimal inventory level for remanufacturables items and the corresponding total cost. For this problem they propose a solution method that consists of a mixed of numerical analysis and search procedure because a closed form solution was not feasible. Results of their analysis suggest that a model with backordering provides an improvement in cost when compared to a model introduced in Koh et al. (2002).

Unlike all inventory lot-sizing models reviewed so far, a model introduced in Tang et al. (2005) is a pioneer model that considers stochastic lead-times for remanufacturing and manufacturing process. In such model, they consider: (i) several remanufacturing lots that alternates with several manufacturing lots in a cycle, and (ii) stochastic lead-times for remanufacturing and manufacturing process, where these are reflected in a stock-out cost of remanufactured items and newly manufactured items. For this problem, they provide a solution procedures and optimisation conditions to determine control parameters for several different cases.

In all inventory lot-sizing models reviewed earlier, it was assumed that used products are accumulated and stored for a certain period of time prior to processing the first remanufacturing lot (figure 3.1). This was necessary to accomplish a constant remanufacturing lot-size (Q_r). However, it was shown in Minner (2000) and Minner and Lindner (2004) that it was not always optimum to implement a constant remanufacturing lot-size.

Furthermore, as illustrated in figure 3.1, a policy with constant remanufacturing lot-sizes would result in delay of remanufacturing process and a carryover of remanufacturables stocks after each remanufacturing process. Consequently, delay of remanufacturing process would lead to a loss of responsiveness to customer demand, particularly, when manufacturing of new products involves a long lead-time.

Carryover of remanufacturables stock after each remanufacturing process would result in excess inventory, which could be costly to store when storage capacity is limited. In addition, as argued in Minner (2001), used products received after the final remanufacturing process have to be stored over the entire manufacturing interval until the next remanufacturing lot is started. Thus, there is a cost incentive to reduce the final remanufacturing lot-size in order to shorten the time interval between the final remanufacturing lot and the next remanufacturing.

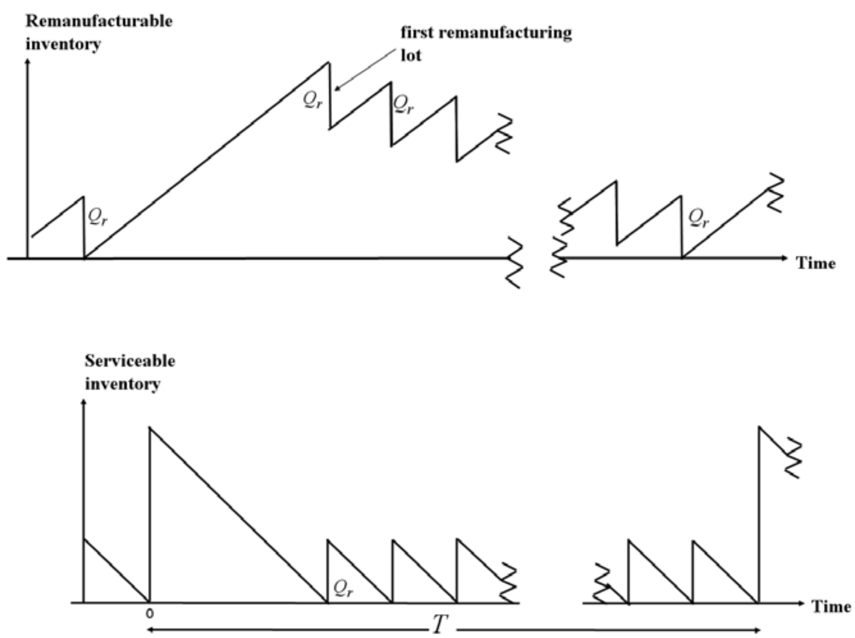


Figure 3.1: Remanufacturables and serviceables inventory profile in a hybrid remanufacturing-manufacturing system (adapted from Schrady, 1967)

Based on the previous argument, a new integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system considering variable remanufacturing lot-sizes is the focus of this chapter. It is noted that the optimal policy might be the case where several manufacturing lots alternating with several remanufacturing lots, however, as argued in Teunter (2004), such a complex policy would be difficult to implement in practice. Therefore, a new integrated inventory lot-sizing model that is developed and analysed in this chapter is restricted to a simple policy where one manufacturing lot alternates with several remanufacturing lots, i.e., a policy of $P(1,n)$.

3.3 A new integrated inventory lot-sizing model in a hybrid remanufacturing-manufacturing system

3.3.1 Model assumptions

The following common underlying assumptions have been applied to develop the new model:

(i) that the planning horizon of the system is infinite, i.e., time is modelled as a continuous variable $t \in [0,\infty]$.

(ii) that customer demand and return of used products are continuous (infinitely divisible items) and deterministic.

(iii) that demand rate is $\lambda > 0$ and return rate of used products is $r\lambda$, where return fraction, r is $r < 1$.

(iv) that used products may be either disposed of or remanufactured at a rate of $u\lambda$, where *u* is remanufacturing fraction and $0 \le u \le r$.

(v) that both serviceable and remanufacturable items are held in stock. In order to increase stock of serviceable items, additional new products may be manufactured or used products may be remanufactured at any time $t \in [0,\infty]$.

(vi) that manufacturing and remanufacturing processes are assumed to be instantaneous. Shortages are not permitted.

The following costs are incurred:

- Setup costs for manufacturing, "K_m".
- Setup cost for remanufacturing, "K_r".
- Disposal cost for scrap used products, "c_d".
- Manufacturing cost for new products, "c_m".
- Remanufacturing cost for used products, "c_r".
- Holding costs per item per unit time for remanufacturable items, "h_n", remanufactured items, "h_r" and newly manufactured products, "h_m".

3.3.2 Model development

Figure 3.2 illustrates the evolution of inventory under a policy assumed for the new model. The upper graph gives the profile of remanufacturables inventory, while the lower graph gives the profile of serviceables inventory.

Referring to the upper graph, $Q_{r1}, Q_{r2},.., Q_n$, denote remanufacturing lot-sizes for used products, where Q_{r1} and Q_n correspond to the first and last lot-size, respectively. Furthermore, Q_{r1} and Q_n also correspond to the largest and smallest remanufacturing lot-sizes, respectively. The first remanufacturing lot-size, Q_{r1} is determined as $Q_{r1} = r\lambda t_1$, where $r\lambda$ is the returned rate of used products and t_1 is the accumulation time. Likewise, subsequent remanufacturing lot-sizes are also calculated as $Q_{r2} = r\lambda t_2$, and $Q_n = r\lambda t_n$. Once remanufacturing process is completed, each lot of remanufactured products is sent to serviceables inventory.

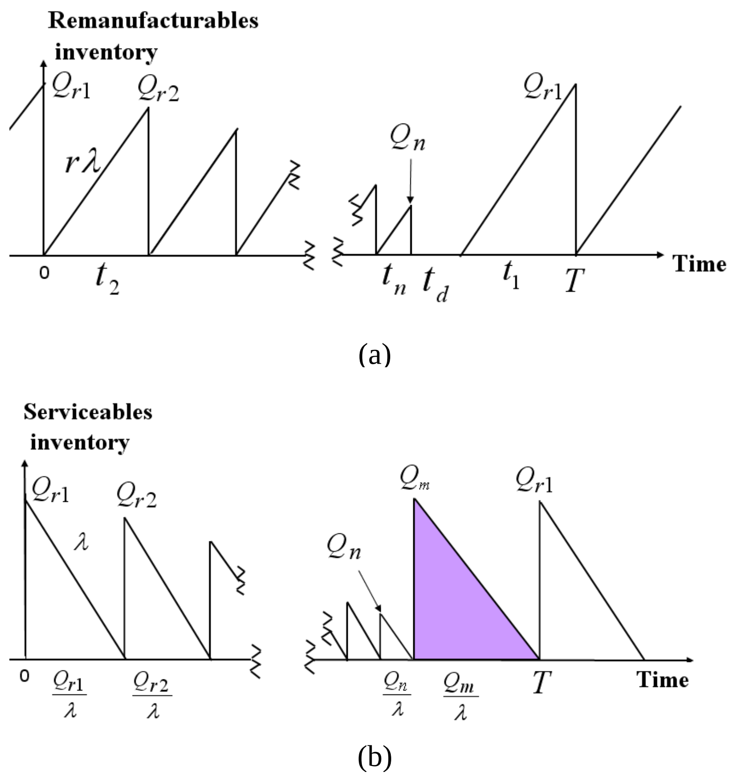


Figure 3.2: Remanufacturables and servicebles inventory profile in a hybrid remanufacturing-manufacturing system considering variable remanufacturing lot-sizes.

Referring to the lower graph, assume that at time $t = 0$, the first remanufacturing lot-size, Q_{r1} arrives at serviceables inventory. This lot-size, Q_{r1} is utilised as serviceable stocks to meet customers' demand at a rate of λ. Thus it would take a time of Q_{r1}/λ to deplete the first lot-size, Q_{r1} to zero. When the first lot-size, Q_{r1} is utilised as serviceable stocks, a second lot of used products, Q_{r2} grows at the remanufacturables inventory. After remanufacturing process, the second lot-size, Q_{r2} arrives at the serviceables inventory when the first lot-size, Q_{r1} is fully depleted to zero, $t_2 = Q_{r1}/\lambda$. Alternatively it can be shown that the second remanufacturing lot-size is $Q_{r2} = r^2 \lambda t_1$ and the relationship between t_2 and t_1 could be given as $t_2 = rt_1$.

Assuming that there are n number of remanufacturing lots per cycle, it is proven that $t_n = r^{n-1}t_1$ and $Q_n = r^{n-1}Q_{r1}$. When the last remanufacturing lot-size, Q_n is depleted to zero, a lot-size of newly manufactured products, Q_m arrives at the serviceables inventory and is utilised to meet customer demand over a period of Q_m/λ. Disposal of used products takes place after the nth remanufacturing lot is started and over a period of $t_d = [(r-u)/u]T$. At the end of the disposal period, used products start to accumulate again at remanufacturables inventory for a period of t_1 resulting in a quantity of first remanufacturing lot-size of $Q_{r1} = r\lambda t_1$.

The material flows at the serviceable inventory over a period of one cycle are illustrated in figure 3.3. In order to have a balance of material flows at the serviceable inventory, the relation expressed in eqn.(1) must hold.

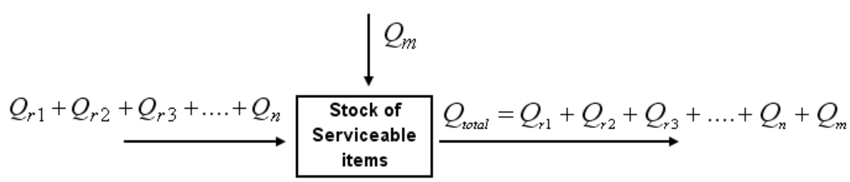


Figure 3.3: Material balance at the serviceables inventory

The remanufacturing fraction, u can be expressed as:

$$u = \frac{Q_{r1} + Q_{r2} + Q_{r3} + ... + Q_n}{Q_{r1} + Q_{r2} + Q_{r3} + ... + Q_n + Q_m} \qquad \text{Eqn.(1)}$$

Rewriting eqn.1 gives:

$$Q_m = \left(\frac{1-u}{u}\right)Q_{r1}\left(1 + r + r^2 + r^3 + ... + r^n\right) \qquad \text{Eqn.(2)}$$

If $B = \left(1 + r + r^2 + r^3 + ... + r^n\right)$, then $B = \frac{r^n - 1}{r - 1}$

Alternatively eqn.(2) can be written as:

$$Q_m = \left(\frac{1-u}{u}\right) Q_{r1} \left(\frac{r^n - 1}{r - 1}\right) \qquad \text{Eqn.(3)}$$

As determined earlier, $Q_{r1} = Q_n \left(\frac{r}{r^n}\right)$, then substituting this into eqn.(3) and after algebraic manipulation gives:

$$Q_n = Q_m \left(\frac{u}{1-u}\right)\left(\frac{r^n}{r}\right)\left(\frac{r-1}{r^n - 1}\right) \qquad \text{Eqn.(4)}$$

From the lower part of figure 3.2, the inventory cycle time, T is given as:

$$T = \frac{Q_{r1}}{\lambda} + \frac{Q_{r2}}{\lambda} + \frac{Q_{r3}}{\lambda} + ... + \frac{Q_n}{\lambda} + \frac{Q_m}{\lambda} \qquad \text{Eqn.(5)}$$

Rewriting $Q_{r2}, Q_{r3}, ...Q_n$ in terms of Q_{r1} gives:

$$T = \frac{1}{\lambda}\left[Q_{r1}\left(1 + r + r^2 + r^3 + ... + r^{n-1}\right) + Q_m\right] \qquad \text{Eqn.(6)}$$

Substituting $\left(1 + r + r^2 + r^3 + ... + r^{n-1}\right)$ with $\frac{r^n - 1}{r - 1}$ and after algebraic manipulation the inventory cycle-time can be expressed as:

$$T = \frac{Q_m}{\lambda(1-u)} \qquad \text{Eqn.(7)}$$

Referring to the upper part of figure 3.2, used products are disposed after the nth remanufacturing lot and for a period of $t_d = \frac{r-u}{r} T$ before being accumulated again for a period of t_1. Accordingly, during period of t_d and t_1 the final lot of remanufactured items, Q_n and a lot of newly manufactured products, Q_m must be utilised to meet customers' demand. Mathematically this situation can be expressed as eqn. (8).

$$\frac{Q_n}{\lambda} + \frac{Q_m}{\lambda} = \frac{r-u}{r}T + t_1 \qquad \text{Eqn.(8)}$$

Substituting for T , Q_n and after algebraic manipulation gives:

$$t_1 = \frac{Q_m}{r\lambda}\left(\frac{u}{1-u}\right)\left(\frac{r-1}{r^n-1}\right) \qquad \text{Eqn.(9)}$$

Analysis of the lower part of figure 3.2, reveals that the average number of remanufactured and newly manufactured products in the serviceable inventory over a period of one cycle is represented by the area under the curve. This is given as the sum of the areas of n unshaded triangles plus one shaded triangle.

If A_s represents the areas under the serviceables inventory curve, then:

$$A_s = \frac{1}{2}Q_{r1}\frac{Q_{r1}}{\lambda} + \frac{1}{2}Q_{r2}\frac{Q_{r2}}{\lambda} + ... + \frac{1}{2}Q_n\frac{Q_n}{\lambda} + \frac{1}{2}Q_m\frac{Q_m}{\lambda} \qquad \text{Eqn.(10)}$$

After algebraic manipulation, A_s can be represented as eqn.(11).

$$A_s = \frac{Q_{r1}^2}{2\lambda}\left(1 + r^2 + r^4 + ... + r^{(n-1)^2}\right) + \frac{Q_m^2}{2\lambda} \qquad \text{Eqn.(11)}$$

If $C = \left(1 + r^2 + r^4 + ... + r^{(n-1)^2}\right)$, then $C = \left(\frac{r^n-1}{r-1}\right)\left(\frac{r^n+1}{r+1}\right)$

Therefore eqn.(11) can be rewritten as:

$$A_s = \frac{Q_m^2}{2\lambda}\left(\frac{u}{1-u}\right)^2\left(\frac{r-1}{r^n-1}\right)\left(\frac{r^n+1}{r+1}\right) + \frac{Q_m^2}{2\lambda} \qquad \text{Eqn.(12)}$$

If A_{rm} and A_m denotes the area under the serviceable curve representing the remanufactured and newly manufactured products respectively then:

$$A_{rm} = \frac{Q_m^2}{2\lambda}\left(\frac{u}{1-u}\right)^2\left(\frac{r-1}{r^n-1}\right)\left(\frac{r^n+1}{r+1}\right) \qquad \text{Eqn.(13)}$$

$$A_m = \frac{Q_m^2}{2\lambda} \qquad \text{Eqn.(14)}$$

Analysis of the upper part of figure 3.2, shows that the average number of used products in remanufacturables inventory over a period of time is represented by the area under the curve. If A_R represents the area under the remanufacturables inventory curve, then;

$$A_R = \frac{r\lambda t_1 t_1}{2} + \frac{r\lambda t_2 t_2}{2} + \frac{r\lambda t_3 t_3}{2} + \ldots\ldots. + \frac{r\lambda t_n t_n}{2} \qquad \text{Eqn.(15)}$$

Through an algebraic manipulation gives:

$$A_R = \frac{r\lambda t_1^2}{2}\left(1 + r^2 + r^4 + \ldots r^{(n-1)^2}\right) \qquad \text{Eqn.(16)}$$

Substituting for t_1, $\left(1 + r^2 + r^4 + \ldots r^{(n-1)^2}\right)$ and after algebraic manipulation A_R can be expressed as:

$$A_R = \frac{Q_m^2}{2r\lambda}\left(\frac{r^n+1}{r+1}\right)\left(\frac{u}{1-u}\right)^2\left(\frac{r-1}{r^n-1}\right) \qquad \text{Eqn.(17)}$$

3.3.3 Total cost per unit time

The total cost per unit time for a policy $P(1,n)$ consists of remanufacturables inventory cycle-cost and serviceables inventory cycle-cost.

The remanufacturables inventory cycle-cost, consists of the following four components:

(i) The remanufacturing setup cost per unit time, $\dfrac{nK_r\lambda(1-u)}{Q_m}$.

(ii) The inventory holding cost per unit time, $\dfrac{h_n Q_m}{2r}\left[\left(\dfrac{u^2}{1-u}\right)\left(\dfrac{r-1}{r^n-1}\right)\left(\dfrac{r^n+1}{r+1}\right)\right]$

(iii) The remanufacturing cost per unit time, $c_r\lambda u$

(iv) The disposal cost of scrap used products per unit time, $c_d\lambda(r-u)$

The servicebles inventory cycle-cost consists of the following four components:

(i) The manufacturing setup cost per unit time, $\dfrac{K_m\lambda(1-u)}{Q_m}$

(ii) The inventory holding cost of remanufactured products per unit time, $\dfrac{h_r Q_m}{2}\left[\left(\dfrac{u^2}{1-u}\right)\left(\dfrac{r-1}{r^n-1}\right)\left(\dfrac{r^n+1}{r+1}\right)\right]$

(iii) The inventory holding cost of newly manufactured products per unit time, $\dfrac{h_m Q_m(1-u)}{2}$

(iv) The manufacturing cost per unit time, $c_m\lambda(1-u)$

Therefore, the total cost per unit time $UTC(Q_m, n, u)$ for a policy $P(1,n)$ is:

$$UTC(Q_{m,}, n, u) = \frac{K_m \lambda(1-u)}{Q_m} + \frac{nK_r \lambda(1-u)}{Q_m} + \frac{h_n Q_m}{2r}\left[\left(\frac{u^2}{1-u}\right)\left(\frac{r-1}{r^n-1}\right)\left(\frac{r^n+1}{r+1}\right)\right] + \frac{h_r Q_m}{2}\left[\left(\frac{u^2}{1-u}\right)\left(\frac{r-1}{r^n-1}\right)\left(\frac{r^n+1}{r+1}\right)\right] + \frac{h_m Q_m(1-u)}{2} + \lambda c_m(1-u) + \lambda c_r u + \lambda c_d (r-u) \qquad \text{eqn.(18)}$$

The problem now is to determine the values of the decision variables (Q_m, n, u) that minimise the total cost per unit time.

3.3.4 Solution methodology

Setting the partial derivative of eqn. (18) with respect to the manufacturing lot-size (Q_m), number of remanufacturing lots (n) and remanufacturing fraction (u) to zero and solving will give values of manufacturing lot-size (Q_m), number of remanufacturing lots (n) and remanufacturing fraction (u) to optimise the total cost per unit time. This resulted in a system of equations that had no simple solution.

Then, consider setting the partial derivatives of eqn.(18) with respect to the manufacturing lot-size (Q_m) and number of remanufacturing lots (n) to zero and solving will give the values for the manufacturing lot-size (Q_m) and number of remanufacturing lots (n), to optimise the total cost per unit time for a given value of remanufacturing fraction (u). Even, in this case, a simple expression for the optimal manufacturing lot-size (Q_m) and number of remanufacturing lots (n) cannot be obtained from the systems of equations.

Consequently, the optimal values for manufacturing lot-size (Q_m) and the number of remanufacturing lots (n) are obtained for given values of remanufacturing fraction (u) and the parameters of the system using the Excel Solver tool. Finally, the optimal values for remanufacturing lot-sizes ($Q_{r1}, Q_{r2}, .., Q_n$) are computed from a set of relationship that are given in subsection 3.3.2 above.

3.4 A benchmark model for the benefit analysis

An inventory lot-sizing model with fixed remanufacturing lot-sizes that is introduced in Teunter (2001) and represented in eqn. (19) was selected as the benchmark model for studying the benefit of the new model. In the benchmark model, the computed number of remanufacturing lots, n, were allowed to be a non-discrete values, which subsequently resulted in non-discrete values for the number of remanufacturing and manufacturing lots. In practice, a non-discrete value for the number of remanufacturing and manufacturing lots cannot be implemented. Therefore, for a practical purpose and the benefit study, the number of remanufacturing lots that was computed in the benchmark model was adjusted to assume a discrete value, using a technique that is introduced in Teunter (2004). Table 3.1 illustrates the procedures and results of the adjustment process.

Table 3.1:
The solution for Q_r, $n*$ and Q_m^* resulting from the adjustment of a benchmark model.

Steps	Decision variables	Remanufacturing fraction, u 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Step 1	Q_m	44.69	44.55	44.22	43.53	42.16	39.51	34.50	25.82
	Q_r	37.80	37.80	37.80	37.80	37.80	37.80	37.80	37.80
Step 2	n	0.13	0.30	0.50	0.77	1.12	1.57	2.13	2.73
Step 3	$n*$	1	1	1	1	1	2	2	3
Step 4	Q_m^*	340	151	88	57	38	50	49	28

$$UTC^* = \frac{K_m\lambda(1-u)}{Q_m} + \frac{K_r\lambda u}{Q_r} + \frac{h_n}{2}\left[uQ_r + Q_m\frac{u^2(1-r)}{r(1-u)}\right] + \frac{h_r u Q_r}{2} + \frac{h_m Q_m(1-u)}{2} + \lambda c_m(1-u) + \lambda c_r u + \lambda c_d(r-u) \qquad \text{eqn.(19)}$$

Analysing, eqn.(18) and eqn.(19), it is clear that the last three cost terms are similar in their structure. Since the parameters settings employed in the case studies are taken from Teunter (2001), the last three terms of eqn.(18) and eqn.(19) would result in the same numerical value. Therefore, these last three costs terms are omitted in the benefit study.

3.5 Case studies

Cases studies have been conducted utilising the parameters that have been collected from the available literature (Teunter, 2001). The parameters setting are: returned fraction, $r = 0.8$; setup cost for manufacturing, $K_m = 100$; setup cost for remanufacturing, $K_r = 100$; demand, $\lambda = 100$; holding cost for remanufactured items, $h_r = 9$; holding cost for newly manufactured item, $h_m = 10$; holding cost for remanufacturable items, $h_n = 5$; manufacturing cost for new items, $c_m = 60$; remanufacturing cost for remanufacturable items, $c_r = 50$; disposal cost for non-remanufacturable items, $c_d = -10$; remanufacturing fraction, $u = 0.1,\ 0.2,\ 0.3,\ 0.4,\ 0.5,\ 0.6,\ 0.7,\ 0.8$.

3.5.1 Examining the behaviour of manufacturing lot-size, number of remanufacturing lots, first remanufacturing lot-size with remanufacturing fraction

In general, the manufacturing lot-size (Q_m), number of remanufacturing lots (n) and the first remanufacturing lot-size (Q_{r1}) change with remanufacturing fraction (u). Specifically as reported in table 3.2, the first remanufacturing lot-size (Q_{r1}) and the number of remanufacturing lots (n) increases as remanufacturing fraction (u) increases, while manufacturing lot-size (Q_m) decreases as remanufacturing fraction (u) increases. This expected finding reflects that increasing the remanufacturing fraction (u) (and hence the quantities of remanufacturables available for remanufacture) would result in increasing the number of remanufacturing lots that have to be processed. Therefore, as the number of remanufacturing lots increases, the number of resulting remanufactured products would increases as well. This subsequently results in manufacturing less quantity of new products (i.e., the manufacturing lot-size decreases as remanufacturing fraction increases).

Furthermore, the computed total cost per unit time (UTC) at remanufacturing fraction (u) of 0.8 is lower $(UTC = 5747)$ than those computed at remanufacturing fraction (u) of 0.1 $(UTC = 5775)$. As expected, the total cost per unit time (UTC) resulting from satisfying customers' demand with remanufactured products would be much cheaper than providing them with newly manufactured products.

Table 3.2:
The solution for Q_m, n and Q_{r1} for a given u

	Remanufacturing fraction, u							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Q_m	63	60	56	49	40	47	46	37
n	1	1	1	1	1	2	3	4
Q_{r1}	7	15	24	33	40	39	44	50
Q_n	7	15	24	33	40	31	28	25
UTC	5775	5730	5701	5692	5702	5713	5727	5747

Thus, it can be established that increasing the remanufacturing fraction (u) would result in more remanufacturing lots to be processed (i.e. more remanufactured products) and less quantities of newly manufactured products required. Furthermore, it can also be established that the satisfying customers demand with remanufactured products is generally cheaper than providing them with newly manufactured products.

3.5.2 Analysis of the benefits of the new model.

Comparable to the analysis discussed in subsection 3.5.1, the parameters for this analysis have been collected from Teunter (2001) where the remanufacturing fraction, u has been assumed to range from 0.5 to 0.8, which is consistent with those typically observed in the real-industries cases.

Result of this analysis (table 3.3) reflects that the new model with variable remanufacturing lot-size is superior to a benchmark model with constant remanufacturing lot-sizes, particularly at higher remanufacturing fraction (u). When the remanufacturing fraction (u) is specified at 0.5, both models result in one number of remanufacturing lot (n) to be processed per period of time, i.e., both models have a policy of $P(m=1, n=1)$. Given that the same parameters were utilised to compute the total cost per unit time (UTC) in each model, the resulting total cost per unit time (UTC) would be similar in both models.

Thus, given a remanufacturing fraction (u) value of 0.5, the benefit of not having any carryover stocks to the next remanufacturing lot as provided by the new model would not be achieved. However, as the remanufacturing fraction (u) increases the benefit of not having any carryover of stocks to the next remanufacturing lot as provided by the new model becomes significant. As expected, when the remanufacturing fraction (u) becomes higher, the quantities of carryover stocks to the next remanufacturing lot in the benchmark model becomes larger, thus resulting in a higher total cost per unit time (UTC) compared to the new model.

Table 3.3:
Percentage of savings in total cost per unit time at different remanufacturing fractions

	Remanufacturing fraction, u			
	0.5	0.6	0.7	0.8
n for new model	1	2	3	4
n^* for benchmark model	1	2	3	3
UTC for new model	503	514	527	548
UTC^* for benchmark model	503	526	556	580
Saving (%)	0	2.3	5.2	5.5

Consequently, it can be established that the new model with variable remanufacturing lot-sizes leads to a lower total cost per unit of time than a model with constant remanufacturing lot-sizes, in particular when the quantities of remanufacturables available for remanufacture is plentiful.

3.5.3 Examining the behaviour of manufacturing lot-size and first remanufacturing lot-size with costs and demand parameters

The standard values for K_m, K_r, h_m, h_n and h_r are the values that are stated in section 3.5. For each cost parameter, nine different levels are obtained by multiplying the standard value of itself by 1/5, ¼, 1/3, ½, 1, 2, 3, 4 and 5 respectively. A different method is employed to select eight levels of demand rate. Since the demand rate is greater than the returned rate, $\lambda > r\lambda$, the level of $r\lambda$ is fix to be the standard value. Then, eight different levels of demand rate are obtained by multiplying the fixed value of $r\lambda$ by 1.5, 2, 2.5, 3, 3.5, 4, 4.5 and 5 respectively.

The behaviour of manufacturing lot-size (Q_m) and the first remanufacturing lot-size (Q_{r1}) with respect to changes in values for K_m, K_r, h_m, h_n, h_r and λ are graphically presented in appendix B (figures B1-B12). The observations made from these graphs are as follows:

- In general, both the manufacturing lot-size (Q_m) and the first remanufacturing lot-size (Q_{r1}) are increasing with the manufacturing and remanufacturing setup costs (K_m and K_r).
- In general, both the manufacturing lot-size (Q_m) and the first remanufacturing lot-size (Q_{r1}) are decreasing with the holding costs (h_m, h_n and h_r).
- In general, both the manufacturing lot-size (Q_m) and the first remanufacturing lot-size (Q_{r1}) are increasing with the demand rate (λ).
- There are several specific observations as indicated below, which have been caused by changes in the number of remanufacturing lots.
    - The first remanufacturing lot-size (Q_{r1}) falls as the manufacturing setup cost (K_m) is increased ;
    - The manufacturing lot-size (Q_m) falls as the remanufacturing setup cost (K_r) is increased;
    - The first remanufacturing lot-size (Q_{r1}) rises as the holding cost for newly manufactured products (h_m) is increased;
    - The manufacturing lot-size (Q_m) rises as the holding cost for remanufactured products (h_r) is increased;
    - The manufacturing lot-size (Q_m) rises as the holding cost for remanufacturable items (h_n) is increased.

The above findings suggest that in general, both the manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) increases with the setup costs and demand rate and decreases with the holding costs. Accordingly, it can be established that the behaviour of the manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) are influenced by the costs and demand parameters.

3.5.4 Sensitivity analysis

A sensitivity analysis has been conducted to assess the robustness of manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) estimates to changes in the costs and demand parameters. Such analysis has been conducted for the following two cases:

(i) Case 1 - The sensitivity of manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) estimates to changes in K_m, K_r, h_m, h_n, h_r and λ at low values of K_m, K_r, h_m, h_n, h_r and λ.

(ii) Case 2 - The sensitivity of manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) estimates to changes in K_m, K_r, h_m, h_n, h_r and λ at high values of K_m, K_r, h_m, h_n, h_r and λ.

Results of the sensitivity analysis (tables B1-B4 in appendix B) show that for both cases, the manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) estimates are generally insensitive to changes in the cost and demand parameters (K_m, K_r, h_m, h_n, h_r and λ). However, there are several instances (below), where the manufacturing lot-size (Q_m) and first remanufacturing lot-size (Q_{r1}) estimates are sensitive to changes in the costs values.

- At low value of remanufacturing setup cost (K_r), the estimate of manufacturing lot-size (Q_m) is sensitive to changes in the K_r at remanufacturing fraction, $u = 0.6$.
- At low value of holding cost for newly manufactured products (h_m), the estimate of manufacturing lot-size (Q_m) is sensitive to changes in h_m at remanufacturing fraction, $u = 0.6$.
- At high value of manufacturing setup cost (K_m), the estimate of manufacturing lot-size (Q_m) is sensitive to changes in K_m at remanufacturing fraction, $u = 0.6$.

- At high value of manufacturing setup cost (K_m), the estimate of first remanufacturing lot-size (Q_{r1}) is sensitive to changes in K_m at remanufacturing fraction, $u = 0.6$.

3.6 Summary

This chapter has discussed the development and analysis of a mathematical model that addresses inventory lot-sizing problems in a hybrid remanufacturing-manufacturing system with varying remanufacturing fractions. Section 3.2 provided a literature review of the existing inventory lot-sizing models in a hybrid remanufacturing-manufacturing system. Section 3.3 discussed the development of a new integrated inventory lot-sizing model with variable remanufacturing lot-sizes. Section 3.4, discussed a benchmark model that has been selected for the benefit study. Finally, section 3.5 discussed case studies that have examined: (i) behaviour of the major decision variables, (ii) benefits of the new inventory lot-sizing model, and (iii) robustness of the major variables with regards to changes in system parameters.

Chapter 4

Integrated production and inventory planning simulation models

4.1 Introduction

This chapter discusses the life-cycle of construction and analysis of the simulation models that are defined in research objectives 2, 3 and 4 (chapter 1). Section 4.2 discusses the formulation of the problems under investigation. Section 4.3 discusses definition, validation and architecture of the conceptual models. Section 4.4 discusses coding and verification of the computer programs, as well as validation of the simulation models. Section 4.5 discusses the architecture of the major segments of the simulation models. The computer programs codes for governing the simulation logic of each segment are discussed in appendix F, G, H, I, J and K. Section 4.6 discusses several issues that pertain to design and execution of the simulation experiments. Finally, section 4.7 reiterates the purpose and content of this chapter.

4.2 Formulation of the problems

A generic remanufacturing process, as discussed in chapter 2, typically consists of four distinctive key-stages with inventory held either as remanufacturables, finished products or a combination of both. Furthermore, it has been established that used products exhibit uncertain quality conditions, which further requires remanufacturables to be graded and sorted into multiple different quality groups. Understandably, the highest priority should be given to process the best quality group of remanufacturables into finished products that are utilised to meet customer demand.

Nonetheless, there might be circumstances when an alternative option that gives equal priority to multiple different quality remanufacturable groups (i.e., simultaneous processing) would lead to a favourable option, particularly when resources are not a constraint or production is driven by customer demand. Consequently, the problem being investigated has been formulated as the analysis of remanufacturing systems considering different remanufacturing policies for a given remanufacturing strategy. Such remanufacturing policy relates to a decision on the priority to process multiple different quality remanufacturable groups and resources that are available for remanufacturing.

Considering a RMTS-strategy, the analysis takes into consideration four alternative configurations of remanufacturing system, that are "*configA*", "*configB*", "*configC*" and "*configD*" (table 4.1). For a RMTO-strategy, the analysis takes into account three alternative configurations of remanufacturing system, that are "*configE*", "*configF*" and "*configG*" (table 4.2). As shown in tables 4.1 and 4.2, each configuration is different with respect to a policy on the priority to process two different quality remanufacturable groups (GI & GII) and resources.

It should be noted that configurations with complex policies other than given in tables 4.1 and 4.2, could result in a better performance. However, considering the difficulties that are associated with modelling and analysis of such complex policies and resources available for this research project, it is reasonable to consider policies that are given in tables 4.1 and 4.2.Furthermore, in practice it would be impractical to implement complex remanufacturing policies.

Table 4.1:
Remanufacturing policy of alternative RMTS-system configurations

Policy regarding	Alternative configurations			
	"configA"	*"configB"*	*"configC"*	*"configD"*
Processing priority	Simultaneous (GI&GII)	Simultaneous (GI&GII)	Sequential (GI/GII) and waiting	Sequential (GI/GII) and switching
Resources	2 units are shared between GI&GII	2 units are dedicated to each GI&GII	2 units are shared between GI&GII	2 units are shared between GI&GII

Table 4.2:
Remanufacturing policy of alternative RMTO-system configurations

Policy regarding	Alternative configurations		
	"configE"	*"configF"*	*"configG"*
Processing priority	GI only and waiting	Sequential (GI/GII) and switching	GII only and waiting
Resources	1 unit	1 unit is dedicated to each GI&GII	1 unit

4.3 Definition, validation and architecture of the conceptual models

A conceptual model of a generic remanufacturing system (figure 4.1) has been developed based on the information that has been collected from the literature on remanufacturing. For this generic conceptual model, its major architecture and features have been validated by the remanufacturing experts from a case study company (appendix E shows the result of the validation process). This generic conceptual model then becomes the basis for developing a conceptual model of each configuration that is given in tables 4.1 and 4.2.

Referring to figure 4.1, the conceptual model consists of four segments that are: (i) inspection and remanufacturables management, (ii) replacement components management, (iii) customer demand management, and (iv) remanufacturing and finished products inventory control management. The following subsections (4.3.1 and 4.3.2) provide discussion on the architecture of conceptual models that correspond to the remanufacturing polices given in tables 4.1 and 4.2.

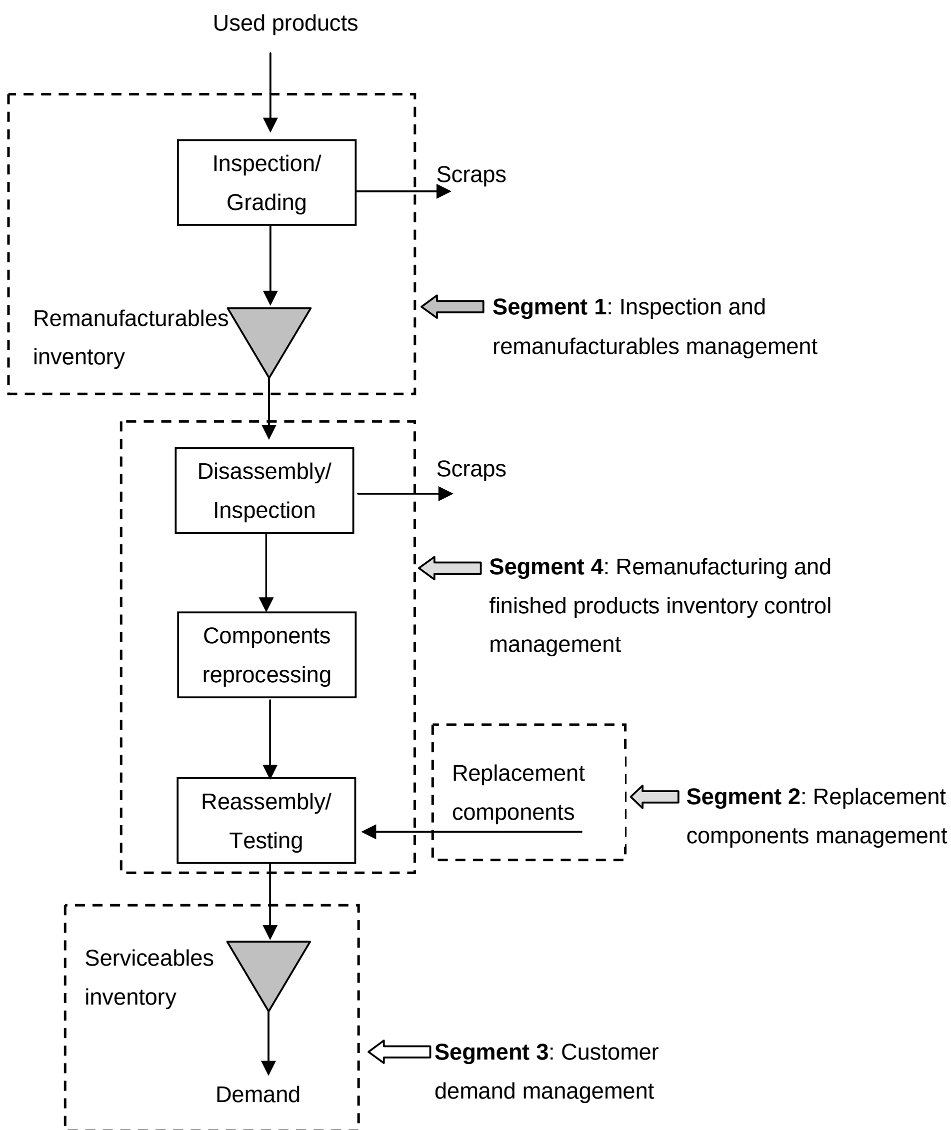


Figure 1: Architecture of a generic conceptual model of remanufacturing system

4.3.1 Architecture of the conceptual models of alternative remanufacture-to-stock system configurations

Figures 4.2, 4.3, 4.4 and 4.5 illustrate the architecture of conceptual models that correspond to "*configA*", "*configB*", "*configC*" and "*configD*", respectively for the remanufacture-to-stock (RMTS) system. In all configurations, used products are obtained either from the customers or brokers. In this thesis it is assumed that the incoming used products contain two-types of constituent components (*compA* and *compB*) that are considered for remanufacture, where *compB* exhibits a more complex structure than *compA*. Upon arrival at the plant, used products are initially inspected to assess their remanufacturability conditions, remanufacturables or scraps. Scraps are either disposed off or sold to scrap brokers.

Remanufacturables are further classified into two different quality groups, (GI & GII), where GI remanufacturables are in a better quality condition than GII remanufacturables. The decision whether to release GI or GII remanufacturables into subsequent remanufacturing stages, mainly depends on a (R, r) inventory control policy; R denotes a target-level of the finished products inventory, r denotes a reorder-level of the finished products inventory and $r < R$. If the current finished products inventory level falls between the target and reorder level, then remanufacturables are released into subsequent remanufacturing stages. Otherwise, remanufacturables are stored in the warehouse, while waiting for the finished products inventory level to reach the reorder-level, hence releasing a production order.

In "*configA*" and "*configB*", both GI & GII quality groups are given the same priority for processing (i.e., simultaneous). Once production is initiated, remanufacturables from both the GI & GII quality groups are released into subsequent remanufacturing stages. In "*configA*", resources are shared between processing remanufacturables from the GI & GII quality groups, where the priority algorithm is a first-come and first-serve basis. On the contrary, in "*configB*" individual resources are dedicated for processing remanufacturables from the GI & GII quality groups. Moreover, in both "*configA*" and "*configB*", if there are insufficient remanufacturable stocks (GI & GII), production is simply suspended while waiting for the incoming remanufacturables.

By contrast, in both "*configC*" and "*configD*", only one quality group is given the priority for processing, where the priority algorithm is principally based on the current finished products inventory level. The priority algorithm states that when the current finished products inventory level is less than a threshold value, the GI quality group should be given a priority for processing; otherwise, the GII quality group would be given the priority. In "*configC*", if there are insufficient remanufacturable stocks from the currently prioritised quality group, production is suspended while waiting for the incoming remanufacturables (although remanufacturables from the other quality group are available). However, in "*configD*" the policy is to switch production to process the other quality group, say GI quality group, if there are insufficient remanufacturable stocks from the currently prioritised quality group (GII), which results in sustaining the remanufacturing process.

In all configurations, the remanufacturing process of remanufacturables from both quality groups is identical and described as follows. Once remanufacturables (GI / GII quality groups) are released for processing, they are disassembled into their constituent components, *compA* and *compB.* These components are then inspected to assess their remanufacturability conditions; remanufacturable components or scrap components. Scrap components are disposed off or sold to scrap brokers and their replacement components are ordered from an external supplier. Remanufacturable components are sent for reprocessing, where good quality components would only require cleaning process, while moderately good quality components would require repair process to restore their quality conditions to original conditions.

Once the cleaning/repair process has completed or replacement components are available, reassembly of *compA/compB* and other relevant constituent components takes place, which is then followed by testing of the assembled products. Next, the finished products are stored in a warehouse (serviceables inventory), while waiting for the incoming customer demand. As already stated, the warehouse implements a (*R*, *r*) inventory control policy, which suspends remanufacturing process once a target-level has been reached and initiates remanufacturing process once a reorder-level has been reached.

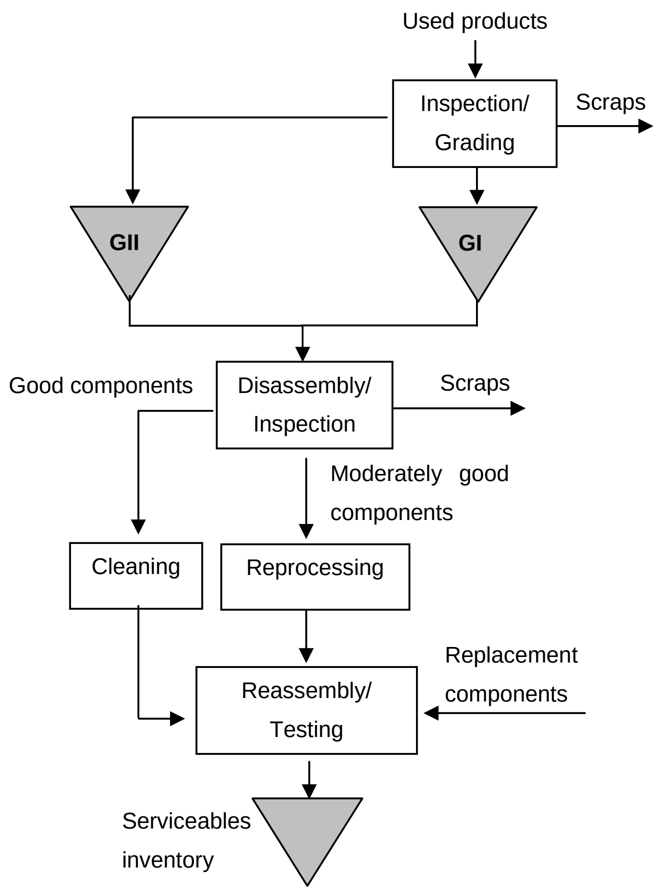


Figure 4.2: Architecture of conceptual model "*configA*"

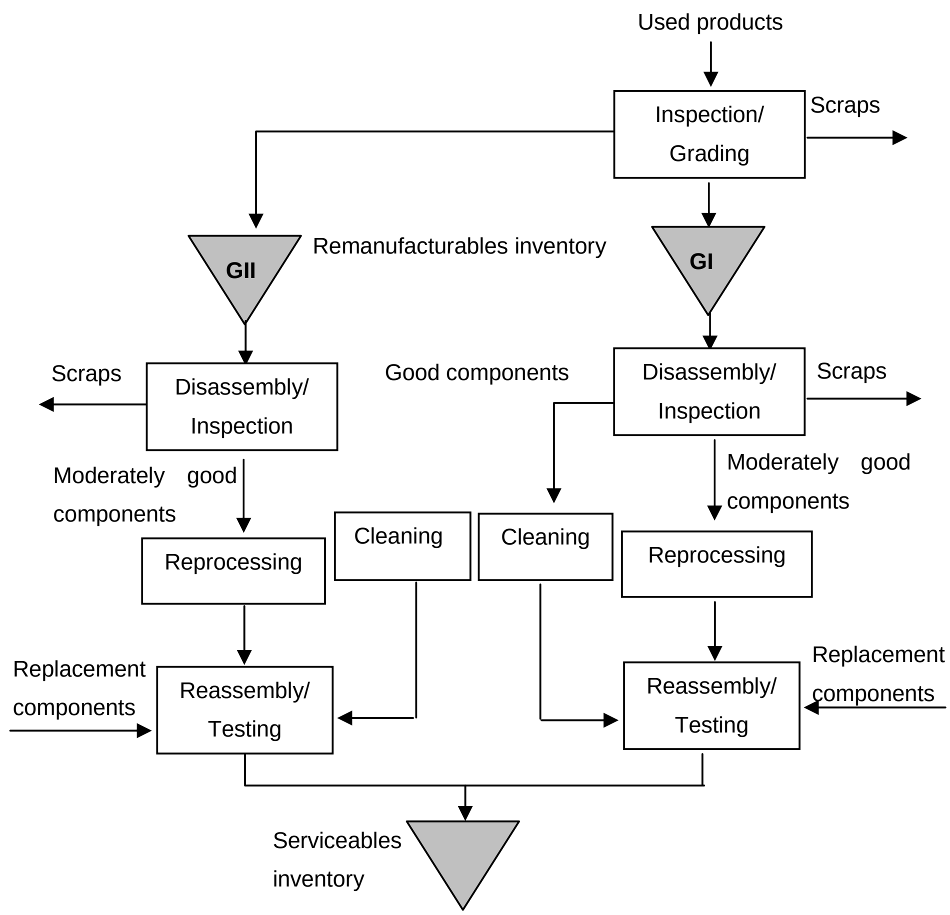


Figure 4.3: Architecture of conceptual model "*configB*"

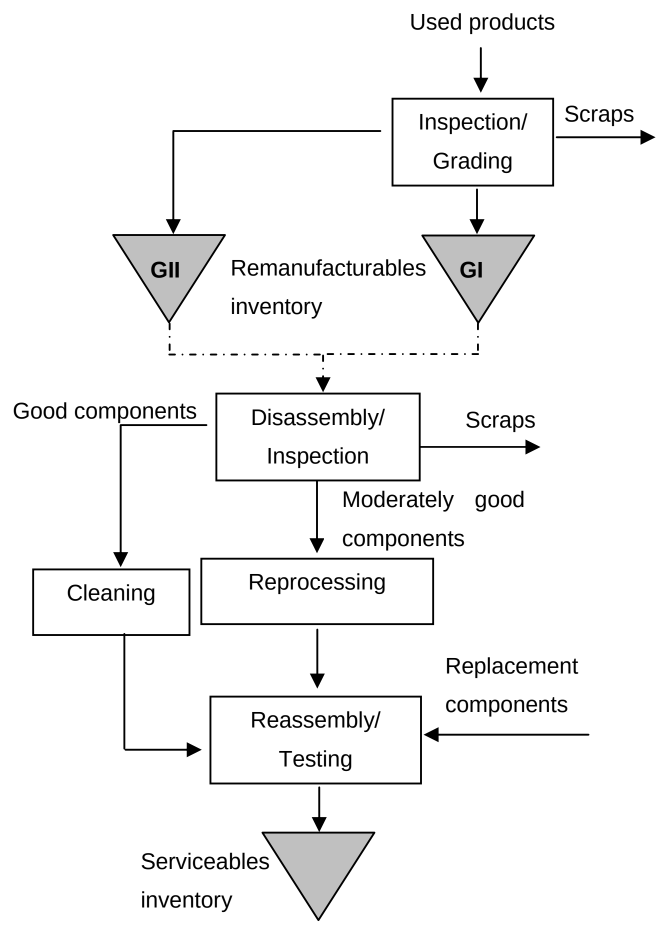


Figure 4.4: Architecture of conceptual model "*configC*"

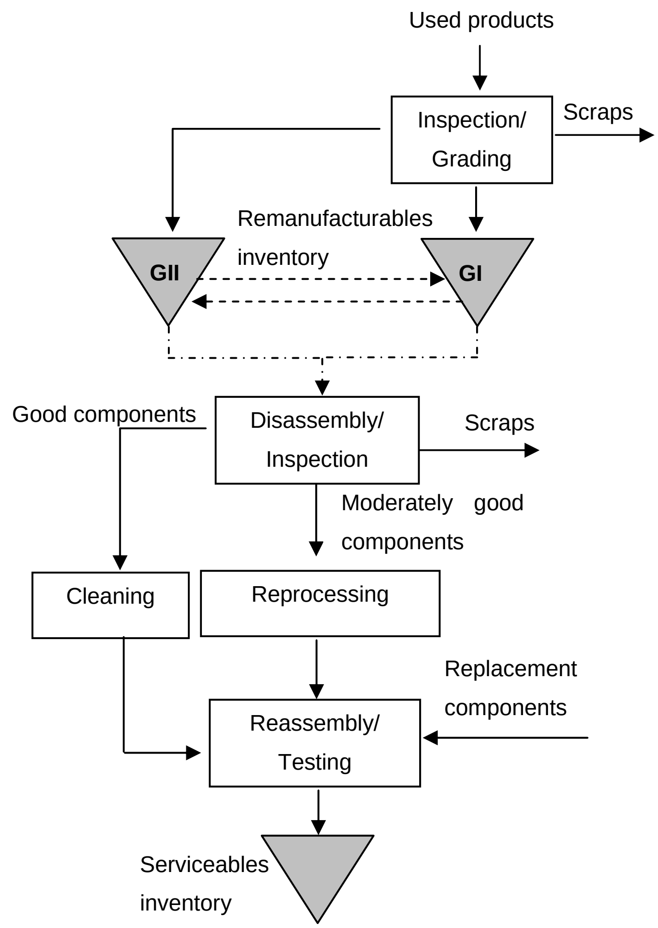


Figure 4.5: Architecture of conceptual model “*configD*”

4.3.2 Architecture of the conceptual models of alternative remanufacture-to-order system configurations

Unlike the RMTS-strategy, in a remanufacture-to-order strategy, remanufacturing process is only initiated once a customer order has been received. In this case, once remanufacturables have been inspected and graded, they are stored either in a GI or GII warehouse, while waiting for a production order. As shown in figure 4.6, in "*configE*", the policy is to give priority to process only remanufacturables from the GI quality group; and if there are insufficient remanufacturable stocks, production is simply suspended while waiting for the incoming remanufacturables.

In "*configF*" (figure 4.7) the policy is to switch production to process remanufacturables from the GII quality group, if there are insufficient remanufacturable from the GI quality group. Production is switched back to process remanufacturables from the GI quality group again, if there are insufficient remanufacturable stocks from the GII quality group. Thus, "*configF*" has a policy that switches between the GI & GII quality groups in order to sustain production. As for "*configG*" (figure 4.8), the policy is to give priority to process only remanufacturables from the GII quality group; and if there are insufficient remanufacturable stocks, production is simply suspended while waiting for the incoming remanufacturables.

The remanufacturing process of remanufacturables from the GI & GII quality groups in all configurations ("*configE*", "*configF*" and "*configG*") are also identical to those described for the RMTS strategy. However, unlike the RMTS strategy, in "*configE*", "*configF*" and "*configG*", the finished products inventory level would drop to zero after a customer's demand has been satisfied.

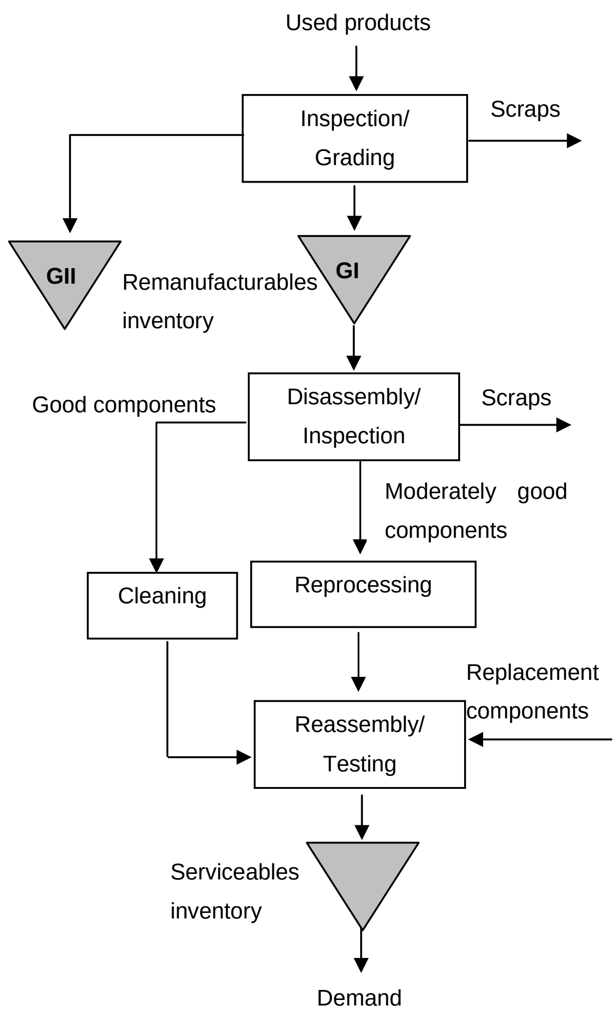


Figure 4.6: Architecture of conceptual model "*configE*"

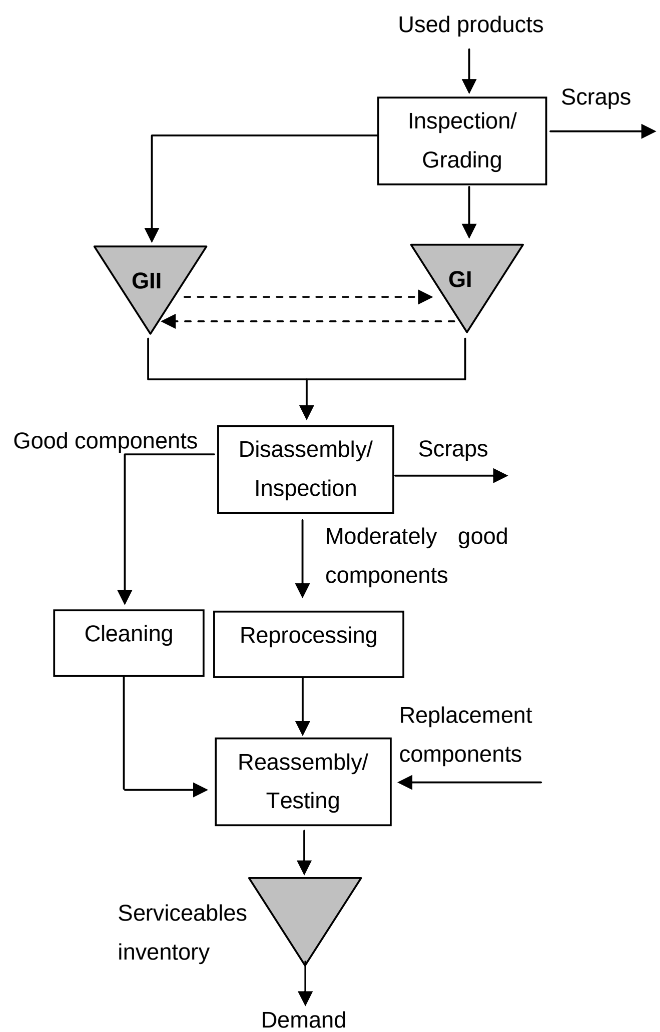


Figure 4.7: Architecture of conceptual model "*configF*"

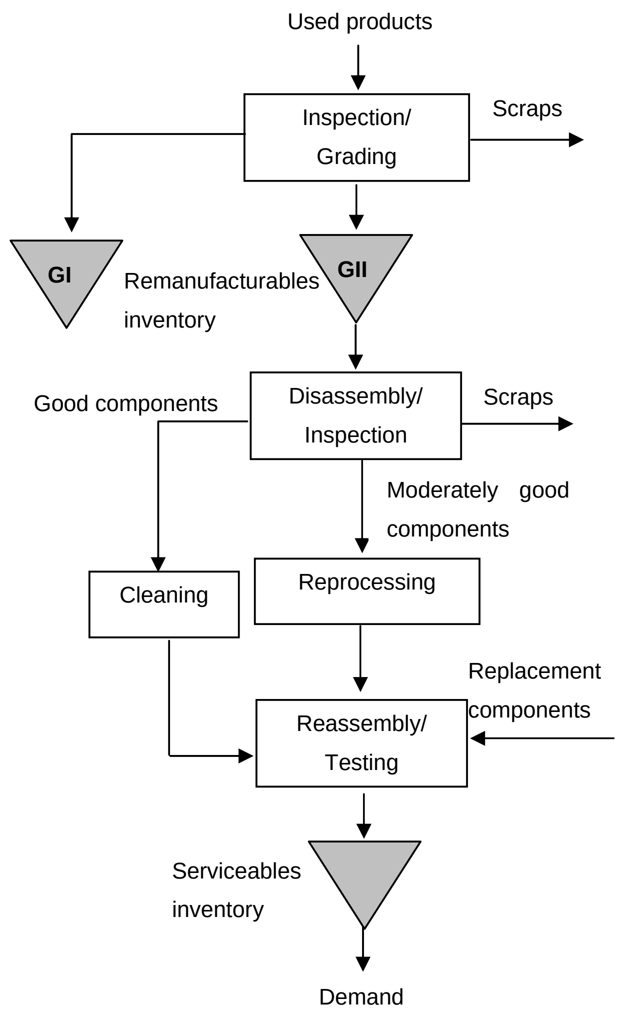


Figure 4.8: Architecture of conceptual model "*configG*"

4.4 Coding and verification of the computer programs and validation of the simulation models

4.4.1 Coding of the computer programs

Each of the conceptual models described earlier has been transformed into its equivalent simulation model. Firstly, a simulation platform for coding the computer programs has been assessed and selected. As stated in chapter 2, the Arena simulation platform (Arena 10.0) has been selected mostly because of its suitability for analysing the remanufacturing systems of interest and also its availability for this research project.

The Arena simulation platform, first released in 1997 is a flexible and powerful tool, which enables users to create animated simulation models that could precisely characterize nearly any system (Takus and Profozich, 1997). The underlying concept of Arena simulation platform (henceforth, simply called simulation platform) is based on an object-oriented design, which is exclusively aimed for developing graphical model. The simulation platform exists as a Microsoft Windows operating system application, which operates on a desktop with a specific system requirements (Kelton et al., 2007).

Secondly, computer programs have been coded to simulate the architecture and features of each segment that comprises the overall conceptual model. Moreover, computer programs have also been coded to govern the simulation logic of each individual segment and the interaction between two segments (e.g. the interaction between customer demand and remanufacturing & finished products inventory control). The computer programs have been coded in a higher level SIMAN simulation language of the simulation platform, which mainly exists as graphical modules (modelling constructs).

Thirdly, the computer programs that govern the simulation logic of all segments and their interactions were executed to simulate the working of the conceptual models, i.e., simulating the conceptual models. Provided that all the computer programs have been correctly coded, simulation of the conceptual models would have been successfully executed without receiving any error messages. Otherwise, some of the computer programs have to be recoded to ensure that the simulation models are successfully executed.

4.4.2 Verification of the computer programs

Verification of the computer programs concerns with ensuring that a conceptual model's assumptions have been correctly translated (coded) into a computer "program", i.e., debugging the simulation computer program (Law and Kelton, 2000). This can be accomplished by applying one of the verification techniques that are widely recommended in the literature (Banks et al., 1998; Law and Kelton, 2000; Kelton et. al., 2007). In this thesis, the animation technique has been selected and applied to verify the computer programs, mainly because of its availability within the simulation platform and its effectiveness for the simulation models that are constructed in this thesis. The verification process has been carried out for the computer programs that govern the simulation logic of each individual segment. Furthermore, for interacting segments their computer programs have been verified simultaneously.

For each segment, the verification process has been conducted as follows. Firstly, the number of entity that is created to circulate within a segment has been specified to be one unit. Secondly, a run control parameter that allows an entity to be animated (seen visually) has been enabled and the animation speed factor has been specified to be low.

Thirdly, the animated entity has been monitored throughout its progress within a segment. Provided that the assumptions of a conceptual model have been correctly translated into the computer programs, the animated entity would progress within a segment according to its planned logic; otherwise the animated entity would deviate from that planned logic. As an example, figure C1 in appendix C shows the verification process for the computer programs that govern the simulation logic of the customer demand segment.

4.4.3 Validation of the simulation models

Validation processes, by contrast establish whether a simulation model (as opposed to computer programs) are an accurate representation of a system, for a particular objectives of a study (Law and Kelton, 2000). In other words, validation processes concerns with determining whether a conceptual model and its equivalent simulation model can be substituted for the real system for the purposes of experimentation. True validation requires data on the real system to be available; however, when a system being investigated and simulated does not exist in real-life, a different method could be applied for the validation processes.

One of such methods is to validate a simulation model qualitatively as opposed to quantitatively (Banks, 1998). This method assumes that qualitative knowledge about certain parts of a simulation model is known and also the direction in which certain factors affect the response variables. In this thesis, the simulation models have been constructed for studying the problems of production and inventory planning within a remanufacturing system. Therefore, for each simulation model, the finished products inventory profile over a period of time has been simulated and documented.

In the traditional make-to-stock production strategy, a typical finished products inventory profile over a period of time under a constant customer demand is widely illustrated in figure 4.9. Referring to figure 4.9(a), the time period up to t_p denotes a period where production and consumption occurs simultaneously, whereas during the time period from t_p to t_1, only consumption occurs. For the make-to-order production strategy, a typical finished products inventory profile over a period of time is shown in figure 4.9(b).

Given that a remanufacturing system is also a production system, the typical finished product inventory profile over a simulated period of time for a RMTS-strategy and a RMTO-strategy would be similar to those shown in figure 4.9(a) and 4.9(b), respectively. Based on figure 4.9, it has been assumed that qualitative knowledge about the finished products inventory is known for the RMTS-strategy and RMTO-strategy. Therefore, the simulation models are validated by comparing the simulated finished products inventory profiles against the profiles that are shown in figure 4.9.

As shown in figures C2-C5 (appendix C), the finished products inventory profiles that have been generated from the simulation models under the RMTS strategy are similar to the profile that is shown in figure 4.9(a). Likewise, as shown in figures C6–C8 (appendix C) the finished products inventory profiles that have been generated from the simulation models under the RMTO-strategy are also similar to the profile that is shown in figure 4.9(b). Consequently, it has been established that the simulation models are accurate representations of the RMTS and RMTO systems of interest.

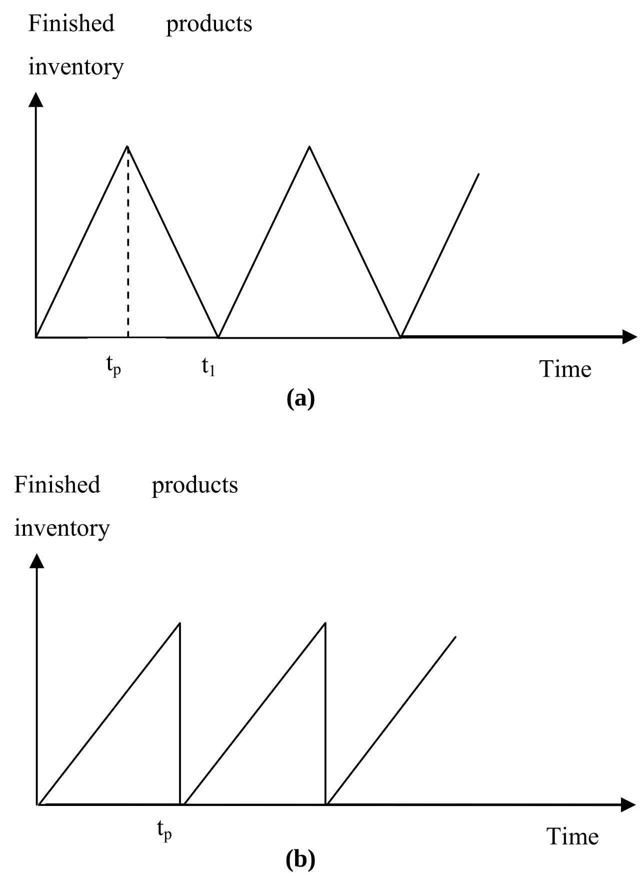


Figure 4.9: A typical finished products inventory profile over a period of time for: (a) manufacture-to-stock system, and (b) manufacture-to-order system (adapted from Hadley and Whitin, 1963; Tersine, 1994; Panneerselvam, 2005)

4.5 Architecture of the major segments of simulation models

Each of the simulation models consists of four major segments: (i) inspection and remanufacturables management, (ii) replacement components management, (iii) customer demand management, and (iv) remanufacturing and finished products inventory control management. The architecture of these major segments are discussed in the following subsections (4.5.1 – 4.5.5).

4.5.1 Inspection and remanufacturables management segment

The architecture and simulation logic of this segment (figure 4.10) are identical in all configurations of the RMTS-system and RMTO-system. This segment manages the inspection process and inventory of remanufacturables that are needed for the remanufacturing process. The computer programs codes for governing the simulation logic of this segment are discussed in appendix F.

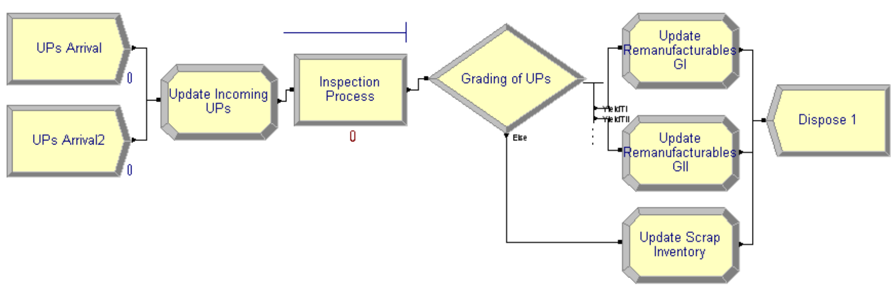
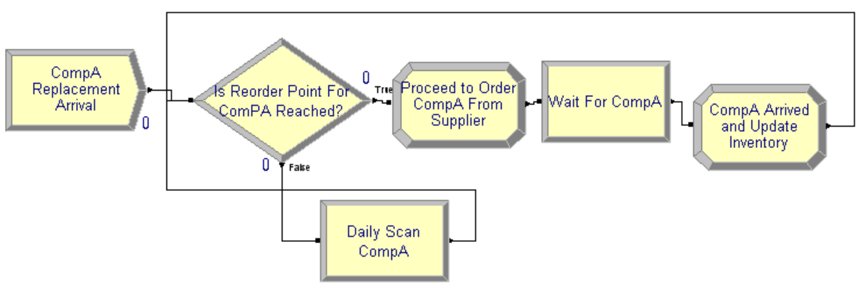


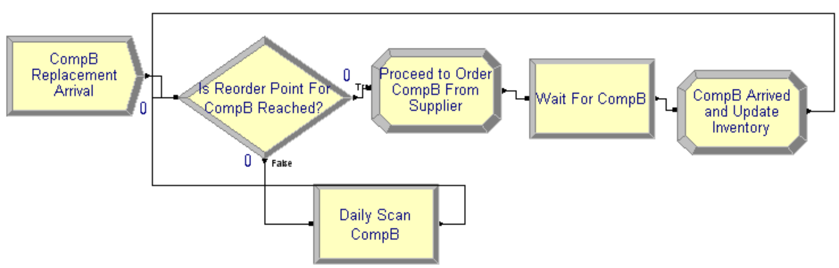
Figure 4.10: Architecture of the inspection and remanufacturables management segment

4.5.2 Replacement components management segment

Similar to the first segment, the architecture and simulation logic of this segment (figure 4.11) are also identical in all configurations of the RMTS-system and RMTO system. This segment is responsible for monitoring the inventory level of replacement components (*compA* and *compB*), placing an outside order when the inventory levels of both components have reached a reorder-level and updates the inventory levels once both replacement components have been received. The computer programs codes for governing the simulation logic of this segment are discussed in appendix G.



(a)



(b)

Figure 4.11: Architecture of the replacement components management segment for (a) component A, (b) component B

4.5.3 Customer demand management segment

(i) Remanufacture-to-stock system

This segment (figure 4.12) manages the customer demand for finished products (remanufactured products) in a remanufacture-to-stock system. Specifically, this segment: (i) monitors the number of customers and their demand for finished products, (ii) processes customer demand, (iii) fulfils or backorders customer demand, and (iv) initiates remanufacture of used products, once a reorder-level of finished products inventory has been reached. The computer programs codes for governing the simulation logic of this segment are discussed in appendix H.

(ii) Remanufacture-to-order system

Unlike the segment given in (i) above, this segment manages the customer demand for finished products in a remanufacture-to-order (RMTO) system. Specifically, this segment: (i) monitors the number of customers and their demand for finished products, (ii) processes customer demand, (iii) initiates remanufacturing process, and (iv) releases customers once their demand have been satisfied. The architecture of this segment (figure 4.13) is simpler than those shown for a RMTS-system. As discussed, for a RMTO strategy, there is no stock of finished product. Remanufacturing process is triggered by the arrival of a customer's order and is suspended once that order has been satisfied. The computer programs codes for governing the simulation logic of this segment are discussed in appendix I.

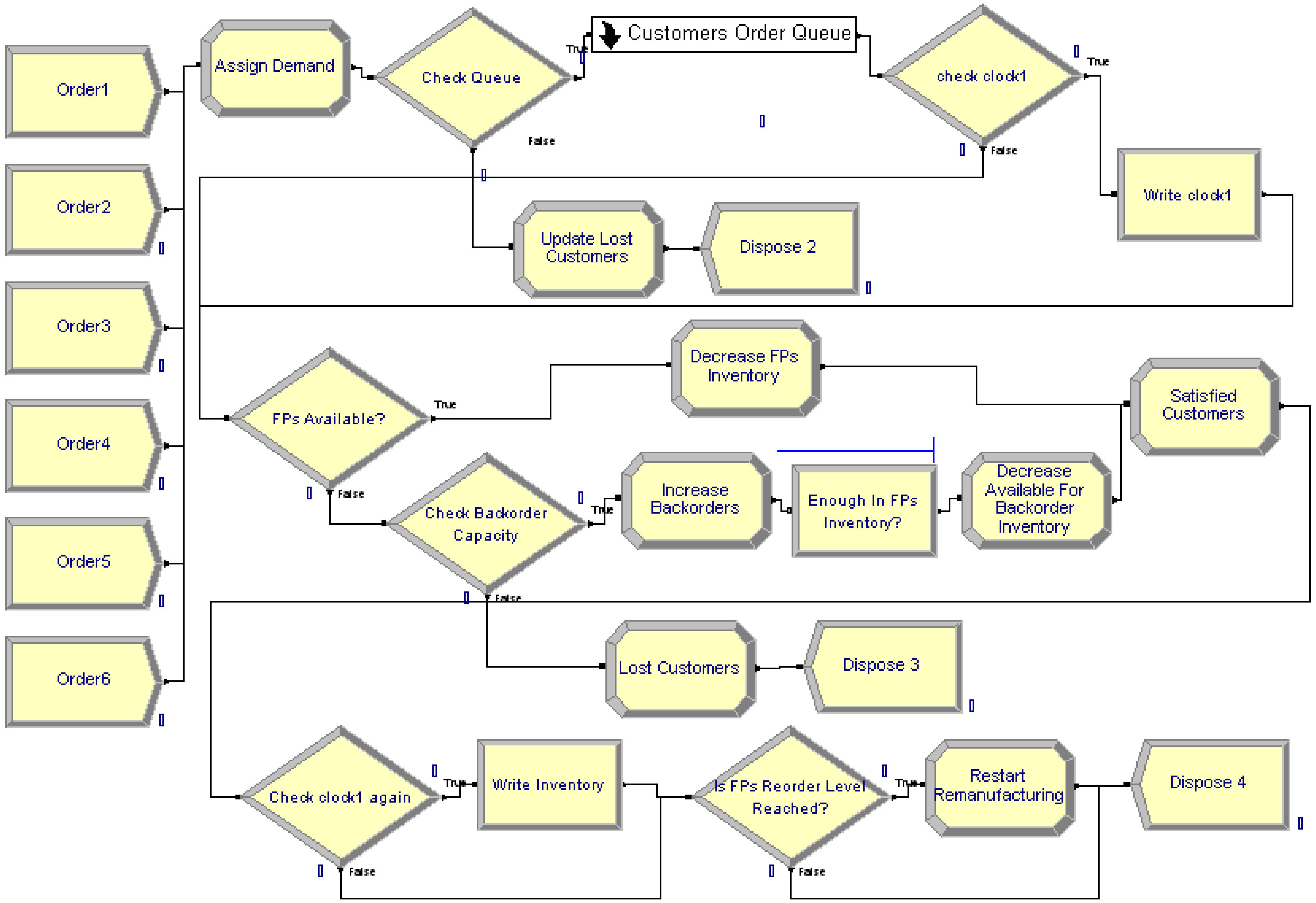


Figure 4.12: Architecture of the customer demand management segment of RMTS-system

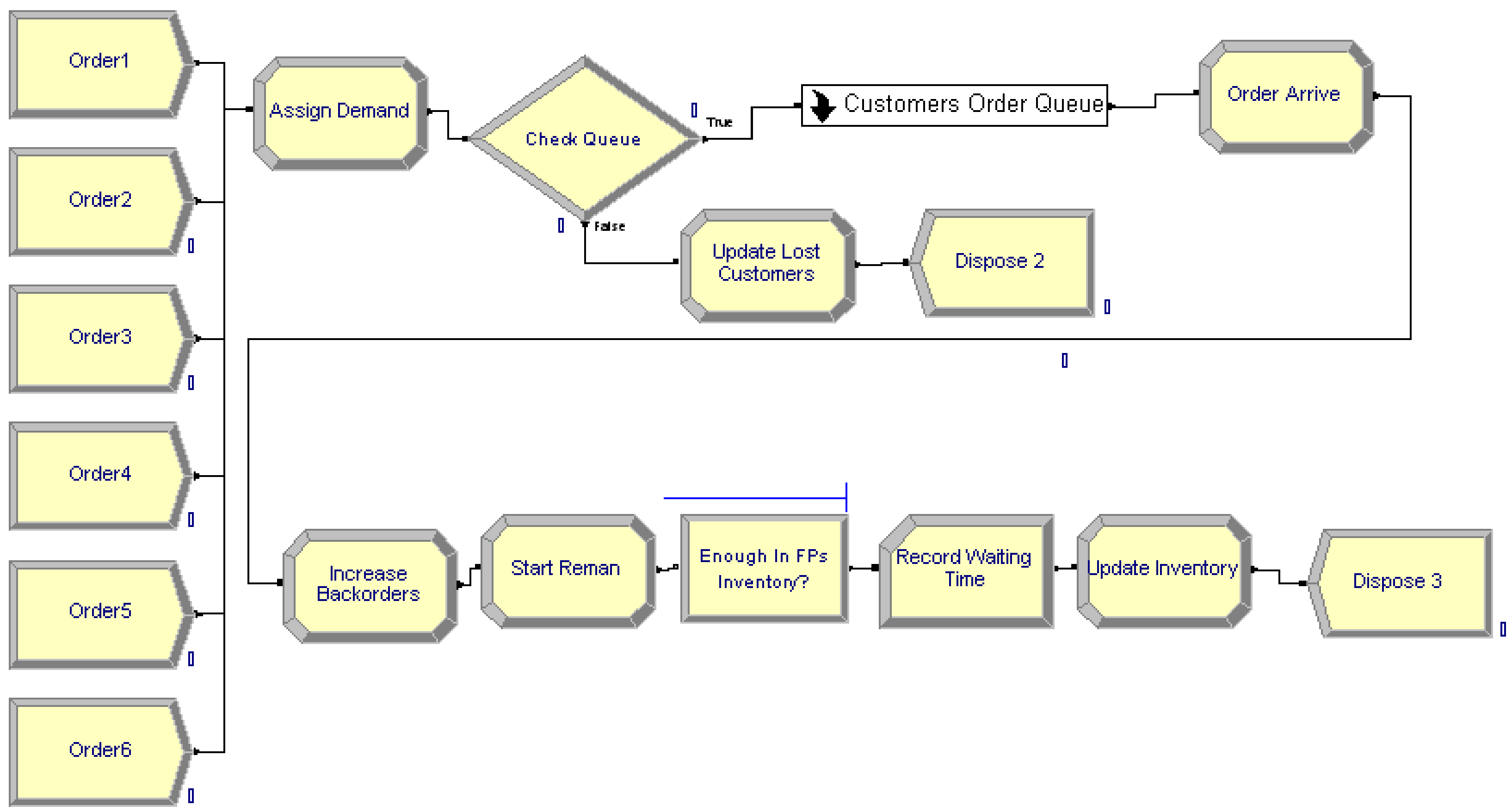


Figure 4.13: Architecture of the customer demand management segment of RMTO-system

4.5.4 Remanufacturing and finished products inventory control management segment of remanufacture-to-stock system

(i) "*configA"*

Figure 4.14 shows the architecture of remanufacturing and finished products inventory control segment of "*configA",* where simultaneous processing of remanufacturables from the G1 & GII quality groups takes place in shared facilities (resources). This segment manages the remanufacturing process and updates the finished products inventory level after each remanufacturing process. The computer programs codes for governing the simulation logic of this segment are discussed in appendix J-a.

(ii) "*configB"*

This configuration represents an improvement of "*configA"*, where simultaneous processing of remanufacturables from the GI & GII quality groups take place in dedicated facilities (resources). This configuration has identical architecture and simulation logic with those described for "*configA",* except different resources names have been specified in the remanufacturing *Submodels*. The computer programs codes for governing the simulation logic of this segment are similar to those discussed in appendix J-a (except for the codes that have been utilised to define the resources names).

(iii) "*configC"*

This configuration (figure 4.15) represents a case of processing one quality group at a time, i.e. processing of GI or GII quality group. In addition, if there are insufficient remanufacturable stocks from the currently prioritised quality group (say GI quality group), production is suspended while waiting for the incoming remanufacturables. The computer programs codes for governing the simulation logic of this segment are discussed in appendix J-b.

(iv) "*configD*"

Similar to "*configC*", this configuration (figure 4.16) represents a case of processing one quality group at a time (GI/GII). However, the decision is to switch production to process remanufacturables from the GII quality group, if there are insufficient remanufacturables from the GI quality group. The computer programs codes for governing the simulation logic of this segment are discussed in appendix J-c.

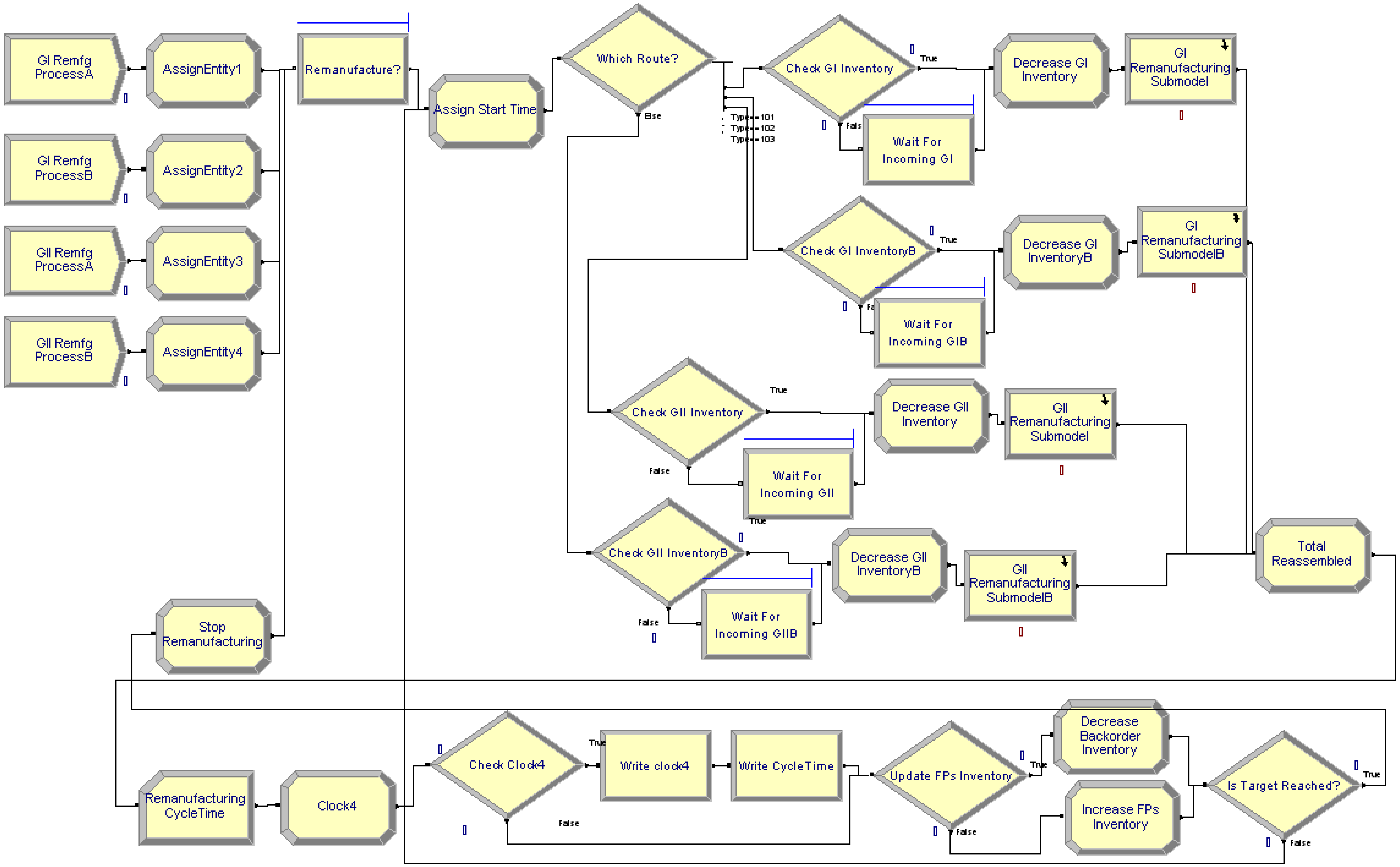


Figure 4.14: Architecture of the remanufacturing and finished products inventory control management segment of "*configA*"

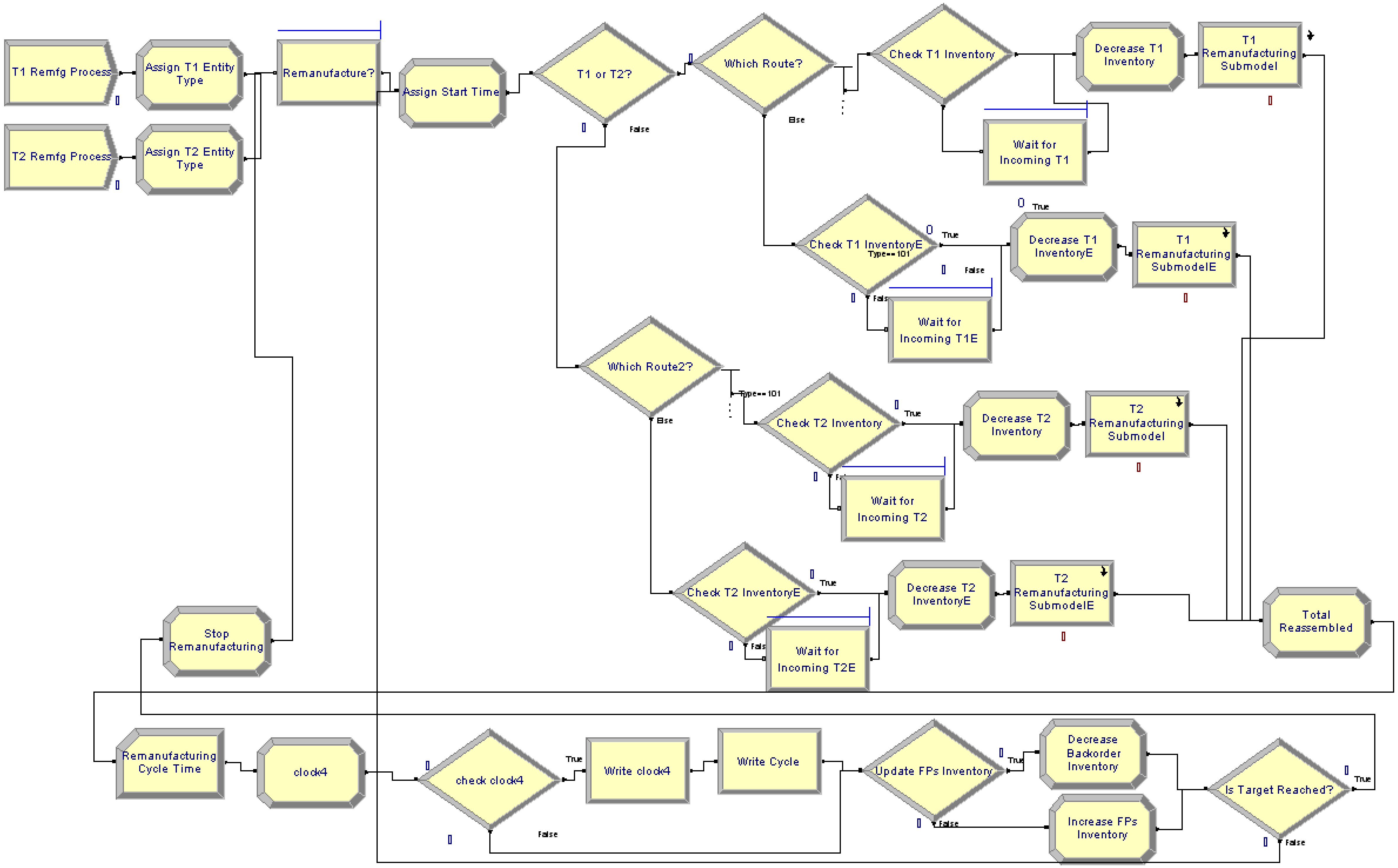


Figure 4.15: Architecture of the remanufacturing and finished products inventory control management segment of "*configC*"

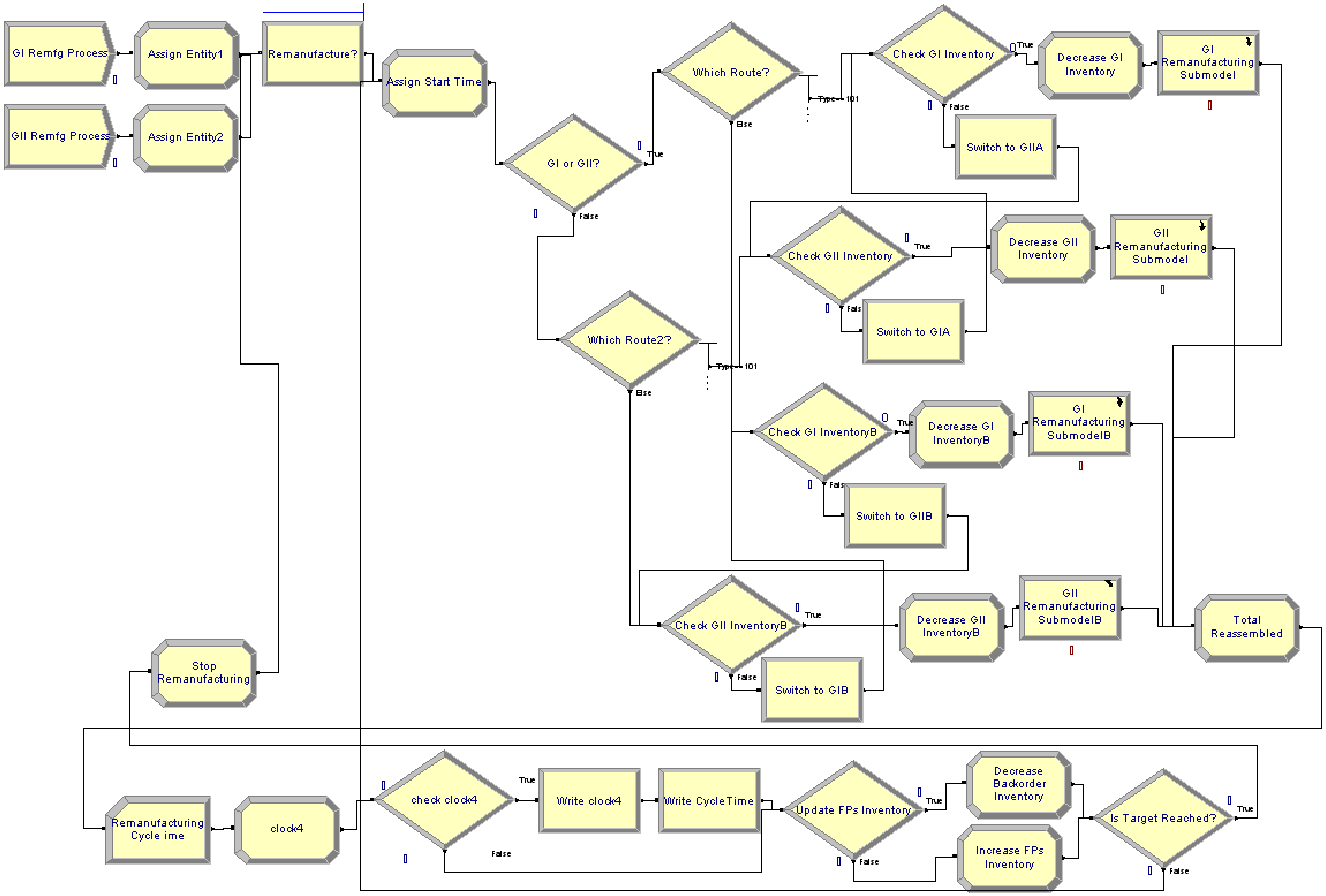


Figure 4.16: Architecture of the remanufacturing and finished products inventory control management segment of “*configD*”

4.5.5 Remanufacturing and finished products inventory control management segment of remanufacture-to-order system

(i) *“configE”*

This configuration (figure 4.17) represents a situation when the customer demand is satisfied by processing only remanufacturables from the GI quality group. As can be seen from figure 4.17, the architecture of this configuration is simpler than “*configF”* because there no remanufacturing logic for the GII quality group. Therefore, if there are insufficient remanufacturable stocks from the GI quality group, production is suspended, while waiting for the incoming remanufacturables (although there are some remanufacturable stocks from the GII quality group). The computer programs codes for governing the simulation logic of this segment are discussed in appendix K-a.

(ii) *“configF”*

This configuration (figure 4.18) represents an improvement of the situation represented in “*configE”*, where production is switched to process remanufacturables from the GI quality group, if there are insufficient remanufacturable stocks from the GII quality group. The computer programs codes for governing the simulation logic of this segment are discussed in appendix K-b.

(iii) *“configG”*

In contrast to “*configE”*, this configuration (figure 4.19) represents the situation when customer demand is satisfied by processing remanufacturables from the GII quality group only. As can be seen from figure 4.19 the architecture and simulation logic of this configuration are similar to those already described for “*configE”*. However, the information that have been specified in each module, relate to processing of remanufacturables from the GII quality group. The computer programs codes for governing the simulation logic of this segment are similar to those discussed in appendix K-a.

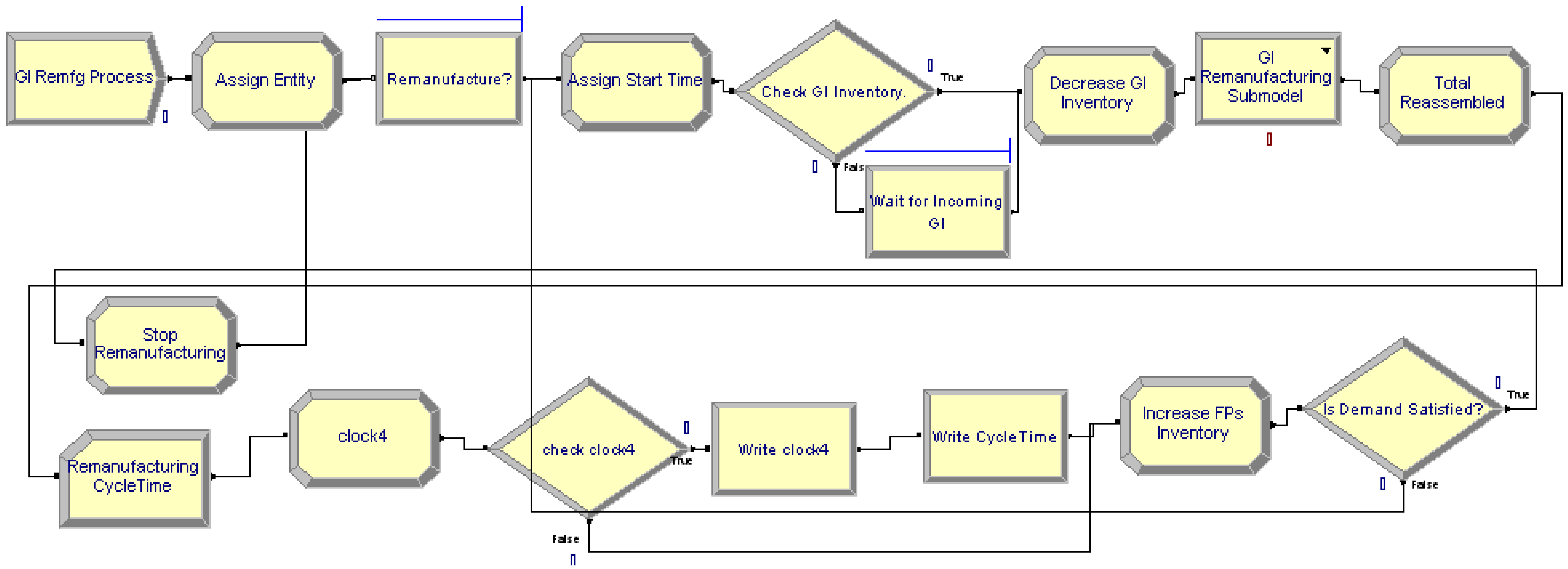


Figure 4.17: Architecture of the remanufacturing and finished products inventory control management segment of *"configE"*

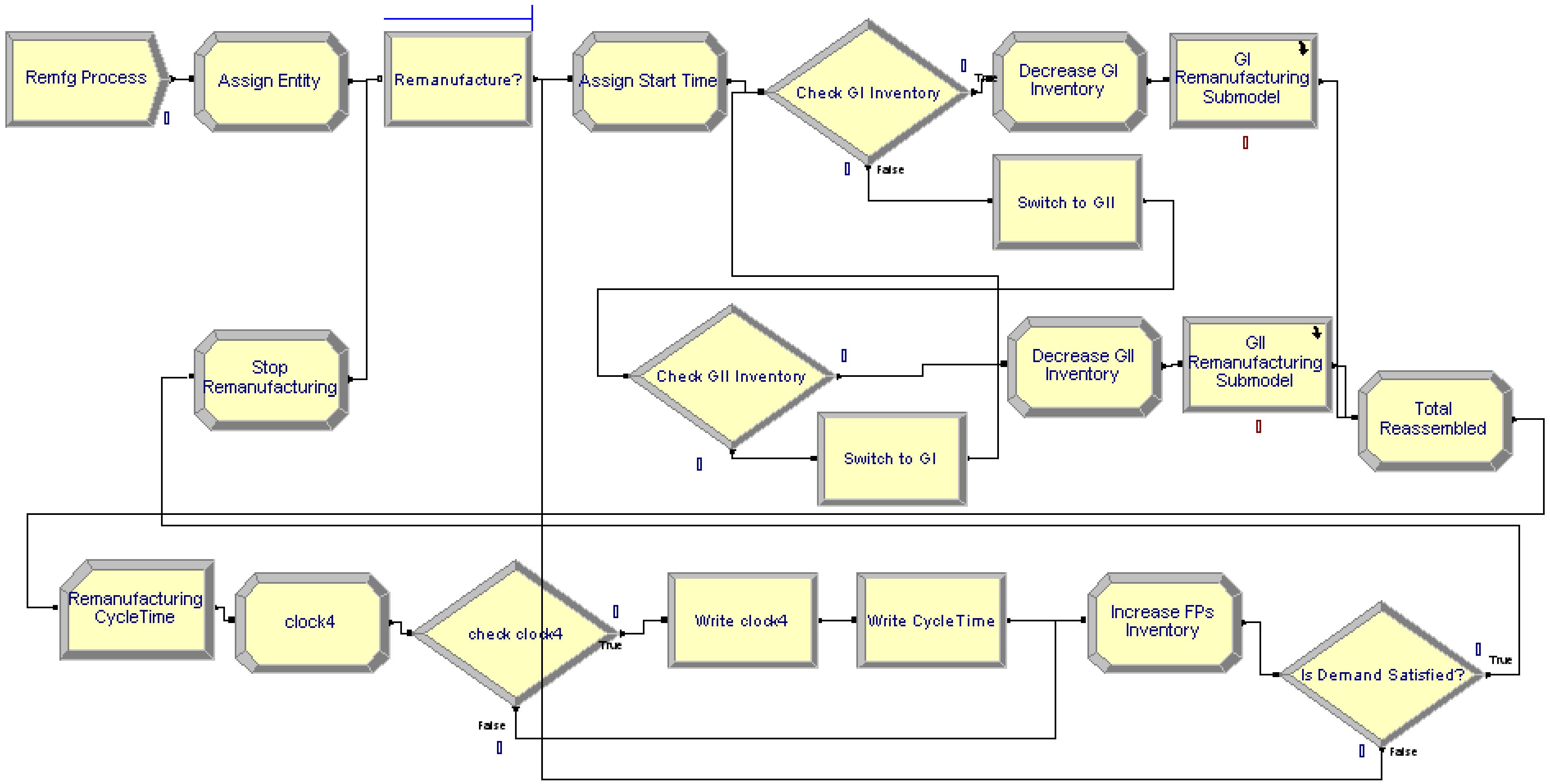


Figure 4.18: Architecture of the remanufacturing and finished products inventory control management segment of "*configF*"

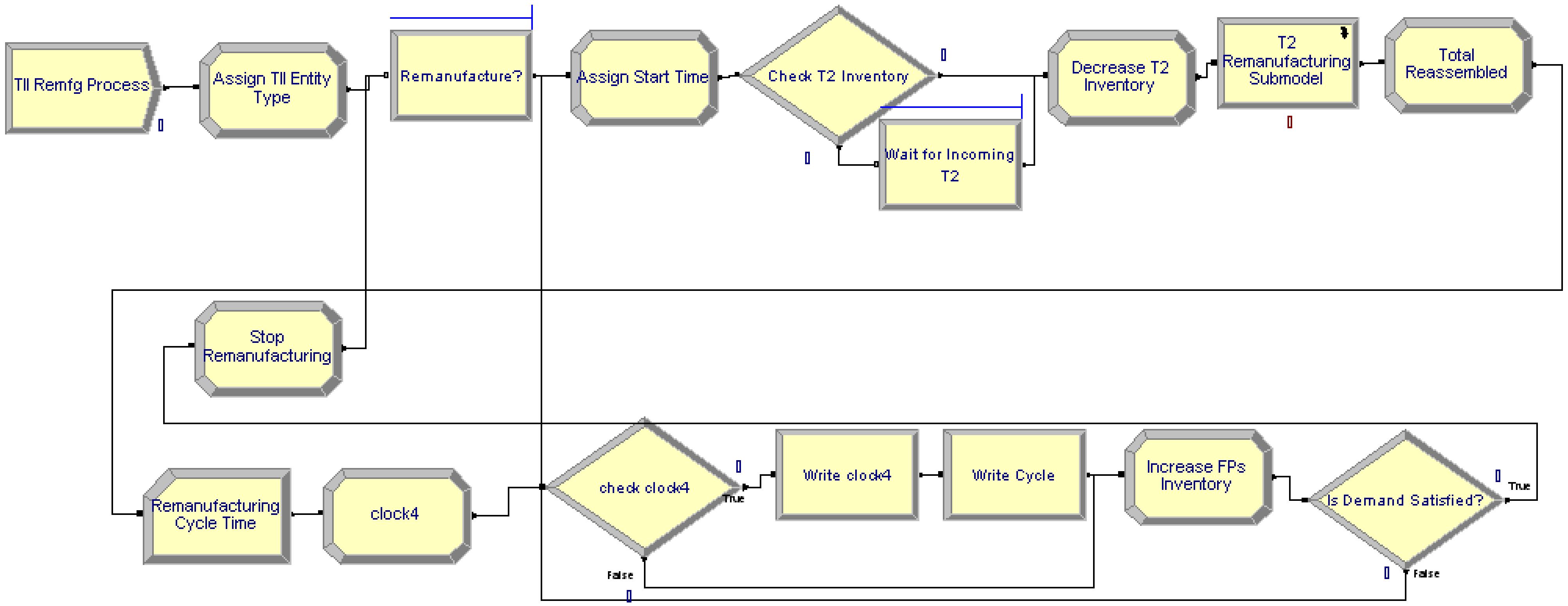


Figure 4.19: Architecture of the remanufacturing and finished products inventory control management segment of “*configG*”

4.6 Design and execution of the simulation experiments

4.6.1 Designing the simulation experiments

The simulation project takes into account three system variables (factors), namely availability of used products (availability), yields of inspection (yield) and alternative configurations of remanufacturing system (configuration). In analyses of remanufacturing systems and strategies, two values of availability (every 20 hours, every 40 hours) and three values of yield (95%, 80%, 65%) have been considered. As for configuration, four values (“*configA”*, “*configB”*, “*configC”*, “*configD”*) have been considered in analyses of RMTS systems and strategy, while three values (“*configE”*, “*configF”*, “*configG”*) have been considered in analyses of RMTO systems and strategy. These results in a $2^2x2^3x2^4$ factorial design (24 cases) in analyses of RMTS systems and strategy (table C1 in appendix C) and a $2^2x2^3x2^3$ factorial design (18 cases) in analyses of RMTO systems and strategy (table C2 in appendix C). Furthermore, data supplied by a case study company (table C3 in appendix C) have been applied as the fixed system parameters (unless indicated otherwise).

4.6.2 Executing the simulation experiments

In this thesis, simulation of the RMTS systems has been treated as a *non-terminating* simulation, whereas simulation of the RMTO systems has been considered as a *terminating* simulation. In a *non-terminating* simulation, it is important to determine a warm-up period after which, the effect of artificial initial conditions has worn off (Chung, 2004; Kelton et al., 2007). In other words, it is important to determine a warm-up period, after which the performance of a system would have been at its steady-state. By contrast, in a *terminating* simulation the determination of a warm-up period is not relevant.

Therefore, a warm-up period has been determined for each case that is given in table C1 (appendix C). This primarily involves executing the simulation model with five numbers of simulation replications and determining for each replication, a warm-up period after which the remanufacturing cycle-time has attained a steady-state condition. Based on these five warm-up periods, an average warm-up period has been determined for each case. The longest average warm-up period has been determined to be 7000 hours. This has been applied as the warm-up period in executing the simulation models at each case given in table C1 (appendix C). As an example, figures C9–C12 in appendix C, show the profiles of remanufacturing cycle-time that have been generated from a simulation model of "*configA*", "*configB*", "*configC*" and "*configD*".

Furthermore, it is important in analysis of both the *terminating* and *non-terminating* systems to determine the numbers of simulation replications that are required to analyse statistically the differences between the simulation models (Chung, 2004; Kelton et al., 2007). Accordingly, a technique introduced by Chung (2004) has been applied to determine the number of simulation replications that are required to analyse statistically the differences between the simulation models. This technique is described as follows.

Firstly, five simulation replications have been assumed and applied when executing the simulation models. Based on these five simulation replications, the mean, standard deviation and standard error of remanufacturing cycle-times have been computed, where the standard error of remanufacturing cycle-times has been computed using a formula that is given in equation 1.

Next, a relative precision (error) has been computed using a formula that is given in equation 2. If the computed relative precision is less than a value that is commonly assumed (0.10), then it is adequate to assume and apply 5 numbers of simulation replications. Otherwise, the number of simulation replications that are required has to be recomputed using a formula that is given in equation 3. Applying this technique, the number of simulation replications that are required to analyse statistically the differences between the simulation models was computed to be five replications.

$$\text{Standard error} = t_{1-\alpha/2,n-1} * s/\sqrt{n} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{eqn.(1)}$$

where;

t = t distribution for 1-α/2 and n – 1 degrees of freedom

s = standard deviation of the replication means

n = number of observations in the sample

$$\text{Relative precision} = \frac{\text{standard error}}{\overset{=}{x}} \;\ldots\ldots\ldots\ldots\ldots\; \text{eqn.(2)}$$

where;

x bar bar = mean of the replication means

$$\text{i} = \left[\frac{\text{standard error}}{\text{Relative precision} * \overset{=}{x}}\right]^{1/2} \;\ldots\ldots\ldots\ldots\ldots\ldots\; \text{eqn.(3)}$$

where;

x bar bar = mean of the replication means

In addition, the following simulation lengths have been assumed and applied to execute the simulation models: (i) fifteen years (28900 hours) in analyses of RMTS systems and strategy, (ii) one year (1920 hours) in analyses of RMTO systems and strategy, and (iii) ten years (19200 hours) in analyses of remanufacturing strategies. Finally, a technique known as a common random number stream that is recommended in the literature (Law and Kelton, 2000; Kelton et al., 2007) has been applied to ensure that differences in the results are due to the different operating conditions and policies, rather than the random effects.

4.7 Summary

This chapter has discussed the life-cycle that corresponds to the construction and analysis of the simulation models that have been defined in research objectives 2, 3 and 4 (chapter 1). Specifically, section 4.2 discussed the formulation of the problems under investigation. Section 4.3 discussed the definition, validation and architecture of conceptual models that correspond to the different remanufacturing policies. Section 4.4 discussed the coding and verification of the computer programs, as well as validation of the simulation models. Section 4.5 discussed the architecture of the major segments of the simulation models, where the computer programs codes for governing the simulation logic of these segments are described in appendix F, G, H, I, J and K. Finally, section 4.6 discussed several important issues that pertain to design and execution of the simulation experiments.

Chapter 5

The Effects of System Variables on The Performance of Remanufacturing Systems and Strategies

5.1 Introduction

This chapter discusses the findings from analyses of the effects of system variables on the performance of remanufacturing systems and strategies. Section 5.2 discusses the results from analyses of the effects of system variables on the performance of alternative RMTS-system configurations. In section 5.3, the outcomes of analyses of the effects of system variables on the performance of alternative RMTO-system configurations are discussed. Section 5.4 discusses the findings from analyses of the effects of system variables on the performance of alternative remanufacturing strategies. Finally, section 5.5 reiterates the purpose and content of this chapter.

5.2 Case study 1: The effects of system variables on the performance of alternative remanufacture-to-stock system configurations

The following subsection (5.2.1) discusses the results from an analysis of the effect of inspection yields on the average remanufacturing cycle-time of each RMTS-system configuration. Next, subsection 5.2.2 discusses the findings from an analysis of the effect of alternative RMTS-system configurations on the finished products inventory profile. In subsection 5.2.3, the results from an analysis of the effect of used products quantities on the percentage of customers whose demand have been satisfied (customer service level) are discussed. Finally, the results from an analysis of the sensitivity of each RMTS-system configuration with regards to changes in used products quantities and inspection yield are examined.

5.2.1 The effect of inspection yields on remanufacturing cycle-time of alternative remanufacture-stock-system configurations

The effect of inspection yields on average remanufacturing cycle-time of each RMTS-system configuration has been analysed under the conditions given in table C1 (appendix C). As given in table C1 (appendix C), the effect of inspection yields (henceforth, simply called yields) on remanufacturing cycle-time of each RMTS-system configuration has been analysed under the presence of used products availability (henceforth, simply called availability). Since there are two system variables of interest, yields (65%, 80%, 95%) and availability (every 2.5 days, every 5 days), the effect of yield on the average remanufacturing cycle-time has been analysed at the collapsed values of availability.

In other words, the reported average remanufacturing cycle-time at a particular value of yield, say, 65% actually corresponds to the average of two average remanufacturing cycle-times (average remanufacturing cycle-time at 65% yield, every 2.5 days availability and average remanufacturing cycle-time at 65% yield, every 5 days availability). This analysis aims to identify a configuration with a specific remanufacturing policy that would result in the shortest average remanufacturing cycle-time under the given conditions.

Figure 5.1 illustrates the findings from an analysis of the effect of yields (at collapsed availability) on the average remanufacturing cycle-time of each RMTS-system configuration. As shown in figure 5.1 and confirmed by a two-way ANOVA, the effect of yields on average remanufacturing cycle-time of each RMTS-system configuration is not significant (figures D1-D4 in appendix D). This suggests that the average remanufacturing cycle-times at collapsed availability are similar across the three percentages of yield.

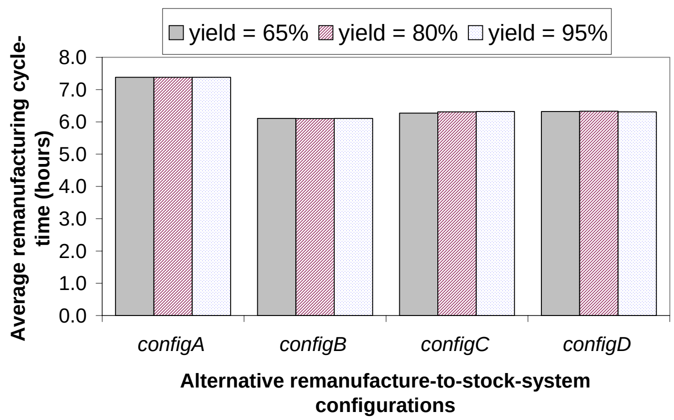


Figure 5.1: Average remanufacturing cycle-time of alternative RMTS-system configurations at different inspection yields.

Furthermore, a *Bonferroni* post-hoc test of ANOVA (figure 5.2) shows that "*configA*" and "*configB*" are significantly different from each other in terms of their average remanufacturing cycle-time. Thus, as shown in figure 5.1, "*configA*" and "*configB*", exhibit the longest and shortest average remanufacturing cycle-time, respectively. The same *Bonferroni* post-hoc test of ANOVA (figure 5.2) also reveals that the average remanufacturing cycle-times that are exhibited by "*configC*" and "*configD*" are not significantly different from each other, under all combinations of yields and availability.

The results that "*configB*" exhibits the shortest average remanufacturing cycle-time, while "*configA*" exhibits the longest average remanufacturing cycle-time confirm their expected features. As discussed in chapter 4, in "*configA*" and "*configB*", remanufacturables from both the GI & GII quality groups are processed simultaneously. In "*configA*", resources are shared for processing remanufacturables from the GI & GII quality groups. By contrast, in "*configB*", individual resources are dedicated for processing remanufacturables from the GI & GII quality groups. Accordingly, between "*configA*" and "*configB*", "*configA*" with a policy of simultaneous processing of remanufacturables from the GI & GII quality groups and utilising shared resources would exhibit a longer remanufacturing cycle-time.

Multiple Comparisons

Dependent Variable:Cycletime

	(I) Model	(J) Model	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Lower Bound	95% Confidence Upper Bound
Bonferroni	*configA*	*configB*	1.27*	.011	.000	1.24	1.30
		configC	1.08*	.011	.000	1.05	1.11
		configD	1.06*	.011	.000	1.03	1.09
	configB	*configA*	-1.27*	.011	.000	-1.30	-1.24
		configC	-.19*	.011	.000	-.22	-.16
		configD	-.21*	.011	.000	-.24	-.19
	configC	*configA*	-1.08*	.011	.000	-1.11	-1.05
		configB	.19*	.011	.000	.16	.22
		configD	-.02	.011	.324	-.05	.01
	configD	*configA*	-1.06*	.011	.000	-1.09	-1.03
		configB	.21*	.011	.000	.19	.24
		configC	.02	.011	.324	-.01	.05

Based on observed means.
The error term is Mean Square(Error) = .002.
*. The mean difference is significant at the .05 level.

Figure 5.2: SPSS Output of ANOVA – *Bonferroni* post-hoc test of remanufacturing cycle-time of alternative RMTS-system configurations

The findings that "*configC*" and "*configD*" are not significantly different from each other with respect to their average remanufacturing cycle-times, contrasted their expected features. As described in chapter 4, in "*configC*", if there are insufficient remanufacturable stocks from the currently processed quality group (e.g. GI quality group), production would be suspended, while waiting for the incoming remanufacturables; although remanufacturables from the GII quality group are available.

By contrast, in "*configD*", if there are insufficient remanufacturable stocks from the currently processed quality group (e.g., GI), production would be switched to process remanufacturables from the GII quality group in order to sustain production. As a result, "*configC*" with a policy of sequential processing of GI/GII quality groups and suspending production while waiting for the incoming remanufacturables would lead to a longer average remanufacturing cycle-time, when compared to "*configD*"; in particular when there is limited supply of used products. However, the findings that the average remanufacturing cycle-times that are exhibited by "*configC*" and "*configD*" are not significantly different from each other, might results from the conditions given in table C1 (appendix C). It is probable that under the conditions given in table C1 (appendix C), a limited supply of used products does not exists.

As already stated, the reported average remanufacturing cycle-time that is plotted in figure 5.1, corresponds to the average of two average remanufacturing cycle-times. Detailed analysis of the reported average remanufacturing cycle-time of "*configA*" shows that the average remanufacturing cycle-times are similar across the six combinations of yield and availability (table 5.1). Furthermore, for "*configB*", "*configC*" and "*configD*", comparable observation is also found (tables D1-D3 in appendix D). Thus, in each of the RMTS-system configuration, the average remanufacturing cycle-times are similar across the six combinations of yields and availability.

Table 5.1:
Average remanufacturing cycle-time (hours) of "*configA*" under six combinations of yields and availability

Availability of used products	Inspection yield (%)		
	65%	80%	95%
Every 2.5 days	7.37	7.38	7.38
Every 5 days	7.39	7.38	7.38

Based on the preceding discussion, it can be established that under the conditions employed in this part of the analysis, the average remanufacturing cycle-time of alternative RMTS-system configurations with different policies is not affected by the inspection yields. Furthermore, it can be established that for processing two different quality remanufacturable groups in a RMTS-system, a policy that specifies simultaneous processing and utilising dedicated resources, provides a better mechanism to achieve a significantly shorter average remanufacturing cycle-time.

By contrast, when resources are finite, a policy that specifies sequential processing and switching between the two quality remanufacturable groups to sustain production provides a better mechanism to achieve a shorter remanufacturing cycle-time. Clearly, in any company the ability of its production facility to achieve a shorter remanufacturing cycle-time is important for replenishing the finished products inventory, which is imperative for providing a high customer service level.

5.2.2 The effect of alternative remanufacture-to-stock system configurations on finished products inventory profile

The effect of alternative RMTS-system configurations on a typical long-run profile of the finished products inventory (henceforth, the long-run term is omitted) has been analysed under the conditions that are indicated by cases No. 3, 9, 15 & 21 in table C1 (appendix C). This analysis aims to identify a remanufacturing policy that would result in the shortest average time to replenish the finished products inventory up to a target-level, which is critical for providing a high customer service level.

Figures 5.3, 5.4, 5.5 and 5.6 illustrate the typical finished products inventory profiles that correspond to the policies that are represented by "*configA*", "*configB*", "*configC*" and "*configD*", respectively. As shown in each figure, the finished products inventory cycle starts with an inventory of 100 units, which then increases progressively with production to a target-level of 500 units. When production is suspended, the inventory level decreases to a reorder-level of 100 units and as the cycle is repeated, it increases progressively with production to a target-level of 500 units.

The average time taken for the finished products inventory to reach its target-level (henceforth, called T_t, target-time) has been computed approximately to be 225 hours for "*configA*", 186 hours for "*configB*", 489 hours for "*configC*" and 459 hours for "*configD*". Likewise, the inventory cycle-time, T_c, has been computed approximately to be 755 hours for "*configA*", 714 hours for "*configB*", 1016 hours for "*configC*" and 988 hours for "*configD*".

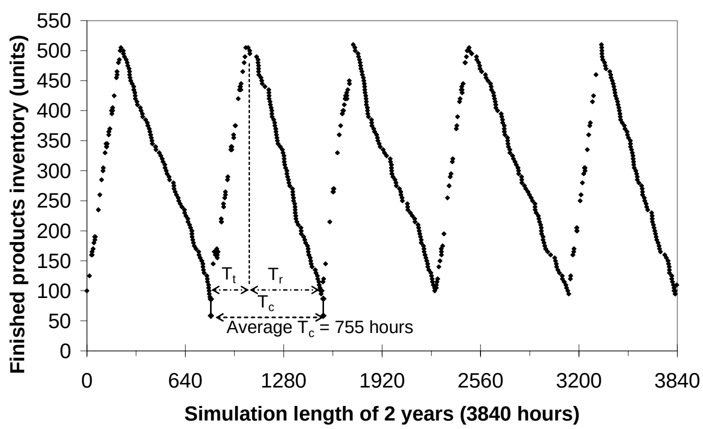


Figure 5.3: A typical finished products inventory profile of "*configA*" simulated over a period of 2 years

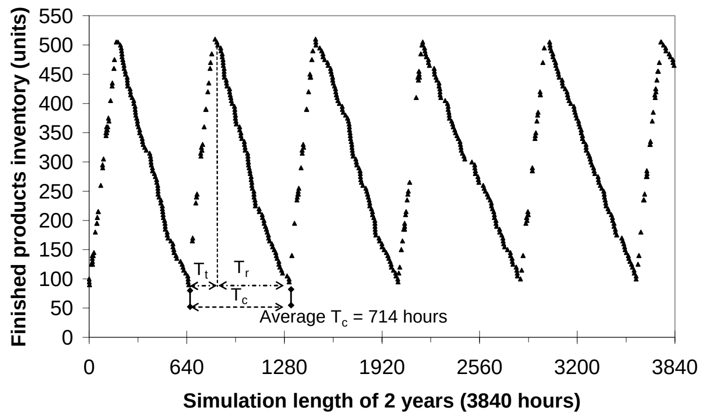


Figure 5.4: A typical finished products inventory profile of "*configB*" simulated over a period of 2 years

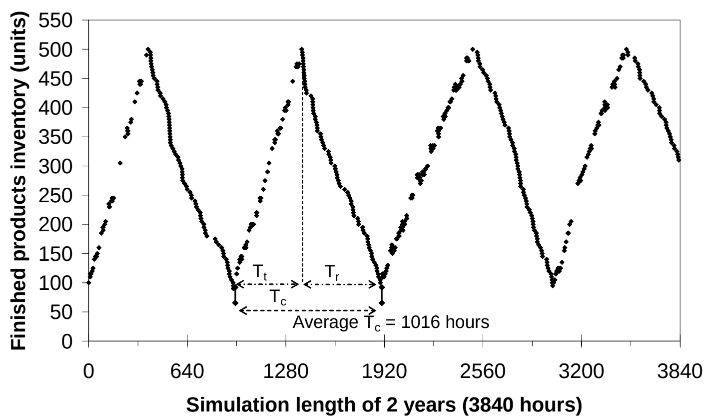


Figure 5.5: A typical finished products inventory profile of "*configC*" simulated over a period of 2 years

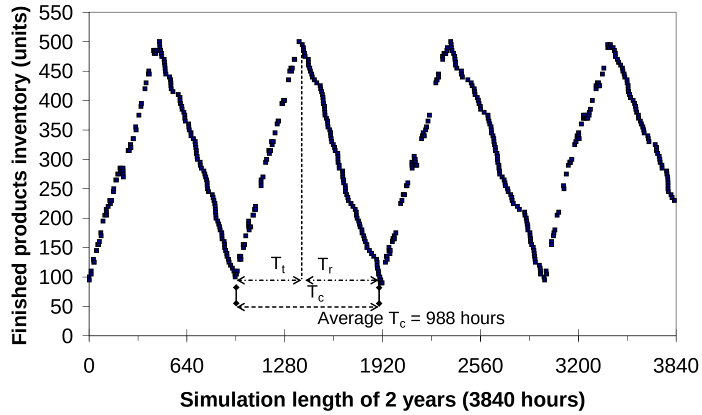


Figure 5.6: A typical finished products inventory profile of "*configD*" simulated over a period of 2 years

The findings show that for processing two different quality remanufacturable groups (GI & GII), "*configB*" with a policy of simultaneous processing and utilising dedicated resources exhibits a shorter average target-time, when compared to "*configA*" with a policy of simultaneous processing and utilising shared resources. As expected, under normal conditions, "*configB*" would exhibit a shorter average remanufacturing cycle-time than "*configA*". Therefore for "*configB*", the shorter average remanufacturing cycle-time would result in a shorter average target-time, which would lead to a higher average on-hand finished products inventory.

Given that the same demand rate is applied in all configurations, the average time taken for the finished products inventory to reach its reorder-level (reorder-time) would be relatively similar. Hence, "*configB*", with a shorter average target-time would have a shorter inventory cycle-time than "*configA*", which would result in more number of inventory cycles. As shown in Figures 5.3 and 5.4, "*configA*" exhibits 6.5 inventory cycles over a period of 2 years, while "*configB*" exhibits a slightly more number of inventory cycles over the same period of time.

The findings also show that "*configC*" with a policy of sequential processing of GI/GII quality groups and suspending production while waiting for the incoming remanufacturables (GI/GII), exhibits a longer average target-time than that is exhibited in "*configB*". As expected, under normal conditions, "*configC*" would exhibit a longer average remanufacturing cycle-time than "*configB*". Therefore, a longer average remanufacturing cycle-time would result in a longer average target-time, which subsequently results in a lower average on-hand finished products inventory. Consequently, between "*configB*" and "*configC*", "*configC*" with a longer average target-time would exhibit a longer inventory cycle-time, which would result in less number of inventory cycles (3.75 over a period of 2 years) than that exhibited by "*configB*".

In "*configC*", a policy of sequential processing of GI/GII quality groups and suspending production, while waiting for the incoming remanufacturables (GI/GII), contributes to its longer average remanufacturing cycle-time, which results in a longer average target-time. The alternative to this policy as provided in "*configD*" with a policy of sequential processing of GI/GII quality groups and switching between the GI & GII quality groups, results in a shorter average remanufacturing cycle-time. This shorter average remanufacturing cycle-time leads to a shorter average target-time, which leads to a higher average on-hand finished products inventory. Therefore, under the same demand rate, "*configD*" with a shorter average target-time would exhibit a shorter inventory cycle-time, which would lead to a more number of inventory cycles than that exhibited by "*configC*".

As already stated, the ability of a production facility to replenish its finished products inventory at a faster rate is important for providing a high customer service level, above all when the customer demand occur more frequently. Findings from the analysis that considers a more frequent arrival of customer demand show that the performances of “*configA*”, “*configC*” and “*configD*” have deteriorated, whereas the performance of “*configB*” has slightly deteriorated. Specifically, when the interarrival of customer demand is every 4 days (i.e., reduced by one day), the resulting average target-times of “*configA*”, “*configB*”, “*configC*” and “*configD*” have been computed approximately to be those tabulated in table 5.2. The corresponding typical finished products inventory profiles that have been generated from “*configA*”, “*configB*”, “*configC*” and “*configD*” , when the interarrival of customer demand is every 4 days are shown in figures D5-D8 in appendix C.

Table 5.2:
Average target-time, reorder-time and inventory cycle-time of alternative RMTS-system configurations

Interarrival of customer demand	Average time (hours)	Alternative configurations			
		“*configA*”	“*configB*”	“*configC*”	“*configD*”
Every 5days	T_t	225	186	489	459
	T_r	530	528	527	529
	T_c	755	714	1016	988
Every 4days	T_t	245	190	661	629
	T_r	439	437	438	438
	T_c	684	627	1099	1067

T_t = target-time ; T_r = reorder-time; T_c = inventory cycle-time

Referring to table 5.2, it can be seen that regardless of the alternative RMTS-system configurations, the average target-time increases as customer demand occurs more frequently. For example, considering "*configA*", the average target-time increases from 225 hours to 245 hours when the interarrival of customer demand is reduced to every 4 days. As expected, when the arrival of customer demand becomes more frequent, the consumption of finished products inventory would also become faster, which results in a longer average target-time. In addition, the frequent arrival of customer demand would also result in a shorter average reorder-time. As shown in table 5.2 and taking "*configA*" as an example, the average reorder-time decreases from 530 hours to 439 hours when the interarrival of customer demand is reduced to every 4 days.

Based on the preceding discussion, it can be established that the typical finished products inventory profile is affected by the alternative RMTS-system configurations with different policies and the arrival frequency of customer demand. Moreover, for processing two different quality remanufacturable groups in a RMTS-system, a policy that specifies simultaneous processing and utilising dedicated resources provides a better mechanism to achieve a faster replenishment rate of the finished products inventory.

By contrast, when resources are finite, a policy that specifies sequential processing and switching between the two quality remanufacturable groups to sustain production, offers a better mechanism to achieve a faster replenishment rate of the finished products inventory. Consequently, on the basis of available resources and arrival frequency of customer demand, companies should select and implement the appropriate remanufacturing policy, such that a high customer service level is achieved. What is more, factors such as demand volume of finished products, quantities of used products and quality conditions of used products have to be considered when selecting the type of remanufacturing policy to implement.

5.2.3. The effect of used products quantities on customer service level of alternative remanufacture-to-stock system configurations

In the previous subsections (5.2.1 & 5.2.2), the analyses have been conducted under the conditions that are given in table C1 (appendix C), where the quantities of used products available for remanufacturing has been considered as relatively sufficient (provided by our case-study company). However, as argued in chapter 2, the quantities of used products available for remanufacturing is quite uncertain, particularly for products that has just been introduced into the market. Consequently, it is important to analyse the effect of uncertain used products quantities on the service level that could be provided to the customers.

In this part of analysis, the customer service level that could be provided by any of the RMTS-system configuration with a specific policy is defined as the percentage of customers whose demand for finished products has been satisfied. Furthermore, the effect of used products quantities on the customer service level has been examined under the following conditions:

- Customers arriving at every 12 hours and their demand for finished product follows a uniform distribution, where the quantity is Unif(3,8) units.
- Used products arriving at every 20 hours and the quantities are 10 units, 20 units, 30 units, 40 units, 50 units, 60 units, 70 units, 80 units, 90 units and 100 units.

The general finding shows that the customer service level is affected by the quantities of used products, where high quantities of used products results in a high percentage of satisfied customers. Moreover, the customer service level is also affected by the alternative RMTS-system configurations with different policies. As depicted in figure 5.7, "*configB*", exhibit the highest percentage of satisfied customers under all conditions of used products quantities. As established, "*configB*" which exhibits the shortest average target-time, would result in the highest average on-hand finished products inventory. Accordingly, under the same demand rate and given period of time, "*configB*" with the highest average on-hand finished products inventory, would lead to the highest percentage of customers whose demand have been satisfied (i.e., the highest customer service level).

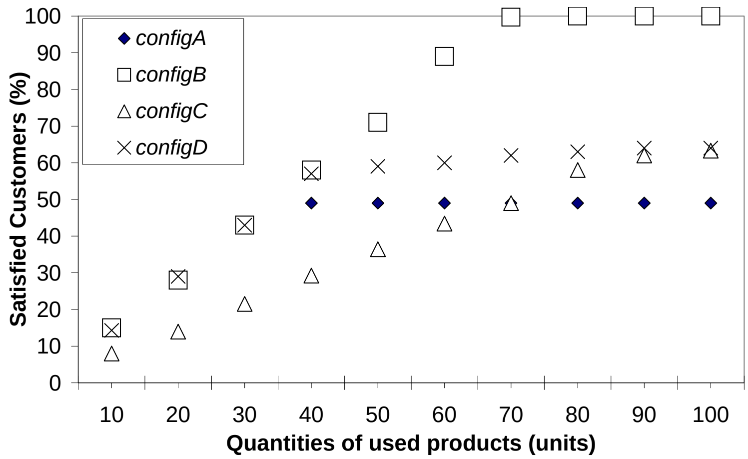


Figure 5.7: The effect of used products quantities on percentage of satisfied customers of alternative RMTS-system configurations.

Figure 5.7 also reflects that between "*configB*", "*configC*" and "*configD*", "*configC*" exhibits the lowest percentage of satisfied customers under all conditions of used products quantities. As expected, between "*configB*", "*configC*" and "*configD*", "*configC*" with the longest average target-time would result in the lowest average on-hand finished products inventory, which would lead to the lowest percentage of satisfied customers. As for "*configA*", it exhibits a similar percentage of satisfied customers with "*configB*" and "*configD*" when the quantities of used products are between 10 units to 30units. Beyond the quantities of used products of 30 units, "*configA*" exhibits a lower percentage of satisfied customers than "*configB*" and "*configD*".

Moreover, it seems that for "*configA*", increasing the quantities of used products beyond 30 units provides little improvement to the customer service level. This further suggests that despite the abundant supply of used products, the service level that could be provided to customers by "*configA*" is constrained by the available resources; a similar case for "*configC*" and "*configD*". Accordingly, for "*configA*", "*configC*" and "*configD*" it would be necessary to allocate surplus resources in order to achieve a 100% customer service level. By contrast, for "*configB*" with two units of resources dedicated for processing each GI & GII quality groups, it seems unnecessary to allocate surplus resources because the maximum achievable customer service level would already be 100%.

Therefore, can it be established that the customer service level in a RMTS system is influenced by the quantities of used products available for remanufacturing. Besides, the customer service level is also influenced by the alternative remanufacturing policies, where a policy that specifies simultaneous processing of GI & GII quality groups and utilising dedicated resources provides a better mechanism to achieve a high percentage of satisfied customers. By contrast, when resources are finite, a policy that specifies sequential processing of GI/GII quality groups and switching between the GI & GII quality groups to sustain production provides a better mechanism to achieve a high percentage of satisfied customers.

5.2.4 The sensitivity of alternative remanufacture-to-stock system configurations with respects to changes in system variables

A sensitivity analysis has been conducted to examine the effect of changes in system variables on the robustness of each RMTS-system configuration. For this analysis, cases No. 6, 12, 18 and 24 in table C1 (appendix C) has been selected as the base case of "*configA*", "*configB*", "*configC*" and "*configD*", respectively. Therefore, this analysis aims to test the performance (remanufacturing cycle-time) of each configuration with a specific policy, with regards to changes in the quantities of used products and yields of inspection.

Findings from the analysis enable the identification of a configuration with a specific policy that is sensitive to changes (+20% and -20%) in the quantities of used products and yields of inspection.

Results of the sensitivity analysis (table 5.3) show that the average remanufacturing cycle-times of "*configA*", "*configB*" and "*configD*" are not affected by changes in the quantities of used products. However, the average remanufacturing cycle-time of "*configC*" is significantly affected by changes in the quantities of used products, where a decrease of 20% in the quantities of used products results in a change of 140% in the average remanufacturing cycle-time. As discussed, "*configC*" with a policy of sequential processing of GI/GII quality groups and suspending production, while waiting for the incoming remanufacturables, exhibits the longest average remanufacturing cycle-time. Thus, a small decrease in the quantities of used products would result in aggravating the remanufacturing cycle-time because production would be suspended more often and for a longer time, while waiting for the incoming remanufacturables.

Table 5.3:
The effect of changes in used products quantities on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand of every 40 hours.

Changes in used products quantities	Alternative configuration			
	"*configA*"	"*configB*"	"*configC*"	"*configD*"
+20%	0%	0%	0%	0%
-20%	0%	0%	140%	0%

Table 5.3 also shows that despite an increase of 20% in the quantities of used products, the average remanufacturing cycle-time of "*configC*" still remains unchanged. This finding support the argument presented in subsection 5.2.4, where additional resources are necessary in order to improve the customer service level. Similar findings were found when considering a more frequent arrival of customer demand.

Specifically, findings show that under conditions of more frequent arrival of customer demand, a decrease of 20% in the quantities of used products results in a change of 170% in the average remanufacturing cycle-time of “*configC*” (table D4 in appendix D). Comparing this percentage of change in the average remanufacturing cycle-time (170%) with those reported earlier (140%), it can be assumed that the effect of decreasing the quantities of used products is more prominent under conditions of more frequent arrival of customer demand.

Regarding a sensitivity analysis related to changes in the inspection yields, results show that the average remanufacturing cycle-time of all configurations is not affected by changes in the yields of inspection (table D5 in appendix D). However, when the sensitivity analysis was conducted considering a more frequent arrival of customer demand, findings show that the average remanufacturing cycle-time of “*configC*” is significantly affected by the changes in the yields of inspection.

Specifically, a decrease of 20% in the yield of inspection results in a change of 99% in the average remanufacturing cycle-time (table 5.4). As discussed, amongst all configurations, “*configC*” exhibits the longest average remanufacturing cycle-time. Therefore, a small decrease in the yields of inspection, will lead to a decrease in the quantities of used products. This would aggravate remanufacturing cycle-time because production would be suspended more often and for a longer time while waiting for the incoming remanufacturables.

Table 5.4:
The effect of changes in inspection yields on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand every 32 hours

Changes in inspection yields	Alternative configurations			
	“*configA*”	“*configB*”	“*configC*”	“*configD*”
+20%	0%	0%	0%	0%
-20%	0%	0%	99%	0%

Therefore, it can be established that the performance of a configuration with a policy that specifies sequential processing of GI/GII quality groups and suspending production while waiting for the incoming remanufacturables is significantly affected by changes in the quantities of used products and yield of inspection. As a natural result of this, it can be established that the replenishment rate of finished products inventory and hence the customer service level would also be significantly affected by changes in the quantities of used products and yields of inspection.

Consequently, it can be established that under conditions of uncertain quantities of used products that are available and yields of inspection, a policy other than sequential processing of GI/GII quality groups and suspending production, while waiting for the incoming remanufacturables would provides a better mechanism to cope with uncertainties. This agrees with the normal real-industries practice, where production is specified to process the available remanufacturable stocks (regardless of the quality groups) in order to sustain production and meet the customer demand.

5.3 Case study 2: The effects of system variables on the performance of alternative remanufacture-to-order system configurations

In the following subsection (5.3.1), the findings from an analysis of the effect of inspection yields on average remanufacturing cycle-time of each RMTO-system configuration are examined. Then, subsection 5.3.2 discusses the findings from an analysis of the effect of used products quantities on the percentage of customers whose demand has been satisfied within one day of placing an order (customer service level). Finally, in subsection 5.3.3, the findings from an analysis of the sensitivity of each RMTO-system configuration with regards to changes in used products quantities and yields of inspection are discussed.

5.3.1 The effect of inspection yields on remanufacturing cycle-time of alternative remanufacture-to-order system configurations

In this part of the analysis, the effect of inspection yields on average remanufacturing cycle-time of each RMTO-system configuration has been analysed under the conditions that are given in table C2 (appendix C). Since there are two system variables of interest, namely yields (65%, 80%, 95%) and availability (every 2.5 days, every 5 days), the effect of yields on remanufacturing cycle-time has been analysed at the collapsed values of availability. This analysis aims to identify a configuration with a specific policy that would result in the shortest average remanufacturing cycle-time under the given conditions.

Figure 5.8 illustrates the finding from an analysis of the effect of yields (at collapsed availability) on the average remanufacturing cycle-time of each RMTO-system configuration. As shown in figure 5.8 and confirmed by a two-way ANOVA (figures D9-D11 in appendix D), the effect of yield on the average remanufacturing cycle-time of each RMTO-system configuration is significant. This suggests that the average remanufacturing cycle-times at collapsed availability are different across the three percentages of yield.

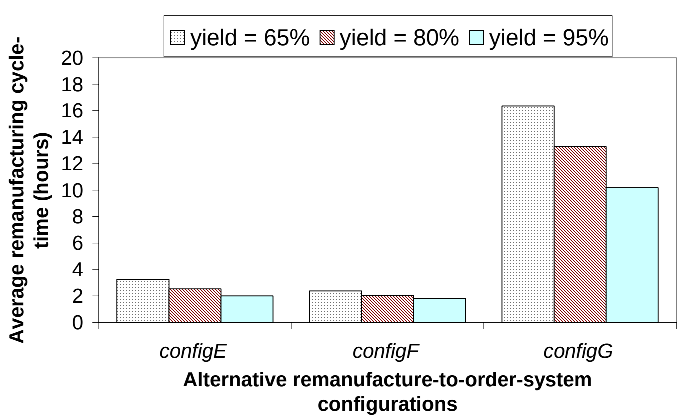


Figure 5.8: Average remanufacturing cycle-time of alternative RMTO-system configurations at different inspection yields.

Furthermore, a *Bonferroni* post-hoc test of ANOVA (figure 5.9) reveals that "*configF*" and "*configG*" are significantly different from each other with respect to their average remanufacturing cycle-time. Thus, as illustrated in figure 5.8, "*configF*" and "*configG*", exhibit the shortest and longest average remanufacturing cycle-time, respectively. The same *Bonferroni* post-hoc of ANOVA also shows that the average remanufacturing cycle-times that are exhibited by "*configE*" and "*configF*" are not significantly different from each other, under all combinations of yields and availability.

The results that "*configF*" and "*configG*", exhibit the shortest and longest average remanufacturing cycle-time, respectively, confirms their expected features. As discussed in chapter 4, in both "*configE*" and "*configG*", one quality remanufacturable group is being processed (GI quality group in "*configE*" and GII quality group in "*configG*"); if there are insufficient remanufacturable stocks, production would be suspended while waiting for the incoming remanufacturables. In "*configF*", even though both GI & GII quality remanufacturable groups are considered for processing, only one quality group is being processed at a time. If there are insufficient remanufacturable stocks from the currently processed quality group, (say GI), production is switched to process remanufacturables from the other quality group (GII).

Multiple Comparisons

Dependent Variable:Cycletime

	(I) Model	(J) Model	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Lower Bound	95% Confidence Upper Bound
Bonferroni	*configE*	*configG*	-10.68*	.250	.000	-11.29	-10.06
		configF	.52	.250	.124	-.09	1.13
	configG	*configE*	10.68*	.250	.000	10.06	11.29
		configF	11.19*	.250	.000	10.58	11.81
	configF	*configE*	-.52	.250	.124	-1.13	.09
		configG	-11.19*	.250	.000	-11.81	-10.58

Based on observed means.

The error term is Mean Square(Error) = .935.

*. The mean difference is significant at the .05 level.

Figure 5.9: SPSS Output of ANOVA – *Bonferroni* post-hoc test of remanufacturing cycle-time of alternative RMTO-system configurations.

Accordingly, amongst all configurations, "*configG*" with a policy that specifies processing remanufacturables from the GII quality group only, would exhibit the longest average remanufacturing cycle-time. As stated in chapter 4, remanufacturables from the GII quality group has a lower quality conditions than those from the GI quality group; thus would require a longer reprocessing times for the constituent components. On the other hand, "*configF*" would exhibit the shortest average remanufacturing cycle-time because of its ability to sustain production by switching between the GI & GII quality remanufacturable groups.

Furthermore, the findings that "*configE*" and "*configF*" are not significantly different from each other with respect to their average remanufacturing cycle-time, contrasted their expected features. It is expected that "*configE*" with a policy that specifies processing remanufacturables from the GI quality group only, would exhibit a longer remanufacturing cycle-time than "*configF*", in particular when there is a limited supply of used products. Nevertheless, the findings that the average remanufacturing cycle-times that are exhibited by "*configE*" and "*configF*" are not significantly different from each other, might result from the conditions that are employed in this part of the analysis. It is probable that under the conditions given in table C2 (appendix C), a limited supply of used products does not exist.

As already stated, the reported average remanufacturing cycle-time that is plotted in figure 5.8, corresponds to the average of two average remanufacturing cycle-times. Detailed analysis of the reported average remanufacturing cycle-time of "*configE*" shows that the average remanufacturing cycle-times are different across the six combinations of yields and availability (table 5.5). Furthermore, for both "*configF*" and "*configG*", detailed analysis of the reported average remanufacturing cycle-time also reveals that the average remanufacturing cycle-times are different across the six combinations of yields and availability (tables D6-D7 in appendix D).

Therefore, in each of the RMTO-system configuration, the average remanufacturing cycle-times are different across the six combinations of yields and availability.

Table 5.5:
Average remanufacturing cycle-time (hours) of "*configE*" under six combinations of yields and availability

Availability of used products	Inspection yield (%)		
	65	80	95
Every 2.5 days	2.29	1.36	1.19
Every 5 days	4.20	3.71	2.83

Based on the above findings, it can be established that under the conditions employed in this part of the analysis, the average remanufacturing cycle-time of each RMTO-system configuration is influenced by the inspection yields. It can also be ascertained that for processing two different quality remanufacturable groups (GI & GII), a policy that specifies sequential processing and switching between the GI & GII quality remanufacturable groups to sustain production ("*configF*"), emerges as a better mechanism to achieve a significantly shorter remanufacturing cycle-time.

Furthermore, it can be established that there are conditions when the policy given in "*configF*" exhibits a similar average remanufacturing cycle-time to those exhibited by a policy which specifies processing the best quality remanufacturable group. Comparable to the case of RMTS system, the ability of a production facility to achieve a shorter remanufacturing cycle-time is crucial for replenishing the finished product inventory up to a customer demand, which is important for providing a high customer service level.

5.3.2 The effect of used products quantities on customer service level of alternative remanufacture-to-order system configurations

Similar to the argument presented in subsection 5.2.3, it is important to analyse the effect of used products quantities on the customer service level; an issue that is very critical in a RMTO production strategy. In the current part of the analysis, the customer service level that could be provided by any of the RMTO-system configuration with a specific policy is defined as the percentage of customers whose demand have been satisfied within one day of placing an order. The effect of used products quantities on the customer service level of each RMTO-system configuration with a specific policy has been analysed under the following conditions:

- Customers arriving at every 40 hours and their demand for finished products follows a uniform distribution, where the quantity is Unif(2,5).
- Used products arriving at every 32 hours and the quantities are 10 units, 20 units, 30 units, 40 units, 50 units, 60 units, 70 units, 80 units, 90 units and 100 units.

General results show that the customer service level is affected by the quantities of used products, where high quantities of used products results in a high percentage of satisfied customers. What's more, the customer service level is also affected by the alternative RMTO-system configurations. As shown in figure 5.10, "*configF*" and "*configG*", exhibit the highest and lowest percentage of satisfied customers, respectively, under all conditions of used products quantities. As expected, "*configF*" with the shortest average remanufacturing cycle-time would result in the fastest rate of replenishing the finished products inventory up to a customer's demand.

By contrast, "*configG*" with the longest average remanufacturing cycle-time time, would lead to the slowest rate of replenishing the finished products inventory up to a customer's demand. Therefore, under the same demand rate and given period of time, "*configF*" with the fastest rate of replenishing the finished products inventory up to a customer's demand, would result in the highest percentage of customers whose demand have been satisfied within one day of requesting the products (i.e., the highest customer service level), while "*configG*" would exhibit the lowest customer service level.

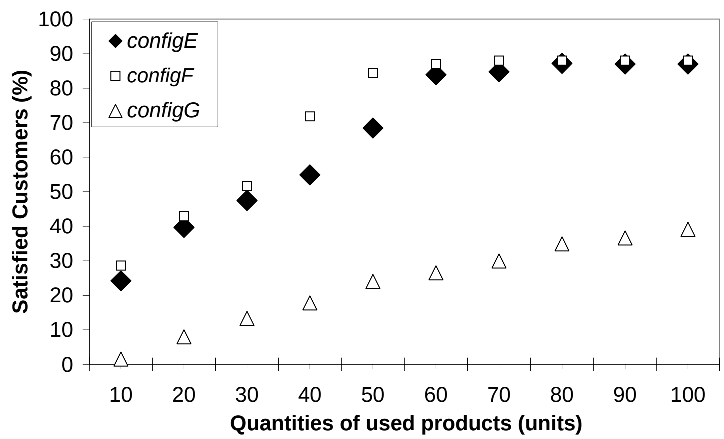


Figure 5.10: The effect of used products quantities on percentage of satisfied customers of alternative RMTO-system configurations

Figure 5.10 also shows that although the customer service level of "*configG*" improves with the quantities of used products, a maximum achievable customer service level has been approximately 39%. Moreover, it seems that increasing the quantities of used products beyond 70 units provide little improvement to the customer service level. This further suggests that despite the plentiful supply of used products, the service level that could be provided by "*configG*" to customers is inhibited by the available resources; a similar case for "*configF*". Thus, for both "*configF*" and "*configG*" with one unit of resource, it would be necessary to allocate surplus resources in order to achieve a 100% customer service level.

Figure 5.10 also reveals that "*configE"*, exhibits a slightly lower percentage of satisfied customers than "*configF"*, under all conditions of used products quantities. As expected, "*configE"* which exhibits a longer average remanufacturing cycle-time than "*configF"*, would result in a slower rate of replenishing the finished products inventory up to a customer's demand. Therefore, under the same demand rate and given period of time, "*configE"* would exhibit a lower percentage of customers whose demand has been satisfied within one day of placing an order (i.e., a lower customer service level) than "*configF"*. Equivalent to the case of "*configF"* and "*configG"*, the customer service level that could be provided by "*configE"* is also constrained by the available resources; thus, it would be necessary to allocate additional resources in order to achieve a 100% customer service level.

Based on the above discussion, it can be established that the customer service level in a RMTO environment is influenced by the quantities of used products available for remanufacturing. Furthermore, the customer service level is also influenced by the alternative configurations with different remanufacturing policies, where a policy which specifies sequential processing of GI/GII quality groups and switching between the GI & GII quality groups to sustain production, provides a better mechanism to achieve a high percentage of satisfied customers.

It can also be established that a policy which specifies simultaneous processing of the GI & GII quality groups and utilising dedicated resources, would provide a much better mechanism to achieve a high customer service level than those provided by a policy represented by "*configF"*. However, the analysis of such policy, which specifies simultaneous processing of GI & GII quality groups in a RMTO system, would lead to complex simulation logic. This would require more research time, therefore, such a policy is not considered in this thesis.

5.3.3 The sensitivity of alternative remanufacture-to-order system configurations with respects to changes in system variables

Similar to the sensitivity analysis that has been discussed in subsection 5.2.4, this subsection discusses a sensitivity analysis that has been conducted to test the performance (remanufacturing cycle-time) of each RMTO-system configuration with respects to changes in the quantities of used products and yields of inspection. Cases No. 6, 12 and 18 in table C2 (appendix C) has been selected as the base case of "*configE*", "*configF*" and "*configG*", respectively. The conclusion of this analysis would lead to the identification of a configuration with a specific policy that is sensitive to changes (+20% and -20%) in the quantities of used products and yields of inspection.

Results from the sensitivity analysis show that the average remanufacturing cycle-time of "*configE*", "*configF*" and "*configG*" are affected by changes in the quantities of used products (table 5.6). Specifically, as shown in table 5.6, an increase of 20% in the quantities of used products results in a change of 34%, 33% and 34% in the average remanufacturing cycle-time of "*configE*", "*configF*" and "*configG*", respectively. As expected, since there is only one unit of resource allocated in all configurations, then an increase of 20% in the quantities of used products would result in a similar percentage of change in the average remanufacturing cycle-time. This finding suggests that regardless of the configuration, the percentage of change in the average remanufacturing cycle-time is constrained by the resources that are allocated in each configuration.

Table 5.6:
The effect of changes in used products quantities on average remanufacturing cycle-time of alternative RMTO-system configurations – customer demand of every 40 hours.

Changes in used products quantities	Alternative configurations		
	"*configE*"	"*configF*"	"*configG*"
+20%	-34%	-33%	-34%
-20%	51%	59%	51%

Table 5.6 also reflects that a decrease of 20% in the quantities of used products results in the largest percentage of change (59%) in the average remanufacturing cycle-time of "*configF*". However, comparing this percentage (59%) with those that are exhibited by "*configE*" (51%) and "*configG*" (51%), reveals a difference of approximately 8%, which could be considered as relatively small. Therefore, it can be assumed that a decrease of 20% in the quantities of used products results in a similar percentage of change in the average remanufacturing cycle-time in all configurations.

Nevertheless, the above assumption becomes invalid when considering a more frequent arrival of customer demand. Specifically, as shown in table 5.7, for "*configF*", a decrease of 20% in the quantities of used products leads to a change of 61% in the average remanufacturing cycle-time, while the percentage remain unchanged in "*configE*" and "*configG*". As a result, it can be implied that the average remanufacturing cycle-time of "*configF*" is significantly affected by a decrease in the quantities of used products, particularly when the arrival of customer demand becomes more frequent.

As discussed, "*configF*" has a policy that specifies sequential processing of GI/GII quality groups and switching between the GI & GII quality groups in order to sustain production. Accordingly, when the arrival of customer demand becomes more frequent and there is less quantity of used products available, the production facility would frequently switch between the GI & GII quality groups in order to sustain production. Therefore, resulting in a greater percentage of change in the average remanufacturing cycle-time, compared to "*configE*" and "*configG*".

Table 5.7:
The effect of changes in used products quantities on average remanufacturing cycle-time of alternative RMTO-system configurations – customer demand of every 28 hours.

Changes in used products quantities	Alternative configurations		
	“configE”	*“configF”*	*“configG”*
+20%	-34%	-31%	-34%
-20%	51%	61%	51%

Results from the sensitivity analysis with respects to changes in the yields of inspection show that the average remanufacturing cycle-time of all configurations is not affected by an increase in inspection yields (table 5.8). By contrast, the average remanufacturing cycle-time is slightly affected by a decrease of 20% in the yields of inspection. The same findings were also found when considering a more frequent arrival of customer demand (table D8 in appendix D).

Table 5.8:
The effect of changes in inspection yields on average remanufacturing cycle-time of alternative RMTO-system configurations – customer demand of every 40 hours

Changes in inspection yields	Alternative configurations		
	“configE”	*“configF”*	*“configG”*
+20%	-18%	-16%	-18%
-20%	23%	29%	24%

As discussed, in a RMTO production strategy, the arrival of a customer’s demand initiates remanufacturing process, which is ended once that demand has been satisfied. If there are insufficient remanufacturable stocks, production would be suspended (even in *configF* when there is none stock of GI/GII remanufacturables), while waiting for the incoming remanufacturables. However, findings suggest that under the conditions that are given in table C2 (appendix C), the effect of changes in yields of inspection on the average remanufacturing cycle-time is not significant. As given in table C2 (appendix C), the lowest yield of inspection has been assumed to be 65%, which is consistent with those that is typically observed in the real-industries.

Therefore, it can be established that the performance of a configuration with a policy that specifies sequential processing of GI/GII quality remanufacturable groups and switching between the GI & GII quality groups is significantly affected by a decrease in the quantities of used products, particularly when the arrival of customer demand becomes more frequent. Therefore, it can be established that the replenishment rate of finished products inventory, would also be significantly affected by a decrease in the quantities of used products.

Secondly, it can be determined that under conditions of uncertain quantities of used products that are available, a policy that specifies sequential processing of GI/GII quality remanufacturable groups switching between the GI & GII quality groups to sustain production, would provide a better mechanism to cope with uncertainties. This as discussed in subsection 5.2.4 agrees with the real-industries practice, where production is specified to process the available remanufacturable stocks (regardless of the quality groups) in order to sustain production and meet the customer demand.

Thirdly, it can be established that under conditions of infinite used product quantities, the percentage of change in remanufacturing cycle-time in all of the configurations is controlled by the available resources. Finally, it can be established that under conditions employed in this part of the analysis, the remanufacturing cycle-time of alternative configurations with different policies is not affected by changes in the yields of inspection. This observation might not always be true in the real-industries, where a specific type of used product which originates from the waste-stream could probably exhibit a very low yield of inspection.

5.4 Case study 3: The effects of system variables on the performance of remanufacturing strategies

Unlike the preceding two sections (5.2 & 5.3), this section discusses the effects of system variables on the performance of two remanufacturing strategies. In this part of the analysis, the system variables of interest are availability of used products (every 2.5 days, every 5 days), inspection yield (65%, 80%, 95%) and configuration of remanufacturing system (*"configA"*, *"configB"*, *"configC"* and *"configD"* for RMTS-strategy and *"configE"*, *"configF"* and *"configG"* for RMTO-strategy); hereafter these system variables are simply referred as availability, yield and configuration.

The next subsections (5.4.1 & 5.4.2) discuss the findings from analyses of the main and interactions effects of availability, yield and configuration on the average remanufacturing cycle-time of RMTS-strategy and RMTO-strategy, respectively. In subsection 5.4.3, the results from an analysis of the effect of alternative remanufacturing strategies (RMTS and RMTO) on the customer service level are discussed.

5.4.1 The main and interactions effects of system variables on average remanufacturing cycle-time of remanufacture-to-stock strategy

The main effects of availability, yield and configuration, as well as their interaction effects on the average remanufacturing cycle-time of a RMTS-strategy has been examined by conducting a three-way analysis of variance (ANOVA). This three-way ANOVA aims to identify whether availability, yield and configuration or their interactions contribute to a significant effect on the average remanufacturing cycle-time of a RMTS-strategy. This part of the analysis has been carried out under the conditions given in table C1 (appendix C).

Firstly, the results from a three-way ANOVA reveal that the main effect of availability on the average remanufacturing cycle-time of the RMTS-strategy is not-significant (figure 5.11). This not-significant main effect suggests that the average remanufacturing cycle-times are similar across the two conditions of used products availability. This finding implies that overall, ignoring whether the yield of inspection is 65%, 80% or 95% and whether the configuration is "*configA*", "*configB*", "*configC*" or "*configD*", the availability of used products does not has a significant effect on the average remanufacturing cycle-time of the RMTS-strategy.

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	29.994a	23	1.304	728.310	.000	.994
Intercept	5112.589	1	5112.589	2855255.793	.000	1.000
Availability	.013	1	.013	7.516	.007	.073
Yield	.003	2	.001	.832	.438	.017
Configuration	29.952	3	9.984	5575.866	.000	.994
Availability * Yield	.000	2	.000	.028	.972	.001
Availability * Configuration	.005	3	.002	.891	.449	.027
Yield * Configuration	.013	6	.002	1.219	.303	.071
Availability * Yield *	.008	6	.001	.718	.636	.043
Error	.172	96	.002			
Total	5142.755	120				
Corrected Total	30.166	119				

a. R Squared = .994 (Adjusted R Squared = .993)

Figure 5.11: SPSS Output of a three-way ANOVA of a RMTS-strategy considering customer demand arriving at every 40 hours.

Secondly, the main effect of yield on the average remanufacturing cycle-time of the RMTS-strategy is also not-significant, which reflects that the average remanufacturing cycle-times are similar across the three conditions of inspection yield. Therefore, overall, ignoring whether the availability of used products is every 2.5 days or every 5 days and whether the configuration is "*configA*", "*configB*", "*configC*" or "*configD*", the yield of inspection does not has a significant effect on the average remanufacturing cycle-time of the RMTS-strategy.

Thirdly, the main effect of configuration on the average remanufacturing cycle-time of the RMTS-strategy is found to be significant, which indicates that the average remanufacturing cycle-times are different across the four conditions of configuration. However, as reported earlier, the *Bonferroni* post-hoc test of ANOVA reveals that the average remanufacturing cycle-time of "*configC*" and "*configD*" was not significantly different from each other. Therefore, overall, ignoring whether the availability of used products is every 2.5 days or every 5 days and whether the yield of inspection is 65%, 80% or 95%, the configuration have a significant effect on the average remanufacturing cycle-time of the RMTS-strategy.

Finally, the interactions effects of the main variables (availability, yield and configuration) on the average remanufacturing cycle-time of the RMTS-strategy are not-significant. These not-significant interactions effects of the main variables (availability, yield and configuration) reflect that the average remanufacturing cycle-times are similar under the presence of all combinations of main variables. Therefore, overall, the presence of availability, yield and configuration altogether does not have a significant effect on the average remanufacturing cycle-time of the RMTS-strategy.

Similar findings were also found when a three-way ANOVA was conducted considering a more frequent arrival of customer demand (figure 5.12). In consequence, it can be implied that under the conditions employed in this part of the analysis, the availability of used products and yield of inspection are not major issues that would have a great impact on the average remanufacturing cycle-time of the RMTS-strategy. However, this might not be always the case in the real-industries, where the unavailability of used products and low yield of inspection, would have a significant impact on the remanufacturing cycle-time, in particular under a more frequent arrival of customer demand. Therefore, it can be established that under the conditions that are investigated in this thesis, the average remanufacturing cycle-time of the RMTS-strategy is primarily influenced by the alternative configurations with different remanufacturing policies.

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	30.167a	23	1.312	894.048	.000	.995
Intercept	5103.439	1	5103.439	3478747.783	.000	1.000
Availability	.001	1	.001	.626	.431	.006
Yield	.003	2	.001	.989	.376	.020
Model	30.131	3	10.044	6846.159	.000	.995
Availability * Yield	.004	2	.002	1.381	.256	.028
UPs * Model	.004	3	.001	.994	.399	.030
Yield * Model	.014	6	.002	1.548	.171	.088
Availability * Yield * Model	.010	6	.002	1.164	.332	.068
Error	.141	96	.001			
Total	5133.747	120				
Corrected Total	30.308	119				

a. R Squared = .995 (Adjusted R Squared = .994)

Figure 5.12: SPSS Output of a three-way ANOVA of a RMTS-strategy considering customer demand arriving at every 32 hours.

5.4.2 The main and interactions effects of system variables on average remanufacturing cycle-time of remanufacture-to-order strategy

Like subsection 5.4.1, the main effects of availability, yield and configuration, as well as their interaction effects on the average remanufacturing cycle-time of a RMTO-strategy have also been examined by using a three-way analysis of variance. This three-way analysis of variance aims to identify whether availability, yield and configuration or their interactions contribute to a significant effect on the average remanufacturing cycle-time of a RMTO-strategy. This part of the analysis has been conducted under the conditions given in table C2 (appendix C).

Firstly, the results from a three-way ANOVA reveal that the main effect of availability on the average remanufacturing cycle-time of the RMTO-strategy is significant (figure 5.13). This significant main effect suggests that the average remanufacturing cycle-times are different across the two conditions of used product availability. This finding implies that overall, ignoring whether the yield of inspection is 65%, 80% or 95% and whether the configuration is "*configE*", "*configF*" or "*configG*", the availability of used products has a significant effect on the average remanufacturing cycle-time of a RMTO-strategy.

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3265.087a	17	192.064	205.368	.000	.980
Intercept	3222.027	1	3222.027	3445.218	.000	.980
Availability	377.485	1	377.485	403.633	.000	.849
Yield	106.365	2	53.183	56.866	.000	.612
Configuration	2395.520	2	1197.760	1280.729	.000	.973
Availability * Yield	21.507	2	10.753	11.498	.000	.242
Availability * Configuration	242.458	2	121.229	129.627	.000	.783
Yield * Configuration	93.358	4	23.340	24.956	.000	.581
Availability * Yield * Configuration	28.394	4	7.098	7.590	.000	.297
Error	67.336	72	.935			
Total	6554.450	90				
Corrected Total	3332.423	89				

a. R Squared = .980 (Adjusted R Squared = .975)

Figure 5.13: SPSS Output of a three-way ANOVA of a RMTO-strategy considering customer demand arriving at every 40 hours.

Secondly, the main effect of yield on the average remanufacturing cycle-time of the RMTO-strategy is also found to be significant, which reflects that the average remanufacturing cycle-times are different across the three conditions of inspection yield. Thus, overall, ignoring whether the availability of used products is every 2.5 days or every 5 days and whether the configuration is "*configE*", "*configF*" or "*configG*", the inspection yield has a significant effect on the average remanufacturing cycle-time of the RMTO-strategy.

Thirdly, the main effect of configuration on the average remanufacturing cycle-time of the RMTO-strategy is found to be significant, which indicates that the average remanufacturing cycle-times are different across the three conditions of configuration. However, as reported earlier, the *Bonferroni* post-hoc test of ANOVA reveals that the average remanufacturing cycle-time of "*configE*" and "*configF*" was not significantly different from each other. Therefore, overall, ignoring whether the availability of used products is every 2.5 days or every 5 days and whether the yield of inspection is 65%, 80% or 95%, the configurations have a significant effect on the average remanufacturing cycle-time of the RMTO-strategy.

Finally, the interactions effects of the main variables (availability, yield and configuration) on the average remanufacturing cycle-time of the RMTO-strategy are found to be significant. These significant interactions effects of variables reflect that the average remanufacturing cycle-times are different under the presence of all combinations of main variables. Consequently, overall, the presence of availability, yield and configuration altogether have a significant effect on the average remanufacturing cycle-time of the RMTO-strategy.

The same findings were also found when a three-way ANOVA was conducted considering a more frequent arrival of customer demand (figure 5.14). In consequence, it can be implied that under the conditions employed in this part of the analysis, the availability of used products, yield of inspection and configuration of remanufacturing systems are the major issues that would have an immense impact on the average remanufacturing cycle-time of a RMTO-strategy. Therefore, it can be established that under the conditions that are investigated in this thesis, the average remanufacturing cycle-time of a RMTO-strategy is influenced by the availability of used products, yield of inspection and alternative configurations with different policies. This supports general knowledge that a RMTO-strategy is more susceptible to a variation in the system's variables.

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2920.542a	17	171.797	430.770	.000	.990
Intercept	3256.486	1	3256.486	8165.446	.000	.991
Availability	331.422	1	331.422	831.022	.000	.920
Yield	94.329	2	47.165	118.263	.000	.767
Model	2188.280	2	1094.140	2743.491	.000	.987
Availability * Yield	18.691	2	9.346	23.434	.000	.394
Availability * Model	201.951	2	100.975	253.190	.000	.876
Yield * Model	67.225	4	16.806	42.140	.000	.701
Availability * Yield * Model	18.643	4	4.661	11.687	.000	.394
Error	28.715	72	.399			
Total	6205.742	90				
Corrected Total	2949.256	89				

a. R Squared = .990 (Adjusted R Squared = .988)

Figure 5.14: SPSS Output of a three-way ANOVA of a RMTO-strategy considering customer demand arriving every 28 hours.

5.4.3 The effect of alternative remanufacturing strategies on customer service level

The effect of two remanufacturing strategies, namely a RMTS-strategy and a RMTO-strategy on the customer service level has been analysed under the following conditions: Customers arriving at every 32 hours and their demand follows a uniform distribution, where the quantities are Unif(3,6). Used products arriving at every 40 hours and the quantities are 112 units. Specifically, this analysis aims to compare the performance of a RMTS-strategy and a RMTO-strategy with respect to the percentage of customers whose demand has been satisfied within one day of placing an order (i.e., the customer service level).

The results from this analysis would enable the identification of a strategy that is better at achieving a high customer service level under the conditions stated above. For the current analysis, "*configD*" (with one unit of resource) and "*configF*" have been selected as the configurations that represent a RMTS-strategy and RMTO-strategy, respectively. The current analysis has been conducted considering one case of RMTO-strategy and five cases of RMTS-strategy, in which the cases of the RMTS-strategy are different in terms of the target-level of the finished products inventory.

The general findings show that the customer service level is affected by the different remanufacturing strategies, where a strategy that specifies carrying some finished products inventory at all times, results in a higher percentage of satisfied customers (figure 5.15). As illustrated in figure 5.15, the RMTO-strategy exhibits the lowest percentage of satisfied customers (36%), while the RMTS-strategy with a target-level of 300 units, exhibits the highest percentage of satisfied customers (98%). As expected, the RMTO-strategy with zero on-hand finished products inventory would result in customers having to wait for their demand. By contrast, the RMTS-strategy with some on-hand finished products inventory would result in the meeting customer demand immediately.

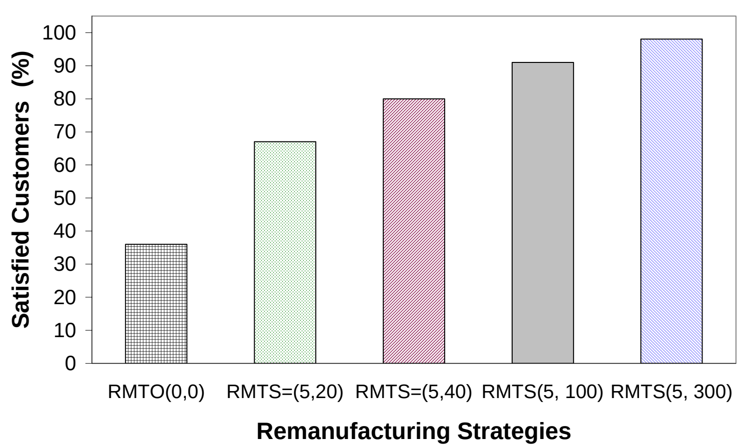


Figure 5.15: The effect of remanufacturing strategies on percentage of satisfied customers

Figure 5.15 also shows that for the RMTS-strategy, the customer service level is influenced by the target-level of the finished products, where a high target-level (300 units) resulted in a high percentage of satisfied customers (98%). As previously mentioned, in a RMTS-strategy the average on-hand finished products inventory is controlled by the target-level of the finished products. Consequently, decreasing the target-level would result in a smaller average on-hand finished products inventory, which would lead to a lower percentage of customers whose demand can be satisfied immediately (i.e., a lower customer service level).

For the RMTS-strategy, the smallest on-hand finished product inventory that has been simulated without violating the simulation logic has been achieved with a reorder-level of 3 units and a target-level of 6 units. This case, which closely resembles a RMTO-strategy, has resulted in a customer satisfaction of 44%, which is higher than a pure RMTO-strategy (36%). This finding suggests that even with a small on-hand finished product inventory, the RMTS-strategy offers a higher percentage of satisfied customers than a pure RMTO-strategy.

Therefore, it can be established that the RMTO-strategy is poor at providing a high customers satisfaction. In this case, it would be necessary to allocate more resources in order to achieve a high remanufacturing rate. Consequently, a higher remanufacturing rate would result in meeting customer demand at an earlier time, thus increasing the customer service level. However, more resources require an extra investment (cost); thus other factors such as volume of demand, quantities of used products and quality conditions of used products have to be considered before allocating more resources.

By contrast, if the storage capacity is limited, the RMTO-strategy would be a better option because it doesn’t require carrying any finished product inventory. The RMTS-strategy, particularly with a high target-level of finished products would require a storage facility for the finished product inventory, which could be costly in the case of a rental facility. However, as reported by our case-study company, the availability of a storage facility is normally related to the volume of finished products that is carried out at a certain time. This has not been a major problem for the case-study company

5.5 Summary

This chapter has discussed the findings from analyses of the effects of system variables on the performance of remanufacturing systems and strategies. Specifically, subsection 5.2.1 discussed the effects of inspection yields on the average remanufacturing cycle-time of four alternative configurations of a RMTS-system with different remanufacturing policies. Subsection 5.2.2 discussed the effects of alternative configurations of a RMTS-system with different remanufacturing policies on the typical profile of finished products inventory. Subsection 5.2.3 discussed the effects of used products quantities on the customer service level, which could be provided by the alternative configurations of a RMTS-system with different remanufacturing policies. Subsection 5.2.4 discussed the sensitivity of the alternative configurations of a RMTS-system with different remanufacturing policies with regards to changes in the quantities of used products and yields of inspection.

Subsection 5.3.1 discussed the effects of inspection yields on the average remanufacturing cycle-time of three alternative configurations of a RMTO-system with different remanufacturing policies. Subsection 5.3.2 discussed the effects of used products quantities on the customer service level, which could be provided by the alternative configurations of a RMTO-system with different remanufacturing policies. Finally, subsection 5.3.3 discussed the sensitivity of the alternative configurations of a RMTO-system with different remanufacturing policies with respect to changes in the quantities of used products and yields of inspection.

Subsection 5.4.1 discussed the main and interactions effects of three system variables on the average remanufacturing cycle-time of a RMTS-strategy. In subsection 5.4.2 the main and interactions effects of three system variables on the average remanufacturing cycle-time of a RMTO-strategy was discussed. Finally, subsection 5.4.3 discussed the effects of different remanufacturing strategies on the customer service level.

Chapter 6

Conclusion and Future Directions

6.1 Conclusion

The conclusion of this research with respect to the objectives defined in chapter 1 are as follows:

1. *Development of an integrated inventory lot-sizing model to concurrently determine the optimal lot-sizes for remanufacturing, number of remanufacturing lots and lot-size for manufacturing in a hybrid remanufacturing-manufacturing system with varying remanufacturing fractions*.

   A new integrated inventory lot-sizing model has been developed, in which variable remanufacturing lot-sizes has been implemented to address a problem of varying remanufacturing fractions in a hybrid remanufacturing-manufacturing system. The resulting model has been utilised to concurrently determine the optimal lots-sizes for remanufacturing, number of remanufacturing lots and lot-sizes for manufacturing for a given remanufacturing fraction. The new model has been shown to be capable of exhibiting the expected inventory-related behaviours, which further serves as a validation of the new model.

Furthermore, the new model has been shown to result in cost savings when compared to a benchmark model that implements a fixed remanufacturing lot-size. Finally, the major decision variables of the new model have been shown to be robust with regards to changes in costs and demand parameters. Overall, it can be established that the new integrated inventory lot-sizing model with variable remanufacturing lot-sizes would serve as a useful decision-making tool in companies that are planning to incorporate remanufacturing activity into normal manufacturing operations.

2. *Development of integrated production and inventory planning simulation models to determine the optimal remanufacturing policy for processing two different quality remanufacturable groups in a remanufacture-to-stock system with varying inspection yields and availability of used products*.

   Four-variants of the integrated production and inventory planning simulation models in a remanufacture-to-stock system have been developed, in which different remanufacturing policies have been examined for processing two different quality remanufacturable groups. The four-variant simulation models have been applied to investigate the effects of system variables on the performance of a remanufacture-to-stock system. It has been shown that the four-variant simulation models are capable of predicting the expected performance measures of a remanufacture-to-stock operation, which further serve as a validation of such variant simulation models.

Furthermore, the four-variant simulation models have also been utilised to determine the optimal remanufacturing policy for processing two different quality remanufacturable groups in a RMTS system with varying inspection yields and availability of used products. It has been demonstrated that a remanufacturing policy which specifies simultaneous processing and utilising dedicated resources emerges as the optimal remanufacturing policy. On the contrary, when resources are finite, a remanufacturing policy that specifies sequential processing and switching between the two quality remanufacturable groups to sustain production emerges as the optimal remanufacturing policy. Overall, it can be established that the four-variant simulation models of integrated production and inventory planning have emerged as valuable tools for determining the optimal remanufacturing policy for implementation in a remanufacture-to-stock system.

3. *Development of integrated production and inventory planning simulation models to determine the optimal remanufacturing policy for processing two different quality remanufacturables groups in a remanufacture-to-order system with varying inspection yields and availability of used products.*

Three-variants of the integrated production and inventory planning simulation models in a remanufacture-to-order system have been developed, in which different remanufacturing policies have been examined for processing two remanufacturable groups of different quality. The three-variant simulation models have been applied to investigate the effects of system variables on the performance of a remanufacture-to-order system. It has been shown that the three-variant simulation models are capable of predicting the expected performance measures in a remanufacture-to-order operation, which further serves as a validation of such variant simulation models.

Furthermore, the three-variant simulation models have also been utilised to determine the optimal remanufacturing policy for processing two different quality remanufacturable groups in a RMTO system with varying inspection yields and availability of used products. It has been shown that a remanufacturing policy which specifies sequential processing and switching between the two quality remanufacturable groups to sustain production emerges as the optimal remanufacturing policy. Overall, it can be established that the three-variant simulation models of integrated production and inventory planning have emerged as valuable tools for determining the optimal remanufacturing policy for implementation in a remanufacture-to-order system.

4. *Development of integrated production and inventory planning simulation models to determine the optimal remanufacturing strategy for processing two different quality remanufacturable groups in a remanufacturing system*.

Two-variants of the integrated production and inventory planning simulation models in a remanufacturing system have been developed, in which different remanufacturing strategies have been assessed for processing two different quality remanufacturable groups. The two-variant simulation models have been applied to investigate the main effects of system variables on the performance of a remanufacturing system under different remanufacturing strategies.

The two-variant simulation models have also been utilised to determine the optimal remanufacturing strategy for processing two different quality remanufacturable groups. It has been demonstrated that a remanufacturing strategy which specifies carrying some finished products inventory at all times (i.e., a remanufacture-to-stock) appears to be the optimal remanufacturing strategy. Overall, it can be established that the two-variant simulation models of integrated production and inventory planning have formed valuable tools for determining the optimal remanufacturing strategy for implementation in a remanufacturing system.

6.2 Future directions

This thesis has introduced a mathematical model of integrated inventory lot-sizing, developed to implement variable remanufacturing lot-sizes to address the problem of varying remanufacturing fractions in a hybrid remanufacturing-manufacturing system. Given that there are several unique characteristics which predominantly and inherently occur in the remanufacturing environment, it is apparent that development of inventory lot-sizing model in a hybrid remanufacturing-manufacturing system has to consider the presence of such unique characteristics. In this context, a future direction could focus on the application of simulation techniques in the modelling and analysis of inventory lot-sizing problems in a hybrid remanufacturing-manufacturing system with unique characteristics.

This thesis has also introduced several-variant of integrated production and inventory planning simulation models in a remanufacturing system, in which different policies have been examined for processing two remanufacturable groups of different quality under a given remanufacturing strategy. The analyses of such variant simulation model, have mainly focused on three system variables (configurations of a remanufacturing system, yield of inspection and availability of used products) in order to manage the analyses tasks and generate a meaningful set of observations.

As established in chapter 2, disassembly yields of constituent components are also essential criteria in the modelling and analysis of a remanufacturing system. Accordingly, a future direction could focus on three factors: (i) varying disassembly yields of two-type constituent components, (ii) stochastic delivery lead times of two-type replacement components, and (iii) varying availability of used products, under a given inspection yield; a situation that is critical in a customer driven environment. Another future direction could focus on the development and analysis of simulation models of a remanufacturing system that could operate either according to a RMTS, RMTO or combined RMTS-RMTO production strategy, depending on the availability of used products, yield of inspection, disassembly yields of multiple-type constituent components and volume of demand.

References

Akcali, E. and Morse, M.A., 2004. Seeding strategies in remanufacturing, in the Proceedings of the IIE Research Conference 2004, on CD Rom, 6 pages.

Aksoy, H.K. and Gupta, S.M., 2001a. Effect of reusable rate variation on the performance of remanufacturing systems, in *Environmentally Conscious Manufacturing*, edited by Surendra M. Gupta, Proceedings of SPIE Vol. 4193 (SPIE, Bellingham, WA, 2001), 13-20.

Aksoy, H.K. and Gupta, S.M., 2001b. Capacity and buffer trade-offs in a remanufacturing system, in *Environmentally Conscious Manufacturing II*, edited by Surendra M. Gupta, Proceedings of SPIE Vol. 4569 (SPIE, Bellingham, WA, 2001), 167-174.

Aksoy, H.K. and Gupta, S.M., 2005. Buffer allocation plan for a remanufacturing cell. *Computers and Industrial Engineering*, 48(3), 657-677.

Altiok, T. and Melamed, B., 2007. Simulation modeling and analysis with Arena, Amsterdam: Elsevier

Aras, N. and Aksen, D., 2008. Locating collection centers for distance- and incentive-dependent returns. *International Journal of Production Economics*, 111(2), 316-333.

Aras, N., Aksen, D. and Tanugur, A.G., 2008. Locating collection centers for incentive-dependent returns under a pick-up policy with capacitated vehicles. *European Journal of Operational Research*, 191(3), 1223-1240.

Aras, N., Boyaci, T., Verter, V., 2004. The effect of categorizing returned products in remanufacturing. *IIE Transactions*, 36(4), 319-331.

Aras, N., Verter, V., Boyaci, T., 2006. Coordination and priority decisions in hybrid manufacturing/remanufacturing systems. *Production and Operations Management*, 15(4), 528-543.

Ayres, R., Ferrer, G., Van Leynseele, T., 1997. Eco-efficiency, asset recovery and remanufacturing. *European Management Journal*, 15(5), 557-574.

Banks, J., 1998a. Principles of simulation, in Handbook of simulation: Principles, methodology, advances, applications, and practice, edited by Banks, J. New York: John Wiley & Sons.

Banks, J., 1998b. Software for simulation, in *Handbook of simulation: Principles, methodology, advances, applications, and practice*, edited by Banks, J. New York: John Wiley & Sons.

Barba-Gutierrez, Adenso-Diaz, B. and Gupta, S.M., 2008. Lot-sizing in reverse MRP for scheduling disassembly. *International Journal of Production Economics*, 111(2), 741-751.

Behret, H. and Korugan, A., 2005. The impact of quality uncertainty of returns in remanufacturing. Proceedings of the 35th International Conference on Computers and Industrial Engineering, , 275-280.

Behret, H. and Korugan, A., 2009. Performance analysis of a hybrid system under quality impact of returns. *Computers and Industrial Engineering*, 56(2), 507-520.

Bhattacharya, S., Guide Jr., V.D.R. and Van Wassenhove, L.N., 2006. Optimal order quantities with remanufacturing across new products generations. *Production and Operations Management*, 15(3), 421-431.

Carrie, A., 1988. Simulation of manufacturing systems. John-Wiley & Sons.

Choi, D.-W., Hwang, H., and Koh, S.-G., 2007. A generalized ordering and recovery policy for reusable items. *European Journal of Operational Research*, 182, 764-774.

Chung, C.A., 2004. Simulation modeling handbook: a practical approach, Boca Raton: CRC Press.

Debo, L. G., Toktay, L. B. and Van Wassenhove, L. N., 2005. Market segmentation and product technology selection for remanufacturable products. *Management Science*, 51(8), 1193-1205.

Denizel, M., Ferguson, M. and Souza, G.C., 2007. Multi-period remanufacturing planning with uncertain quality of inputs. http://smartech.gatech.edu/bitstream/1853/18986/1/StochProdPlan_v5.2.pdf, accessed 3rd May 2007.

Dowlatshahi, S., 2000. Developing a theory of reverse logistics. *Interfaces*, 30, 143 -155.

Eldabi, T., Macredie, R.D. and Paul, R.J., 2008. Simulation modelling as a decision-making aid in economic evaluation for randomized clinical trials, in *Simulation and modeling: Current technologies and applications*, edited by Sheikh, A.E., Ajeeli, A.A. and Abu-Taieh, E.M, Hershey, New York: IGI Publishing, 219-243.

Evans, G.W. and Biles, W.E., 1992. Simulation of advanced manufacturing systems. Proceedings of the 1992 Winter Simulation Conference, eds., Swain, J.J., Goldsman, R.C., and Wilson, J.R., 163-169.

Ferrer, G., 1997. The economics of tire remanufacturing. *Resources, Conservation and Recycling*, 19(4), 221-255.

Ferrer, G., 2001. On the widget remanufacturing operation. *European Journal of Operational Research*, 135(2), 373-393.

Ferrer, G., 2003. Yield information and supplier responsiveness in remanufacturing operations. *European Journal of Operational Research*, 149(3), 540-556.

Ferrer, G. and Ketzenberg, M.E., 2004. Value of information in remanufacturing complex products. *IIE Transaction*, 36(3), 265-277.

Ferrer, G., and Swaminathan, J. M., 2009. Managing New and Differentiated Remanufactured Products. *European Journal of Operational Research*, doi:10.1016/j.ejor.2009.08.007.

Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., van der Laan, E., van Nunen, Jo.A.E.E., and Van Wassenhove, L.N., 1997. Quantitative models for reverse logistics: A review. *European Journal of Operational Research*, 103(1), 1-17.

Galbreth, M.R. and Blackburn, J.D., 2006. Optimal acquisition and sorting policies for remanufacturing. *Production and Operations Management*, 15(3), 384-392.

Giuntini, R. and Gaudette, K., 2003. Remanufacturing: The next great opportunity for boosting US productivity. *Business Horizons*, November-December, 41-48.

Graehl, D. 1992. Insights into Carrier Control: A simulation of a power and free conveyor through an automotive paint shop, Proceedings of the 1992 Winter Simulation Conference, eds., J. Swain, D. Goldsman, R. C. Crain, J. Wilson, IEEE, Picataway, 925-932.

Guide Jr, V.D.R., 1995. A simulation model of drum-buffer-rope for production planning and control at a naval aviation depot. *Simulation*, 65(3), 157-168.

Guide Jr., V.D.R., 1996. Scheduling using drum-buffer-rope in a remanufacturing environment. *International Journal of Production Research*, 34(4), 1081-1091.

Guide Jr, V.D.R., 1997. Scheduling with priority dispatching rules and drum-buffer-ropes in a recoverable manufacturing system. *International Journal of Production Economics*, 53, 101-116.

Guide Jr., V.D.R., 2000. Production planning and control for remanufacturing: industry practice and research needs. *Journal of Operations Management*, 18(4), 467-483.

Guide Jr., V.D.R., Jayaraman, V., and Linton, J.D., 2003b. Building contingency planning for closed-loop supply chains with product recovery. *Journal of Operations Management*, 21(3), 259-279.

Guide Jr., V.D.R., Jayaraman, V., and Srivastava, R., 1999. The effect of lead time variation on the performance of disassembly release mechanisms. *Computers & Industrial Engineering*, 36(4), 759-779.

Guide Jr., V.D.R., Kraus, M.E. and Srivastava, R.. 1997c. Scheduling policies for remanufacturing. *International Journal of Production Economics*, 48(2), 187-204.

Guide Jr, V.D.R., Souza, G.C. and van der Laan, E., 2005. Performance of static priority rules for shared facilities in a remanufacturing shop with disassembly and reassembly. *European Journal of Operational Research*, 164(2), 341-353.

Guide Jr, V.D.R. and Spencer, M.S., 1997. Rough-cut capacity planning for remanufacturing firms. *Production Planning Control*, 8(3), 237-244.

Guide Jr., V.D.R. and Srivastava, R., 1997a. An evaluation of order release strategies in a remanufacturing environment. *Computers & Operations Research*, 24(1), 37-47.

Guide Jr., V.D.R. and Srivastava, R., 1997b. Buffering from material recovery uncertainty in a recoverable manufacturing environment. *The Journal of the Operational Research Society*, 48(5), 519-529.

Guide Jr, V.D.R. and Srivastava, R., 1998. Inventory buffers in recoverable manufacturing. *Journal of Operations Management*, 16(5), 551-568.

Guide Jr., V.D.R., Srivastava, R., and Kraus,M. E., 1997a. Product structure complexity and scheduling of operations in recoverable manufacturing. I*nternational Journal of Production Research*, 35(11), 3179 - 3199.

Guide Jr., V.D.R., Srivastava, R., and Kraus,M. E., 1998. Proactive expediting policies for recoverable manufacturing. *The Journal of the Operational Research Society*, 49(5), 479-491.

Guide Jr, V.D.R., Srivastava, R. and Spencer, M.S., 1997b. An evaluation of capacity planning techniques in a remanufacturing environment. *International Journal of Production Research*, 35(1), 67-82.

Guide Jr., V.D.R., Teunter, R.H. and Van Wassenhove, L.N., 2003a. Matching demand and supply to maximize profits from remanufacturing. *Manufacturing & Service Operations Management*, 5(4), 303-316.

Guide Jr.V.D.R., and Van Wassenhove, L.N., 2001. Managing product returns for remanufacturing. *Production and Operations Management*, 10(2), 142-155.

Gungor, A., and Gupta, S. M., 1999. Issues in environmentally conscious manufacturing and product recovery: a survey. *Computers and Industrial Engineering*, 36(4), 811-853.

Gupta, T. and Arasakesari, S., 1991. Capacity planning in wood products industry using simulation, Proceedingss of the 1991 Winter Simulation Conference, eds., Nelson, B.L., Kelton, W.D. and Clark, G.M., 435-440.

Gupta, S.M. and Taleb, K.N., 1994. Scheduling disassembly. *International Journal of Production Research*, 32(8), 1857-1866.

Hadley, G. and Whitin, T.M., 1963. Analysis of inventory systems. Englewood Cliffs: Prentice-Hall.

Hakala, J. W., 1995. Combat simulation modeling in naval special warfare mission planning. Master’s Thesis, Naval Postgraduate School, Monterey, California.

Hedjar, R., Bounkhel, N. and Tadj, L., 2005. Receding horizon control of a hyrid production system with deteriorating items. *Nonlinear Analysis*, 63, 405-422.

Hou, Y. and Zhang, H., 2005. Performance analysis on a complex remanufacturing system. *Asia-Pacific Journal of Operational Research*, 22(3), 327-347.

Inderfurth, K., 2005. Impact of uncertainties on recovery behaviour in a remanufacturing environment: A numerical analysis. *Journal of European Industrial Training*, 35(5), 318-336.

Inderfurth, K. and Langella, I.M., 2006. Heuristics for solving disassemble-to-order problems with stochastic yields. *OR Spectrum*, 28(1), 73-99.

Inderfurth, K. and Van der laan, E., 2001. Leadtime effects and policy improvement for stochastic inventory control with remanufacturing. *International Journal of Production Economics*, 71, 381-390.

Jayaraman, V., 2006. Production planning for closed-loop supply chains with product recovery and reuse: an analytical approach. *International Journal of Production Research*, 44(5), 981-998.

Kang, K. and Roland, R.J., 1998. Military simulation, in Handbook of simulation: principles, methodology, advances, applications and practice edited by Banks, J. New York: John Wiley & Sons, 645-658.

Kelton, W.D., Sadowski, R.P., and Sturrock, D.T., 2007. Simulation with Arena (3rd eds.) Singapore: McGraw-Hill.

Ketzenberg, M.E., Souza, G.C., and Guide Jr., V.D.R., 2003. Mixed assembly and disassembly operations for remanufacturing. *Production and Operations Management*, 12(3), 320-335.

Kiesmuller, G.P., 2003. A new approach for controlling a hybrid stochastic manufacturing/remanufacturing system with inventories and different leadtimes. *European Journal of Operational Research*, 147, 62-71.

Kim, H.-J., Lee, D.-H. and Xirouchakis, P., 2006. Two-phase heuristic for disassembly scheduling with multiple product types and parts commonality. *International Journal of Production Research*, 44(1), 195-212.

Kim, J.-G., Jeon, H.-B., Kim, H.-J., Lee, D.-H. and Xirouchakis, P., 2006b. Disassembly scheduling with capacity constraints: minimizing the number of products disassembled. Proceedings of IMechE Vol. 220 Part B: J. Engineering Manufacture, 1473-1481.

Klausner, M., Grimm, W.M. and Hendrickson, C.T., 1998. Reuse of Electric Motors in Consumer Products: Design and Analysis of an Electronic Data Log. *Journal of Industry Ecology*, 2(2), 89–102.

Klausner, M. and Hendrickson, C.T., 2000. Reverse-logistics strategy for product take-back. *Interfaces*, 30(3), 156-165.

Koh, S.-G., Hwang, H., Sohn, K.-I., and Ko, C.-S., 2002. An optimal ordering and recovery policy for reusable items. *Computers & Industrial Engineering*, 43(1-2), 59-73.

Kongar, E. and Gupta, S.M., 2006. Disassembly sequencing using genetic algorithm. *The International Journal of Advanced Manufacturing Technology*, 30(5-6), 497-506.

Konstantaras, I. and Papachristos, S., 2006. Lot-sizing for a single-product recovery system with backordering. *International Journal of Production Research*, 44(10), 2031-2045

Kumar, N., Guide Jr, V.D.R, Van Wassenhove, L.N., 2002. Managing product returns at Hewlett, Packard, teaching case 05/2002-4940, INSEAD.

Lambert, A.J.D. and Gupta, S.M., 2002. Demand-driven disassembly optimization for electronic products. *Journal of Electronics Manufacturing*, 11(2), 121-135.

Langella, I.M., 2007. Heuristics for demand-driven disassembly planning. C*omputers and Operations Research*, 34(2), 552-577.

Laughery, R., Plott, B. and Scott-Nash, S., 1998. Simulation of service systems in Handbook of simulation: principles, methodology, advances, applications and practice edited by Banks, J. New York: John Wiley & Sons, 629-644.

Law, A.M., and Kelton, W.D., 2000. Simulation modeling and analysis (3rd eds.) Singapore: McGraw-Hill.

Lebreton, B., and Tuma, A., 2006. A quantitative approach to assessing the profitability of car and truck tire remanufacturing. *International Journal of Production Economics*, 104(2), 639-652.

Lee, D.-H. and Xirouchakis, P., 2004. A two-stage heuristic for disassembly scheduling with assembly product structure. *Journal of the Operational Research Society*, 55(3), 287-297.

Li, J., Gonzalez, M. and Zhu, Y., 2009. A hybrid simulation optimization method for production planning of dedicated remanufacturing. *International Journal of Production Economics*, 117(2), 286-301.

Linton, J.D., 2008. Assessing the economic rationality of remanufacturing products. *The Journal of Product Innovation Management*, 25(3), 287-302.

Lund, R.T., 1984a. Remanufacturing: The experience of the United States and implications for developing countries. *World Bank Technical Paper*, No. 31.

Lund, R. T., 1984b. Remanufacturing. *Technology Review 87*, 18(8).

Mabini, M.C., Pintelon, L.M., and Gelders, L.F., 1992. EOQ type formulations for controlling repairable inventories. *International Journal of Production Economics*, 28(1), 21-33.

Maslennikova, I., and Foley, D., 2000. Xerox's Approach to Sustainability. *Interfaces*, 30(3), 226-233.

Minner, S., 2001. Economic Production and Remanufacturing Lot-sizing Under Constant Demands and Returns in Operations Research Proceedings 2000, Springer, Berlin Heidelberg New York, 328-332.

Minner, S., and Lindner, G., 2004. Lot Sizing Decisions in *Product Recovery Management. in Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains* edited by Dekker, R., Fleischmann, M., Inderfurth, K. and Van. Wassenhove, L.N., Springer, Berlin ; New York, 157-179.

Muckstadt, J.A., Isaac, M.H., 1981. An analysis of single item inventory systems with returns. *Naval Research Logistics Quarterly*, 28(2), 237-254.

Musselman, 1998. Guidelines for success, in *Handbook of simulation: principles, methodology, advances, applications and practice*, edited by Banks, J. New York: John Wiley & Sons, 721-743.

Nahmias, S., and Rivera, H., 1979. A deterministic model for a repairable item inventory system with a finite repair rate. *International Journal of Production Research*, 17(3), 205.

Ostlin, J., Sundin, E. and Bjorkman, M., 2009. Product life-cycle implications for remanufacturing strategies. *Journal of Cleaner Production*, 17(11), 999-1009.

Panneerselvam, R., 2005. Production and Operations Management (2nd. eds) New Delhi: Prentice Hall.

Richter, K., 1996a. The EOQ repair and waste disposal model with variable setup numbers. *European Journal of Operational Research*, 95(2), 313-324.

Richter, K., 1996b. The extended EOQ repair and waste disposal model. *International Journal of Production Economics*, 45(1-3), 443-447.

Rockwell Automation. 2005. Arena Simulation Software: Release 10.

Rogers, D. S and Tibben-Lembke, R.S., 1999. Going Backwards:Reverse logistics trends and practices. Reverse Logistics Executive Council, Pittsburgh, PA.

Rohrer, M.W, 1998. Simulation of manufacturing and material handling systems, in Handbook of simulation: principles, methodology, advances, applications and practice edited by Banks, J., New York: John Wiley & Sons, 519-545.

Ross, S.M., 1997. Simulation (2nd ed.). San diego: Academic Press

Rubio, S. and Corominas, A., 2008. Optimal manufacturing-remanufacturing policies in a lean production environment. *Computers and Industrial Engineering*, 55(1), 234-242.

Rudi, N., Pyke, D.F., and Sporsheim, P.O., 2000. Product recovery at the Norwegian National Insurance Administration. *Interfaces*, 30(3), 166-179.

Sandvall, F. and Stelin, C., 2006. The remanufacturing offer: A case study of Volvo construction equipment implementing and expanding Reman in Russia. Bachelor's Thesis. Stockholm University.

Schrady, D.A., 1967. A deterministic model for reparable items. *Naval Research Logistics Quarterly*, 14, 391-398.

Seitz, M.A., 2007 A critical assessment of motives for product recovery: the case of engine remanufacturing. *Journal of Cleaner Production*, 15(11-12), 1147-1157.

Shyong, S-R., 2002. Advanced planning and scheduling in the United States air force depot-level maintenance. Master's Thesis, Air University.

Souza, G.C. and Ketzenberg, M.E., 2002. Two-stage make-to-order remanufacturing with service-level constraints. *International Journal of Production Research*, 40(2), 477-493.

Souza, G.C., Ketzenberg, M.E. and Guide Jr., V.D.R., 2002. Capacitated remanufacturing with service level constraints. *Production and Operations Management*, 11(2), 231-248.

Srivastava, R., 2004. Reusing Single Use Devices in Hospitals: A Case Study, in Environmentally Conscious Manufacturing III, edited by Surendra M. Gupta, Proceedings of SPIE Vol. 5264 (SPIE, Bellingham, WA, 2004), 1-5.

Stefanou, C.J., 2004. System development life cycle. *Encyclopaedia of Information systems*, 329-344.

Steinhilper, R., 1998. Remanufacturing: The ultimate form of recycling. Stuttgart: Fraunhofer IRB Verlag, D-70569.

Sundin, E., 2004. Product and process design for successful remanufacturing. Ph.D-Series in General Management 28, Dissertation No. 906, Linkopings universitet, Institut of Technology.

Takus, D. A., & Profozich, D. M., 1997. Arena Software Tutorial. Proceddings of the 1997 Winter Simulation Conference, eds Andradottir, S., Healy, K.J., Withers, D.H. and Nelson, B.L., 541-543.

Taleb, K.N. and Gupta, S.M., 1997. Disassembly of multiple product structures. *Computers and Industrial Engineering*, 32(4), 949-961.

Tang, O., and Grubbstrom, R. W., 2005. Considering stochastic lead times in a manufacturing/remanufacturing system with deterministic demands and returns. *International Journal of Production Economics*, 93-94, 285-300.

Tang, O., Grubbstrom, R.W. and Zanoni, S., 2007. Planned lead time determination in a make-to-order remanufacturing system. *International Journal of Production Economics*, 108(1/2), 426-435.

Tersine, R.J., 1994. Principles of inventory and materials management (4th eds.) Englewood Cliffs: Prentice Hall.

Teunter, R.H., 2001. Economic ordering quantities for recoverable item inventory systems. *Naval Research Logistics*, 48(6), 484-495.

Teunter, R, 2004. Lot-sizing for inventory systems with product recovery. *Computers and Industrial Engineering*, 46(2), 431-441.

Ulgen, O. and Gunal, A., 1998. Simulation in the automobile industry, in Handbook of simulation: principles, methodology, advances, applications and practice, edited by Banks, J. New York: John Wiley & Sons, 547-570.

Van der Laan, E., 1997. The effect of remanufacturing on inventory control. Ph.D-Series in General Management 28, Delft: Eburon.

Van der laan, E., Salomon, M., and Dekker, R., 1999. An investigation of lead-time effects in manufacturing/remanufacturing systems under simple PUSH and PULL control strategies. *European Journal of Operational Research*, 115, 195-214.

van der Laan, E., Salomon, M. Dekker, R. and Van Wassenhove, L.N., 1999. Inventory control in hybrid systems with remanufacturing. *Management Science*, 45(5), 733-747.

Vigus, S.E., 2003. A simulation-based analysis of the impact of in-sourcing a major process element on the cost guard HH-60J depot maintenance process. Master's Thesis, Air University.

Wee, H. M., Yu, J. C. P., Su, L.-H., and Wu, T.-C., 2006. Optimal ordering and recovery policy for reusable items with shortages. In Simulated Evolution and Learning, Proceedings, edited by Wang, T.-D., Vol. 4247, 284-291.

Werner, S., 2006. Simulation of manufacturing processes, in Electronic Process Technology, eds Sauer, W., London: Springer-Verlag, 119-172.

Zikopoulus, C. and Tagaras, G., 2007. Impact of uncertainty in the quality of returns on the profitability of a single-period refurbishing operation. *European Journal of Operational Research,* 182(1), 205-225.

Zikopoulus, C. and Tagaras, G., 2008. On the attractiveness of sorting before disassembly in remanufacturing. *IIE Transactions*, 40(3), 313-323.

Zussman, E., and Seliger, G., 1999. Product Remanufacturing. in Shimon Y. Nof (ed), Handbook of Industrial Robotics (2nd), New York: Wiley & Sons, 1037-1043.

Internet resources

Canon Global, 2008. Canon sustainability report 2008. http://www.canon.com/environment/report/pdf/report2008e_05.pdf, accessed 13th January, 2007.

Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles (Directive 2000/53/EC - the "ELV), available at http://ec.europa.eu/environment/waste/elv_index.htm, accessed 3rd June, 2007.

Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE) (Directive/2002/96/EC), available at http://www.environ.ie/en/Legislation/Environment/Waste/WEEE/FileDownLoad,613,en.pdf, accessed 3rd June, 2007.

FujiXerox, Australia (2007a). Information extracted from FujiXerox, Australia official website: http://www.fujixerox.com.au/about/eco_manufacturing.jsp, accessed 25-11-2007.

FujiXerox, Australia (2007b). Information extracted from FujiXerox, Australia official website: http://www.fujixerox.com.au/about/media/articles/207, accessed 25-11-2007.

Hauser, W. and R. T. Lund (2003). Remanufacturing: An American resource. Teaching materials on remanufacturing, available at http://www.bu.edu/reman/RemanSlides.pdf, accessed 19-05-2007.

Krazit, T., 2003. Ink cartridges getting smarter: Vendors look to halt use of third party supplies. InfoWorld, http://www.infoworld.com/t/hardware/ink-cartridges-getting-smarter-840, accessed 23rd September, 2007.

MRI (Aust) Pty Ltd, 2007. Information extracted from MRI (Aust) Pty Ltd official website: http://www.mri.com.au/websiteBETA/MRI-EbrochureV2.pdf, accessed 27-11-2007.

Nintendo DSi (2009). Information extracted from Nintendo DSi official website: http://www.nintendodsi.com/meet-dsi-explore.jsp, accessed 01-06-2009.

APPENDIX A

(a) Photo copy machines

(b) Computer monitor

(c) Mobile phones

(d) Vending machines

Figure A1: Examples of remanufactured products (source Steinhilper, 1998)

Table A1:

Key stages for remanufacturing of toner cartridges, automotive engines and washing machines (source Sundin, 2004).

Toner cartridges	Automotive engines	Washing machines
1. Inspection	1. Disassembly	1. Testing
2. Disassembly	2. Cleaning	2. Disassembly
3. Reassembly and refill toner	3. Machining process	3. Part replacement
4. Testing	4. Assembly	4. Cleaning
	5. Testing	5. Testing

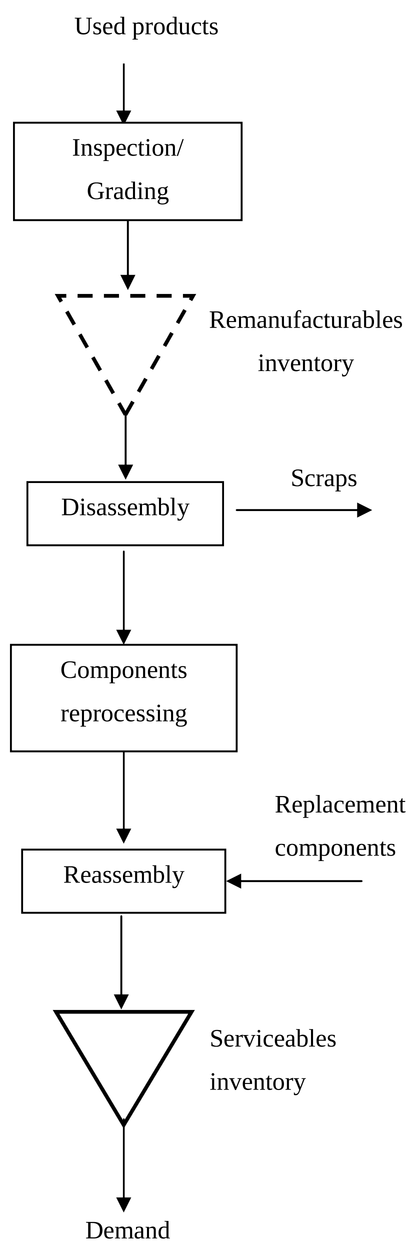


Figure A2: The position of inventory in a RMTS system

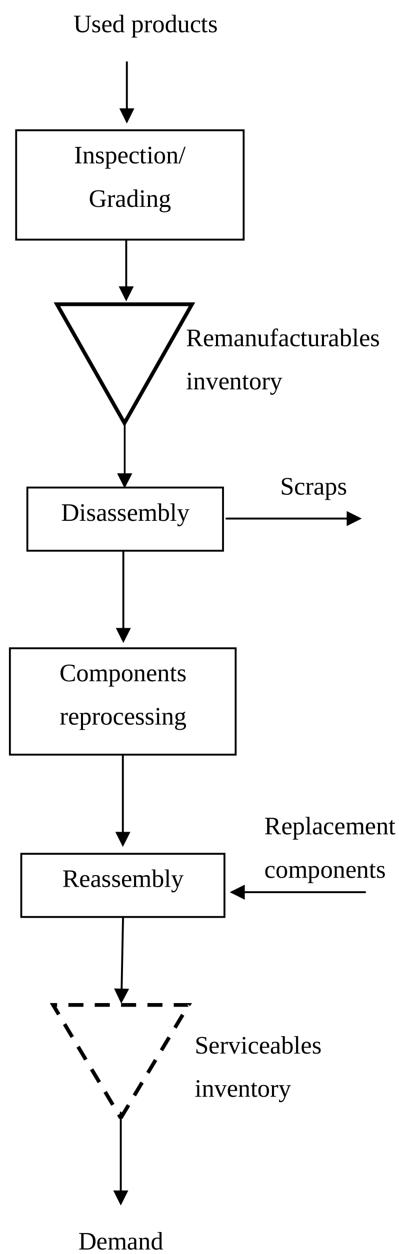


Figure A3: The position of inventory in a RMTO system

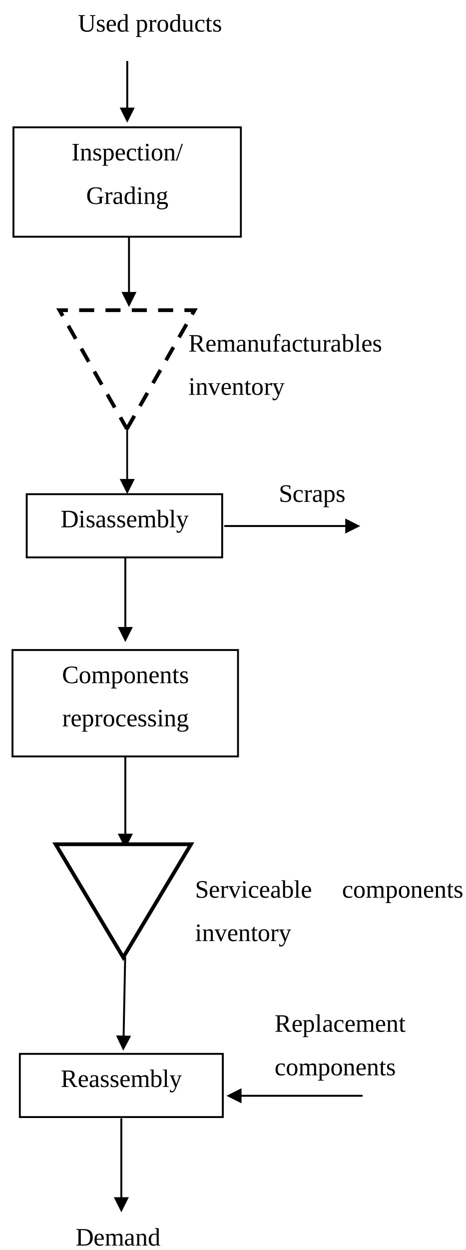


Figure A4: The position of inventory in a RATO system

APPENDIX B

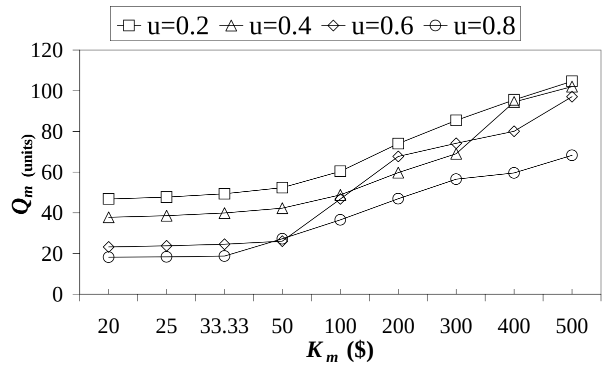


Figure B1: The effect of manufacturing setup cost, K_m on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u .

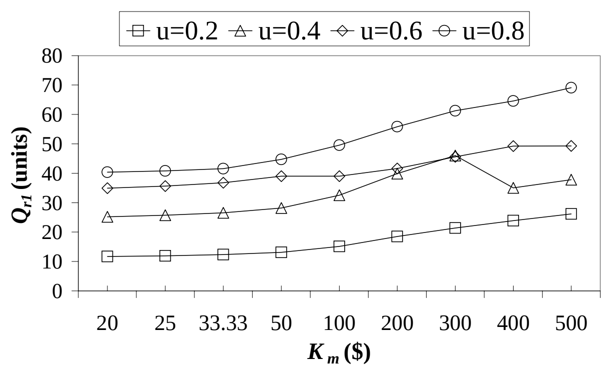


Figure B2: The effect of manufacturing setup cost, K_m on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u .

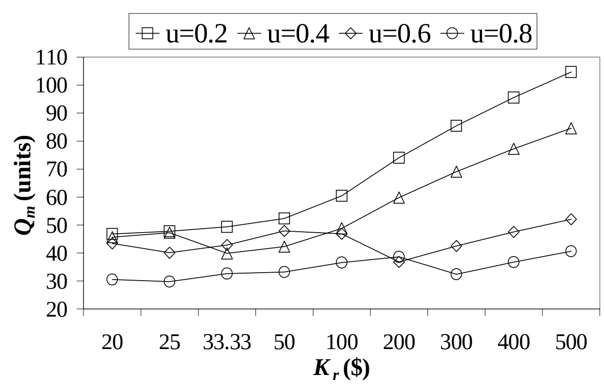


Figure B3: The effect of remanufacturing setup cost, K_r on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u .

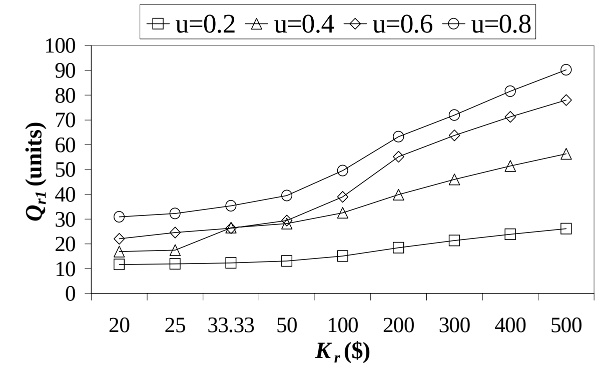


Figure B4: The effect of remanufacturing setup cost, K_r on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u .

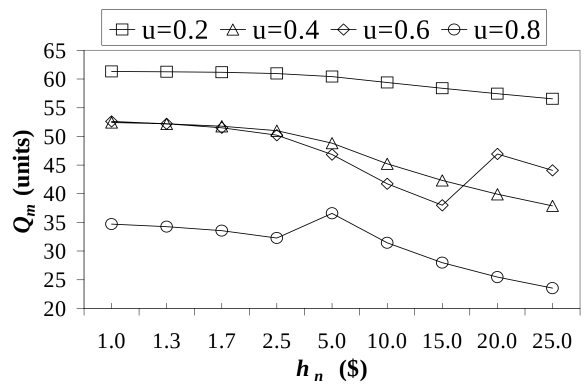


Figure B5: The effect of remanufacturables holding cost, h_n on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u .

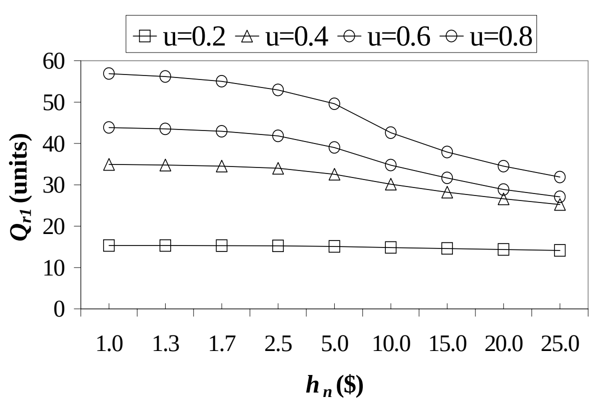


Figure B6: The effect of remanufacturables holding cost, h_n on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u .

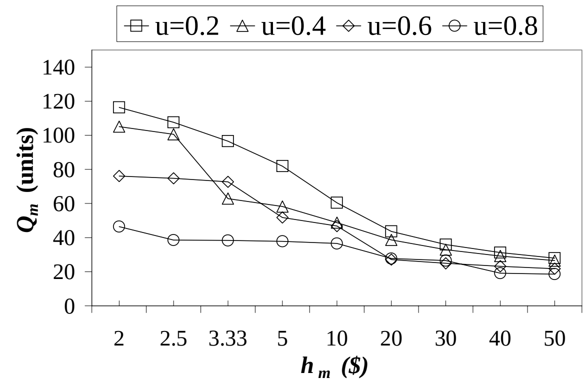


Figure B7: The effect of new products holding cost, h_m on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u .

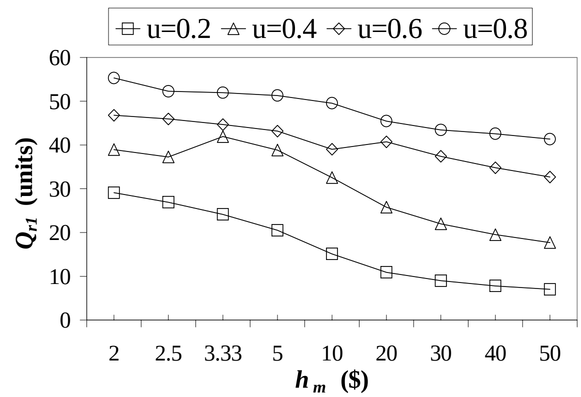


Figure B8: The effect of new products holding cost, h_m on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u .

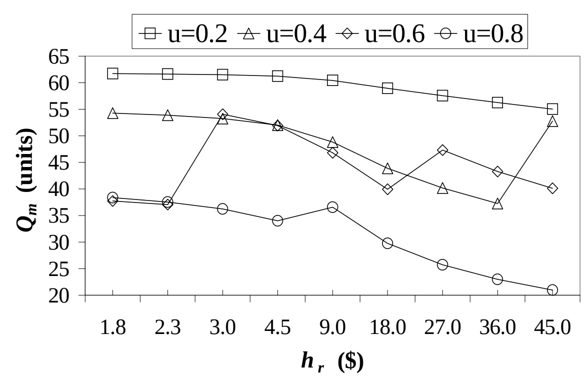


Figure B9: The effect of remanufactured products holding cost, h_r on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u .

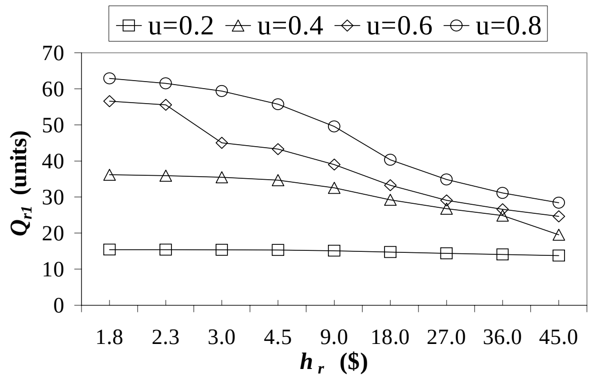


Figure B10: The effect of remanufactured products holding cost, h_r on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u .

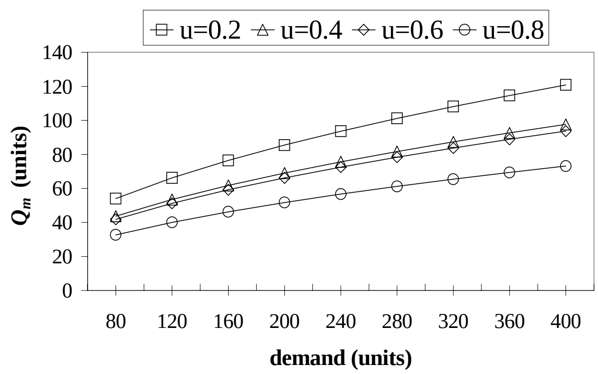


Figure B11: The effect of demand quantity on estimate of manufacturing lot-size, Q_m at different values of remanufacturing fraction, u .

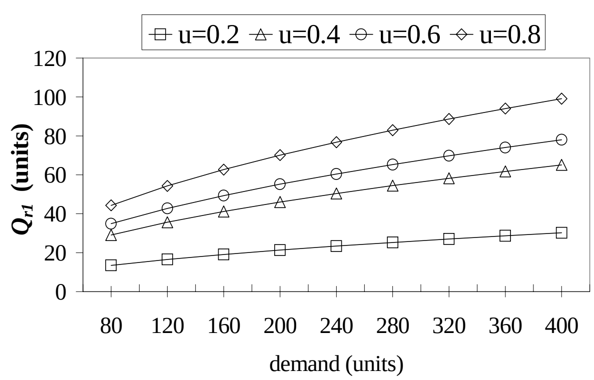


Figure B12: The effect of demand quantity on estimate of first remanufacturing lot-size, Q_{r1} at different values of remanufacturing fraction, u .

Table B1:
The effect of changes in costs and demand parameters on manufacturing lot-size at different remanufacturing fraction – case 1.

		% change in Q_m at different remanufacturing fraction, u			
Parameters	% change	$u = 0.5$	$u = 0.6$	$u = 0.7$	$u = 0.8$
$K_m = 25$	+5%	0.50	0.50	0.50	0.28
	-5%	-0.50	-0.50	-0.50	-0.28
$K_r = 25$	+5%	-0.83	-1.07	-1.38	-1.49
	-5%	-15.17	-12.80	1.40	1.51
$h_m = 5$	+5%	0.97	0.55	0.37	0.18
	-5%	-1.00	-34.19	-0.37	-0.18
$h_n = 2.5$	+5%	0.37	0.39	0.51	0.58
	-5%	-0.34	-0.36	-0.48	-0.54
$h_r = 4.5$	+5%	0.54	0.57	0.78	0.89
	-5%	-0.55	-0.58	-0.79	-0.91
$demand = 80$	+5%	-2.47	-2.47	-2.47	-2.47
	-5%	2.53	2.53	2.53	2.53

Table B2:
The effect of changes in costs and demand parameters on manufacturing lot-size at different remanufacturing fraction – case 2

		% change in Q_m at different remanufacturing fraction, u			
Parameters	% change	$u = 0.5$	$u = 0.6$	$u = 0.7$	$u = 0.8$
$K_m = 400$	+5%	18.08	15.66	1.11	1.00
	-5%	-1.68	-1.44	-1.12	-1.01
$K_r = 400$	+5%	-1.98	-1.98	-1.98	-2.20
	-5%	2.02	2.02	2.02	2.25
$h_m = 50$	+5%	1.86	0.93	0.93	0.71
	-5%	-1.97	-0.95	-0.95	-0.73
$h_n = 25$	+5%	1.28	1.62	1.62	1.78
	-5%	-1.33	-1.70	-1.70	-1.89
$h_r = 45$	+5%	1.55	1.88	1.88	2.03
	-5%	-1.62	-1.99	-1.99	-2.17
$demand = 400$	+5%	-2.47	-2.47	-2.47	-2.47
	-5%	2.53	2.53	2.53	2.53

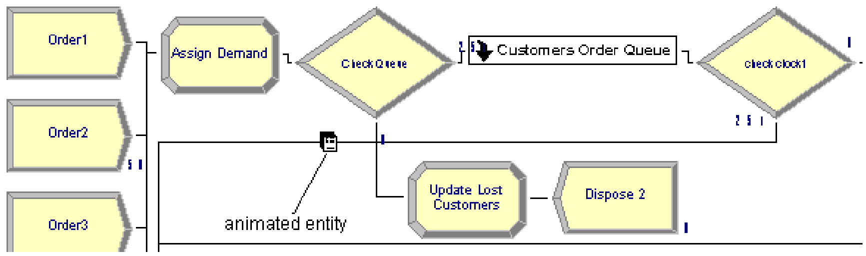
Table B3:
The effect of changes in costs and demand parameters on first remanufacturing lot-size at different remanufacturing fraction – case 1.

		% change in Q_{r1} at different remanufacturing fraction, u			
Parameters	% change	$u = 0.5$	$u = 0.6$	$u = 0.7$	$u = 0.8$
$K_m = 25$	+5%	0.50	0.50	0.50	0.28
	-5%	-0.50	-0.50	-0.50	-0.28
$K_r = 25$	+5%	-0.83	-1.07	-1.38	-1.49
	-5%	15.04	6.76	1.40	1.51
$h_m = 5$	+5%	0.97	0.55	0.37	0.18
	-5%	-1.00	1.01	-0.37	-0.18
$h_n = 2.5$	+5%	0.37	0.39	0.51	0.58
	-5%	-0.34	-0.36	-0.48	-0.54
$h_r = 4.5$	+5%	0.54	0.57	0.77	0.88
	-5%	-0.55	-0.58	-0.79	-0.91
$demand = 80$	+5%	-2.47	-2.47	-2.49	-2.47
	-5%	2.53	2.53	2.53	2.53

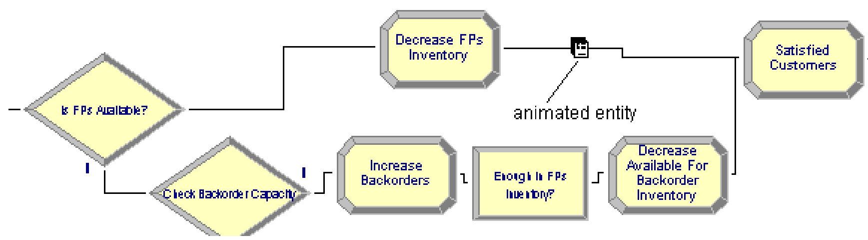
Table B4:
The effect of changes in costs and demand parameters on first remanufacturing lot-size at different remanufacturing fraction – case 2

		% change in Q_{r1} at different remanufacturing fraction, u			
Parameters	% change	$u = 0.5$	$u = 0.6$	$u = 0.7$	$u = 0.8$
$K_m = 400$	+5%	-12.89	-4.40	1.11	1.00
	-5%	-1.71	-1.46	-1.13	-1.02
$K_r = 400$	+5%	-1.98	-1.98	-1.98	-2.20
	-5%	2.02	2.02	2.02	2.25
$h_m = 50$	+5%	1.86	1.45	0.93	0.71
	-5%	-1.97	-1.52	-0.95	-0.73
$h_n = 25$	+5%	1.28	1.44	1.62	1.78
	-5%	-1.33	-1.50	-1.70	-1.89
$h_r = 45$	+5%	1.55	1.71	1.88	2.03
	-5%	-1.62	-1.80	-1.99	-2.17
$demand = 400$	+5%	-2.47	-2.47	-2.47	-2.47
	-5%	2.53	2.53	2.53	2.53

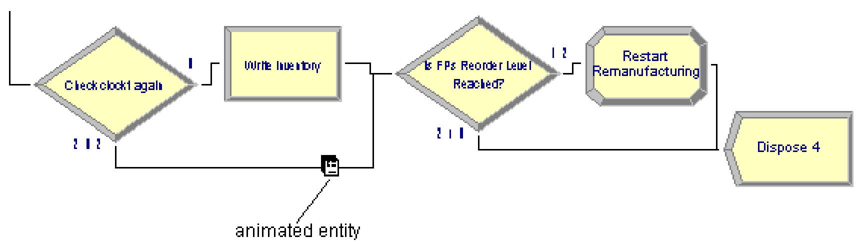
APPENDIX C



(a)



(b)



(c)

Figure C1: Verification of the computer programs of the customer demand segment. An animated entity at the (a) beginning of the segment, (b) middle of the segment, and (c) end of the segment.

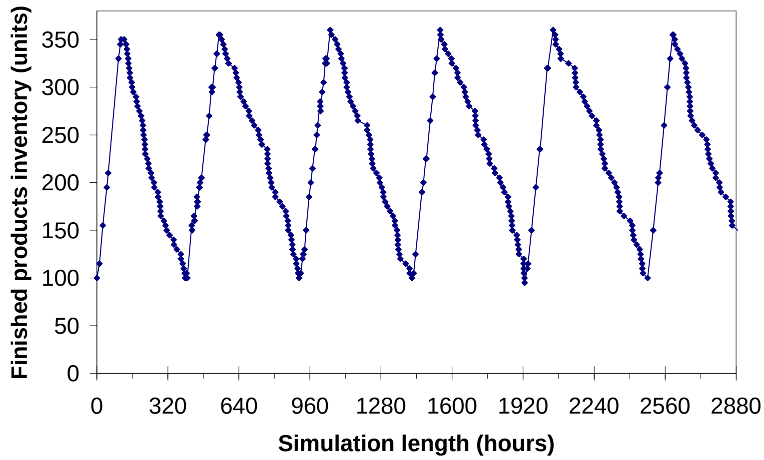


Figure C2: A profile of finished products inventory generated from simulation model "*configA*"

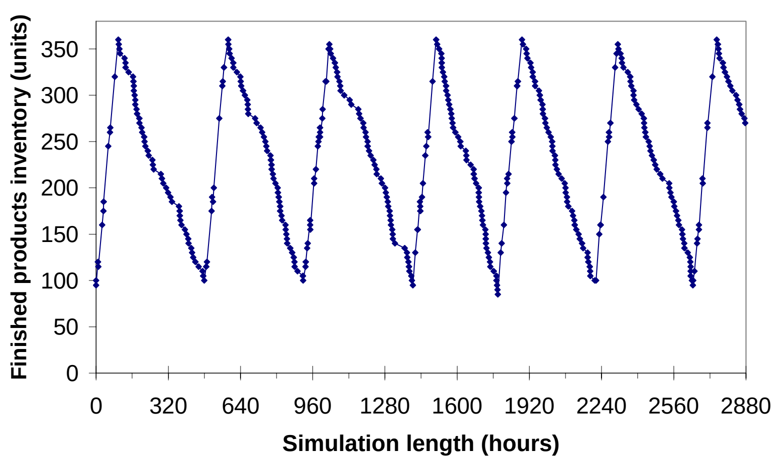


Figure C3: A profile of finished products inventory generated from simulation model "*configB*"

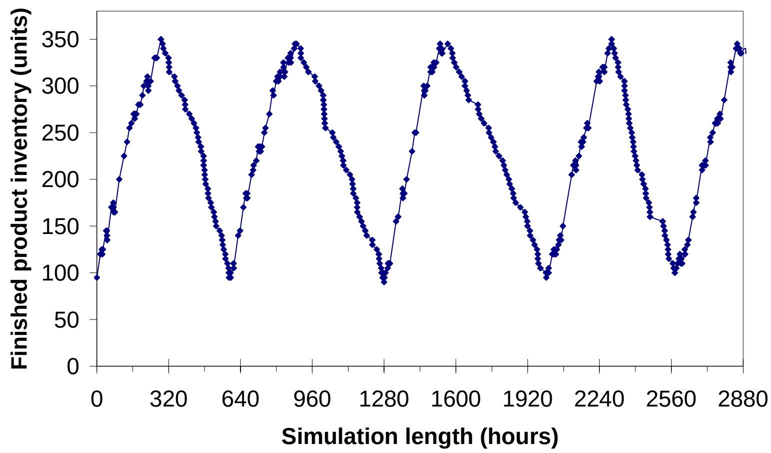


Figure C4: A profile of finished products inventory generated from simulation model "*configC*"

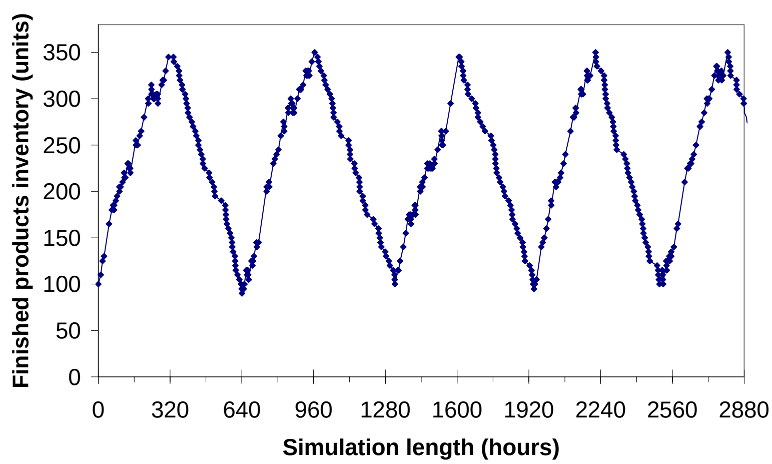


Figure C5: A profile of finished products inventory profile generated from simulation model "*configD*"

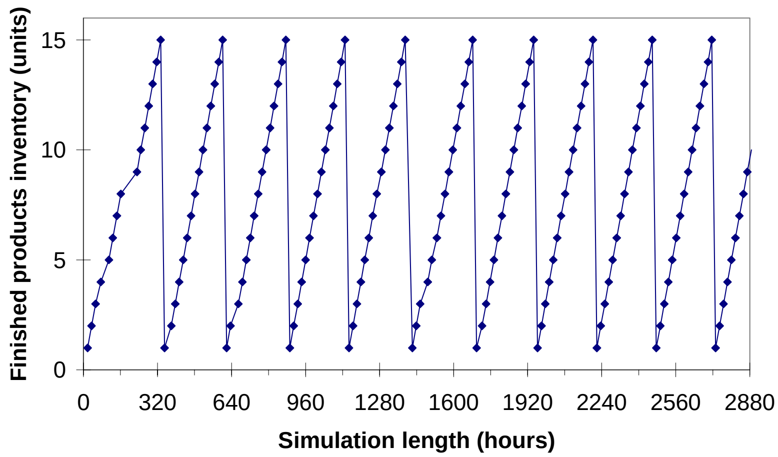


Figure C6: A profile of finished products inventory generated from simulation model *"configE"*

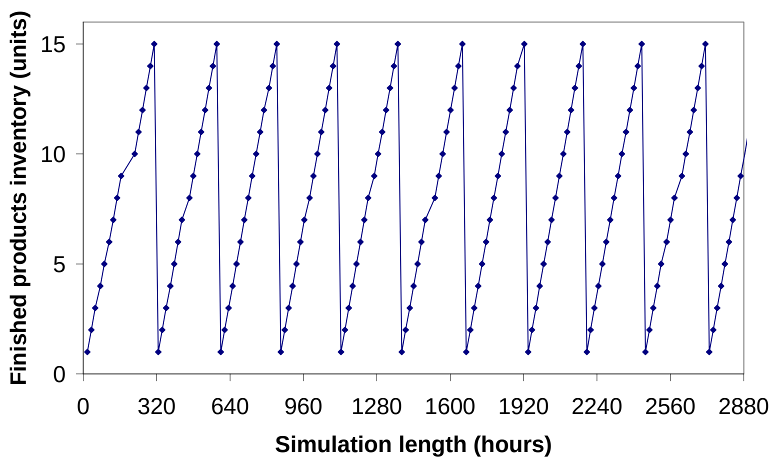


Figure C7: A profile of finished products inventory generated from simulation model *"configF"*

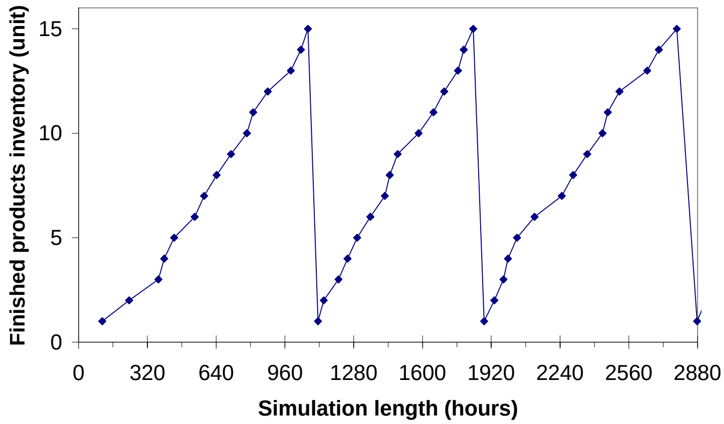


Figure C8: A profile of finished products inventory generated from simulation model *"configG"*

Table C1:
Design of the simulation experiments for analyses of RMTS systems and strategy

Cases	Configuration	Availability (every hours)	Yield (%)
1.	*"configA"*	20	95
2.	*"configA"*	40	95
3.	*"configA"*	20	80
4.	*"configA"*	40	80
5.	*"configA"*	20	65
6.	*"configA"*	40	65
7.	*"configB"*	20	95
8.	*"configB"*	40	95
9.	*"configB"*	20	80
10.	*"configB"*	40	80
11.	*"configB"*	20	65
12.	*"configB"*	40	65
13.	*"configC"*	20	95
14.	*"configC"*	40	95
15.	*"configC"*	20	80
16.	*"configC"*	40	80
17.	*"configC"*	20	65
18.	*"configC"*	40	65
19.	*"configD"*	20	95
20.	*"configD"*	40	95
21.	*"configD"*	20	80
22.	*"configD"*	40	80
23.	*"configD"*	20	65
24.	*"configD"*	40	65

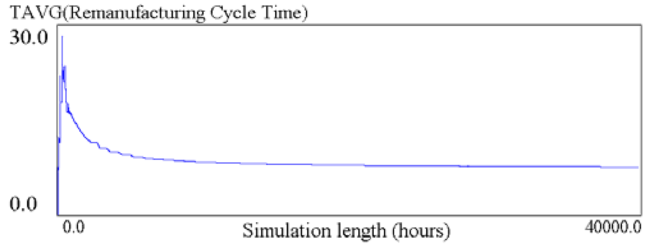
Table C2:
Design of the simulation experiments for analyses of RMTO systems and strategy

Cases	configurations	Availability (every hours)	Yield (%)
1.	“*configE*”	20	95
2.	“*configE*”	40	95
3.	“*configE*”	20	80
4.	“*configE*”	40	80
5.	“*configE*”	20	65
6.	“*configE*”	40	65
7.	“*configF*”	20	95
8.	“*configF*”	40	95
9.	“*configF*”	20	80
10.	“*configF*”	40	80
11.	“*configF*”	20	65
12.	“*configF*”	40	65
13.	“*configG*”	20	95
14.	“*configG*”	40	95
15.	“*configG*”	20	80
16.	“*configG*”	40	80
17.	“*configG*”	20	65
18.	“*configG*”	40	65

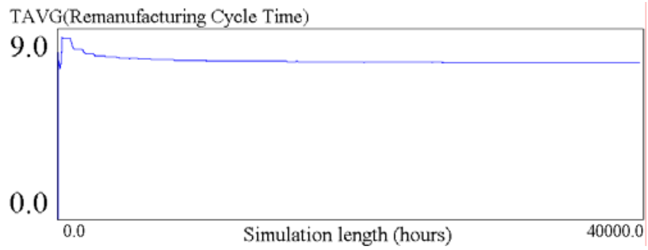
Table C3:

Fixed system parameters for analyses of remanufacturing systems and strategies

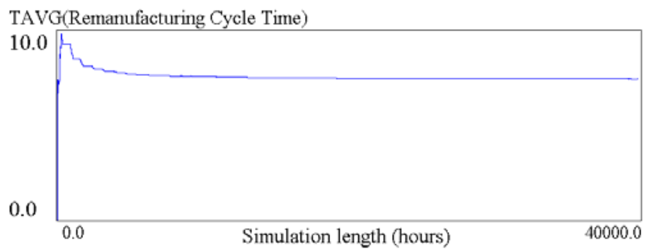
1.	Used products arrival rate = 67 400 units per month. Down scale to 449 units per month (112 units per week).
2.	Customers demand rate = 21 000 units per month. Down scale to 140 units per month (35 units per week).
2.	Inspection time of used products per unit (mins.) = TRIA(1.5, 2, 3.4)
3.	Reassembly time per unit (mins.) = TRIA (13.6, 14, 15.2)
4.	Disassembly time per unit (mins.) = TRIA(13.6, 14, 15.2)
5.	Repair time per unit for compA of GI remanufacturables (mins.) = TRIA(28.4, 30, 32.2)
6.	Repair time per unit for compB of GI remanufacturables (mins.) = TRIA(39, 40, 42.6)
7.	Repair time per unit for compA of GII remanufacturables (mins.) = TRIA(43.8, 45, 48.2)
8.	Repair time per unit for compB of GII remanufacturables (mins.) =TRIA(49, 50, 54)
9.	Disassembly yield of compA of GI remanufacturables (%) = 95
10.	Disassembly yield of compB of GI remanufacturables (%) = 93
11.	Disassembly yield of compA of GII remanufacturables (%) = 91
12.	Disassembly yield of compB of GII remanufacturables (%) = 89
13.	Reorder-level, *R* of finished products inventory for a RMTS-strategy = 100 units
14.	Target-level, *r* of finished products inventory for a RMTS-strategy = 500 units
15.	Threshold-level of finished products inventory for a RMTS-strategy = 200 units
16.	Initial finished products inventory level for a RMTS-strategy = 100 units
17.	Delivery lotsize of replacement components = 5 units
18.	Delivery leadtime of replacement components (hrs.) = 40
19.	Reorder-level of replacement components = 4 units



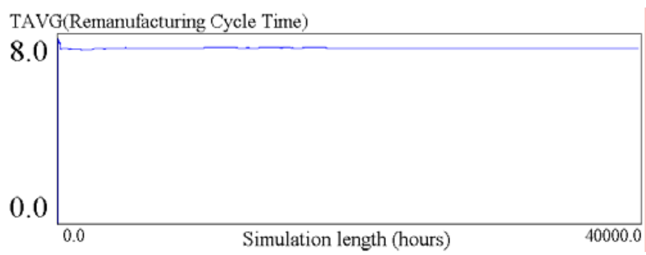
(a) replication 1



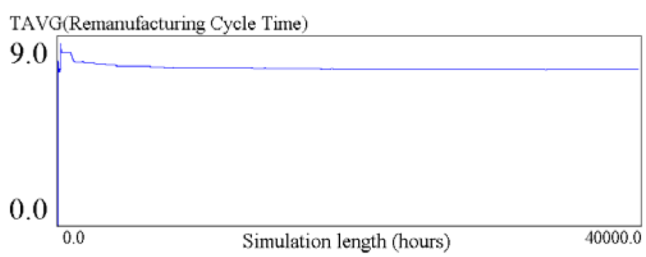
(b) replication 2



(c) replication 3

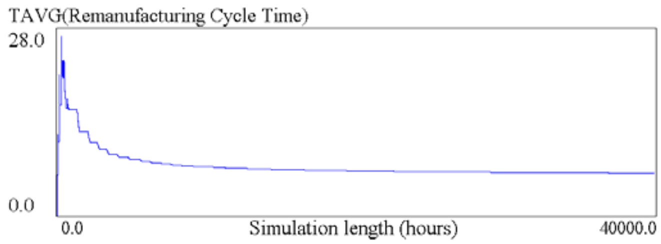


(d) replication 4

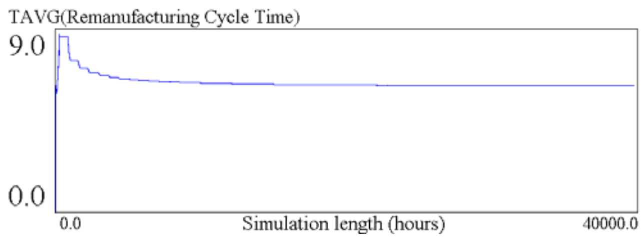


(e) replication 5

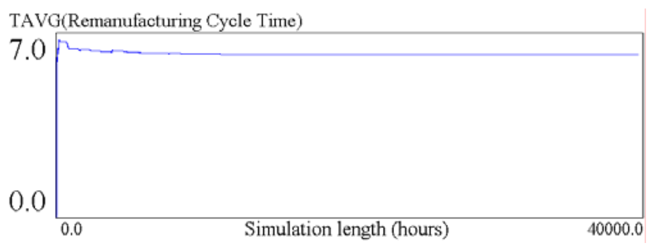
Figure C9: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model "*configA*"



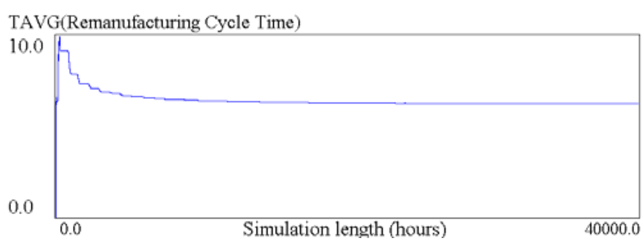
(a) replication 1



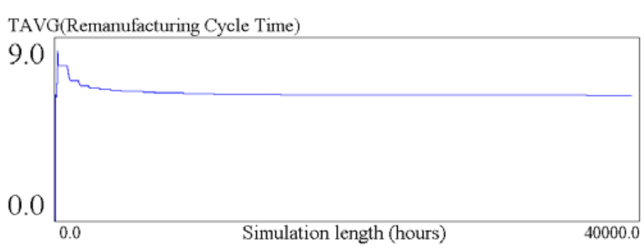
(b) replication 2



(c) replication 3

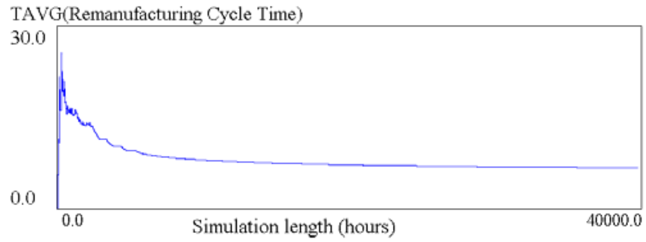


(d) replication 4

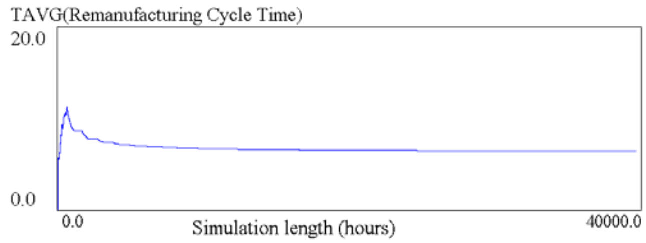


(e) replication 5

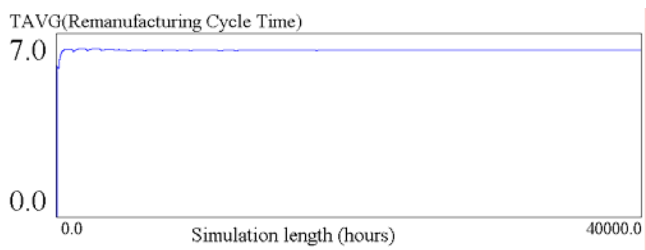
Figure C10: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model “*configB*”



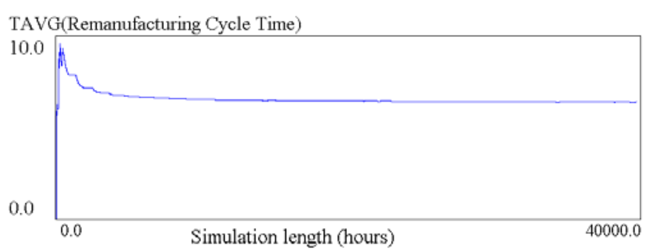
(a) replication 1



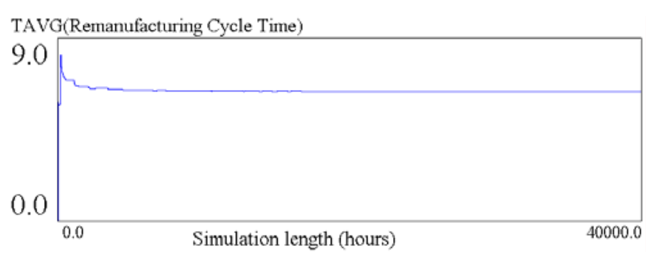
(b) replication 2



(c) replication 3

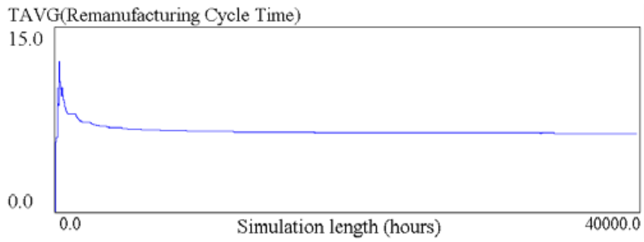


(d) replication 4

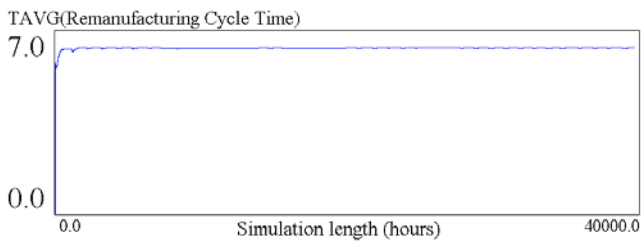


(e) replication 5

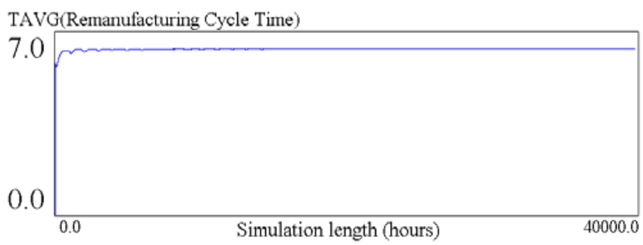
Figure C11: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model "*configC*"



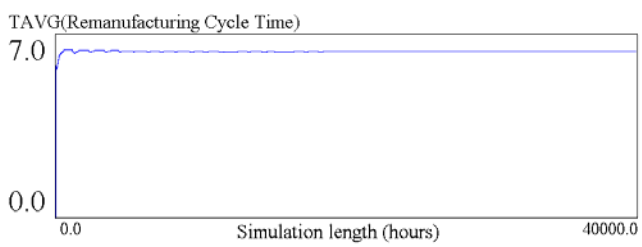
(a) replication 1



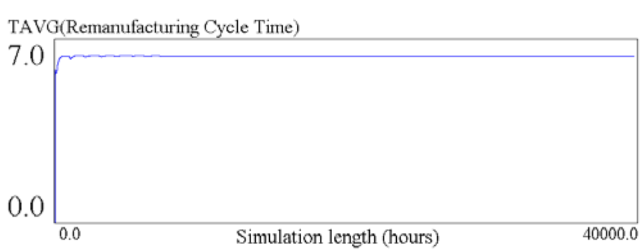
(b) replication 2



(c) replication 3



(d) replication 4



(e) replication 5

Figure C12: Profiles of remanufacturing cycle-time over 5 replications generated from simulation model "*configD*"

APPENDIX D

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.001a	5	.000	.471	.794	.089
Intercept	1634.080	1	1634.080	6244890.204	.000	1.000
Availability	.000	1	.000	1.541	.226	.060
Yield	.000	2	.000	.051	.950	.004
Availability * Yield	.000	2	.000	.357	.704	.029
Error	.006	24	.000			
Total	1634.087	30				
Corrected Total	.007	29				

a. R Squared = .089 (Adjusted R Squared = -.100)

Figure D1: SPSS Output of a two-way ANOVA of "*configA*".

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.003a	5	.001	.800	.561	.143
Intercept	1118.741	1	1118.741	1678112.000	.000	1.000
Availability	.001	1	.001	2.000	.170	.077
Yield	.001	2	.000	.500	.613	.040
Availability * Yield	.001	2	.000	.500	.613	.040
Error	.016	24	.001			
Total	1118.760	30				
Corrected Total	.019	29				

a. R Squared = .143 (Adjusted R Squared = -.036)

Figure D2 : SPSS Output of a two-way ANOVA of "*configB*".

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.028a	5	.006	1.488	.231	.237
Intercept	1190.826	1	1190.826	311734.556	.000	1.000
Availability	.012	1	.012	3.247	.084	.119
Yield	.014	2	.007	1.860	.178	.134
Availability * Yield	.002	2	.001	.236	.791	.019
Error	.092	24	.004			
Total	1190.946	30				
Corrected Total	.120	29				

a. R Squared = .237 (Adjusted R Squared = .078)

Figure D3: SPSS Output of a two-way ANOVA of "*configC*".

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	.010a	5	.002	.865	.519	.153
Intercept	1198.894	1	1198.894	496637.686	.000	1.000
Availability	.004	1	.004	1.699	.205	.066
Yield	.001	2	.001	.244	.786	.020
Availability * Yield	.005	2	.003	1.068	.359	.082
Error	.058	24	.002			
Total	1198.962	30				
Corrected Total	.068	29				

a. R Squared = .153 (Adjusted R Squared = -.024)

Figure D4: SPSS Output of a two-way ANOVA of "*configD*".

Table D1.
Average remanufacturing cycle-time (hours) of "*configB*" under six combinations of yields and availability

Availability of	Inspection yield (%)		
used products	65%	80%	95%
Every 2.5 days	6.10	6.10	6.10
Every 5 days	6.12	6.10	6.12

Table D2.
Average remanufacturing cycle-time (hours) of "*configC*" under six combinations of yields and availability

Availability of	Inspection yield (%)		
used products	65	80	95
Every 2.5 days	6.24	6.30	6.30
Every 5 days	6.30	6.32	6.34

Table D3.
Average remanufacturing cycle-time (hours) of "*configD*" under six combinations of yields and availability

Availability of	Inspection yield (%)		
used products	65	80	95
Every 2.5 days	6.32	6.30	6.31
Every 5 days	6.32	6.36	6.32

Table D4: The effect of changes in used products quantities on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand of every 32 hours.				
Change in used products quantities	Alternative configuration			
	“configA”	*“configB”*	*“configC”*	*“configD”*
+20%	0%	0%	0%	0%
-20%	0%	0%	170%	-2%

Table D5: The effect of changes in inspection yields on average remanufacturing cycle-time of alternative RMTS-system configurations - customer demand of every 40 hours.				
Change in inspection yields	Alternative configurations			
	“configA”	*“configB”*	*“configC”*	*“configD”*
+20%	0%	0%	0%	0%
-20%	0%	0%	0%	0%

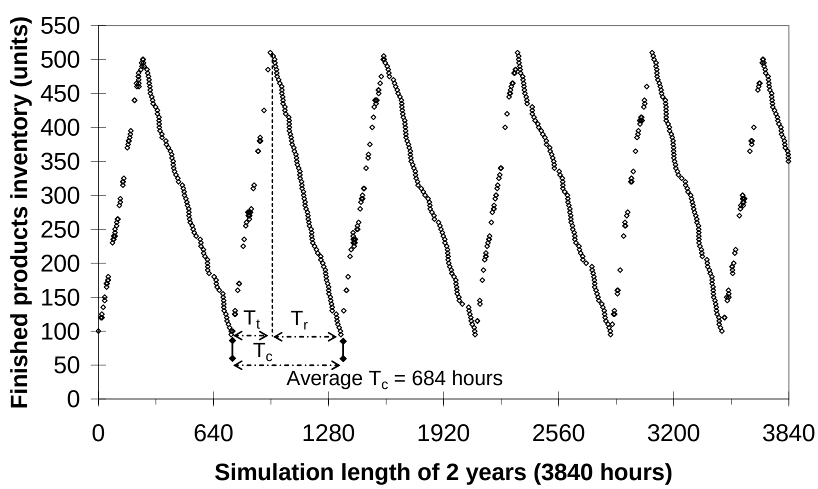


Figure D5: A typical finished products inventory profile of “*configA*” simulated over a period of 2 years - customers demand arriving every 4 days.

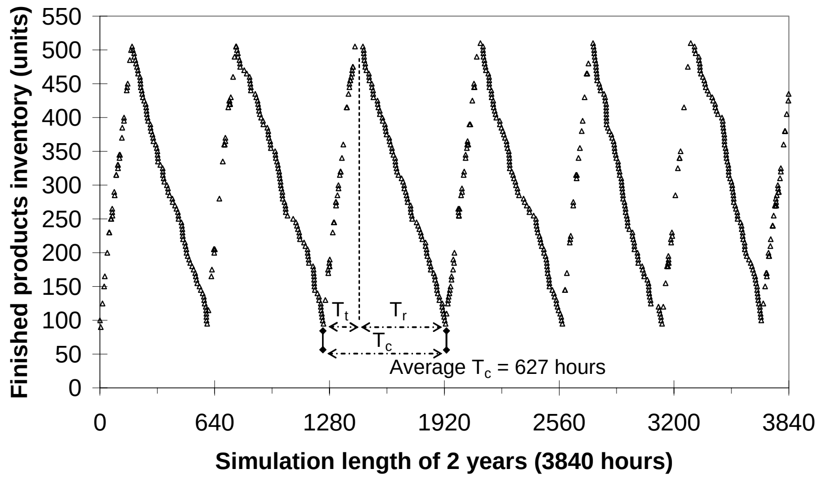


Figure D6: A typical finished products inventory profile of "*configB*" simulated over a period of 2 years - customers demand arriving every 4 days.

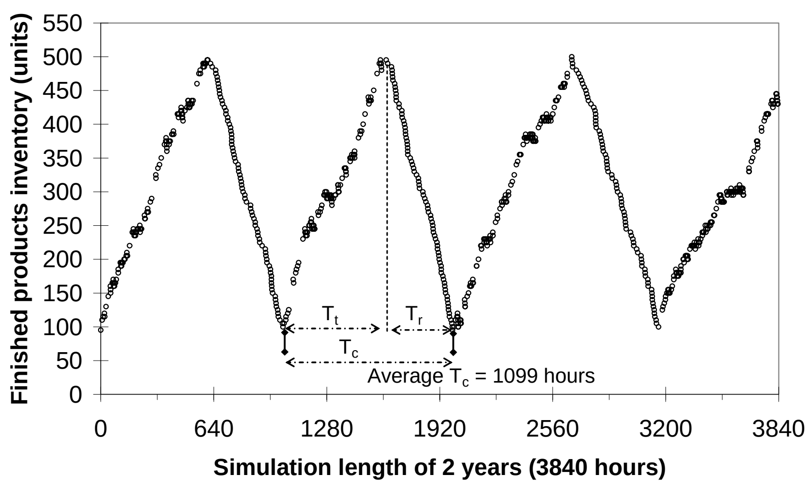


Figure D7 : A typical finished products inventory profile of "*configC*" simulated over a period of 2 years - customers demand arriving every 4 days.

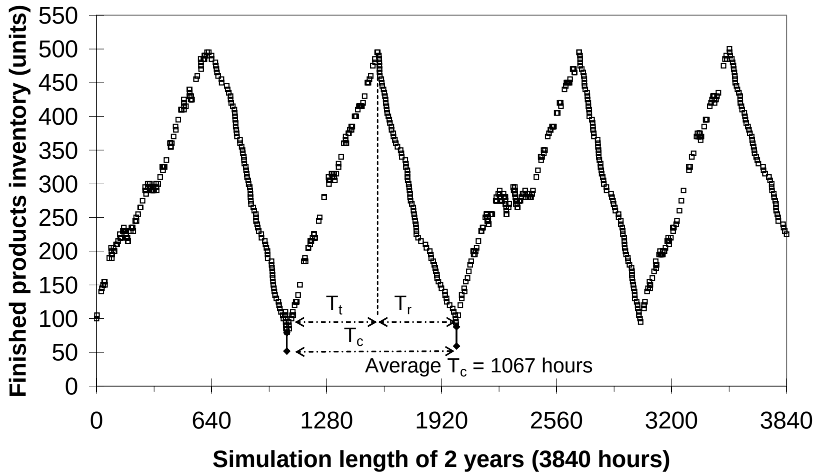


Figure D8: A typical finished products inventory profile of "*configD*" simulated over a period of 2 years - customers demand arriving every 4 days.

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	37.221a	5	7.444	56.922	.000	.922
Intercept	202.446	1	202.446	1548.014	.000	.985
Availability	28.953	1	28.953	221.390	.000	.902
Yield	7.623	2	3.812	29.146	.000	.708
Availability * Yield	.645	2	.322	2.465	.106	.170
Error	3.139	24	.131			
Total	242.805	30				
Corrected Total	40.359	29				

a. R Squared = .922 (Adjusted R Squared = .906)

Figure D9: SPSS Output of a two-way ANOVA of "*configE*".

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	21.324a	5	4.265	124.673	.000	.963
Intercept	129.661	1	129.661	3790.365	.000	.994
Availability	18.957	1	18.957	554.168	.000	.958
Yield	1.752	2	.876	25.603	.000	.681
Availability * Yield	.615	2	.308	8.995	.001	.428
Error	.821	24	.034			
Total	151.806	30				
Corrected Total	22.145	29				

a. R Squared = .963 (Adjusted R Squared = .955)

Figure D 10: SPSS Output of a two-way ANOVA of "*configF*".

Tests of Between-Subjects Effects

Dependent Variable:Cycletime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	811.023a	5	162.205	61.426	.000	.928
Intercept	5285.441	1	5285.441	2001.556	.000	.988
Availability	572.033	1	572.033	216.625	.000	.900
Yield	190.349	2	95.174	36.042	.000	.750
Availability * Yield	48.641	2	24.320	9.210	.001	.434
Error	63.376	24	2.641			
Total	6159.840	30				
Corrected Total	874.399	29				

a. R Squared = .928 (Adjusted R Squared = .912)

Figure D11: SPSS Output of a two-way ANOVA of "*configG*".

Table D6.

Average remanufacturing cycle-time (hours) of "*configF*" under six combinations of yields and availability.

Availability of used products	Inspection yield (%)		
	65	80	95
Every 2.5 days	1.44	1.21	1.20
Every 5 days	3.35	2.86	2.41

Table D7.

Average remanufacturing cycle-time (hours) of "*configG*" under six combinations of yields and availability.

Availability of used products	Inspection yield (%)		
	65	80	95
Every 2.5 days	10.36	9.06	7.30
Every 5 days	22.34	17.52	13.06

Table D8:

The effect of changes in inspection yields on average remanufacturing cycle-time of alternative RMTO-system configurations – customer demand of every 40 hours

Changes in inspection yields	Alternative configurations		
	"*configE*"	"*configF*"	"*configG*"
+20%	-18%	-15%	-18%
-20%	23%	30%	24%

APPENDIX E

Department of Mechanical and Aerospace Engineering,
Monash University, Melbourne, Australia

Questionnaire on Remanufacturing of Used Products

Please tick one answer, except when indicated otherwise.

1. Does your organization remanufacture multiple types of used products? (e.g. printers, scanners, photocopiers, etc)

	No, please specify the product. ____________________
X	Yes, please list the products in the spaces provided below.

We remanufacture major sub assemblies that are used in servicing our products (Printers , Copiers , Multifunctional Devices (M.F.D) and also export these items to the wjhole of Fuji Xerox Group of companies in the Asia Pacific region.

In the case of multiple product types, please answer the following questions based on information relating to a single product type that is regularly remanufactured (e.g. only photocopiers).

2. Are used products acquired directly from customers? *Please select all possible answers.*

	Yes.
	No, they are acquired from third party collector(s).
X	Other(s), please specify Our service operation , third party hired collectors as well as our custiomer and dealerships.

3. Are used products firstly inspected & graded prior to disassembly?

X	Yes, they are inspected and graded into groups based on their quality conditions.
	Yes, they are inspected but not graded into quality groups.
	No.

Department of Mechanical and Aerospace Engineering,
Monash University, Melbourne, Australia

4. Are used products completely disassembled into their constituent parts?

	Yes.
	No, they are only disassembled into subassemblies.
X	Other, please specify - Some items are disassemble into their constituent parts Others such as motors , electromechanical assemblies , Powersupplies . PWBA's in to subassemblies.

5. Are constituent parts (or subassemblies or other specified in question 4) inspected & graded after disassembly?

X	Yes, they are inspected and graded into several quality groups.
	Yes, they are inspected but not graded into several quality groups.
	No.

6. Are all types of constituent parts (or subassemblies or other specified in question 4) remanufactured?

	Yes.
X	No, only remanufacture selected type of parts/subassemblies (e.g. only roller)

7. Are selected parts (or subassemblies or other specified in question 6) reassembled back with other parts into their original product? *Please tick all relevant answers.*

X	Yes.
	They are sold as spare parts.
	They are assembled with other new parts to make a different product.

End of Questionnaire

Thank You For Your Time

APPENDIX F

Computer programs codes for the inspection and remanufacturables management segment

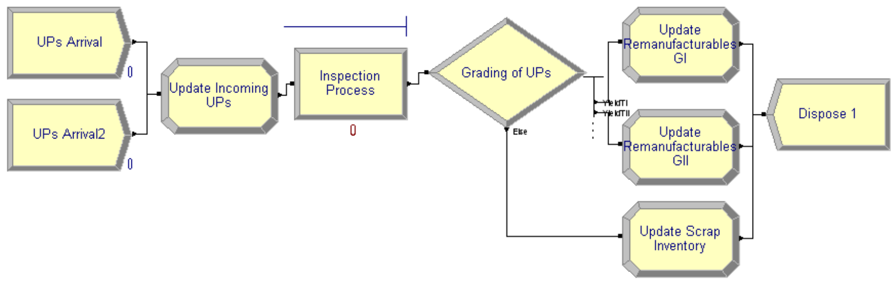


Figure F1: Architecture of the inspection and remanufacturables management segment (duplicated from subsection 4.5.1 of chapter 4)

In figure F1, the *Create* modules called "*UPs Arrival*" and "*UPs Arrival2*" generate arrivals of used product entities into the remanufacturing plant. Used products' arrivals related features (time between arrivals, number of entities per arrival, maximum number of arrivals and first time an arrival is created) are specified in this *Create* module. Once created, a used product entity (hereafter just referred to as entity for simplicity) proceeds to an *Assign* module, called "*Update Incoming UPs*", where it increases the variable *UP* by 1 unit.

Then the entity goes to a *Process* module, called "*Inspection Process*" and waits until a time equivalent to the inspection process has elapsed. After the inspection time has elapsed, the entity goes on to a *Decide* module, called "*Grading of UPs*", to check which route it would take. This *Decide* module represents grading of used products after they have been inspected by the inspection process. The probability of taking one of the exit points is specified in variables *YieldTI* and *YieldTII* which are further defined in a *Variable* module.

If the current entity is graded as GI remanufacturables, it would take the first exit point and arrives at an *Assign* module called "*Update Remanufacturables G1"*, where it increases the variable *UPG1* by one unit. Then the entity proceeds to a *Dispose* module, called "*Disposed 1"*, where it is disposed off. If the current entity is graded as scrap, it would take the last exit point and goes to an *Assign* module, called "*Update Scrap Inventory"*, where it increases the variable *UPS* by one unit. Then it goes to the *Dispose* module and is disposed off.

APPENDIX G

Computer programs codes for the replacement components management segment

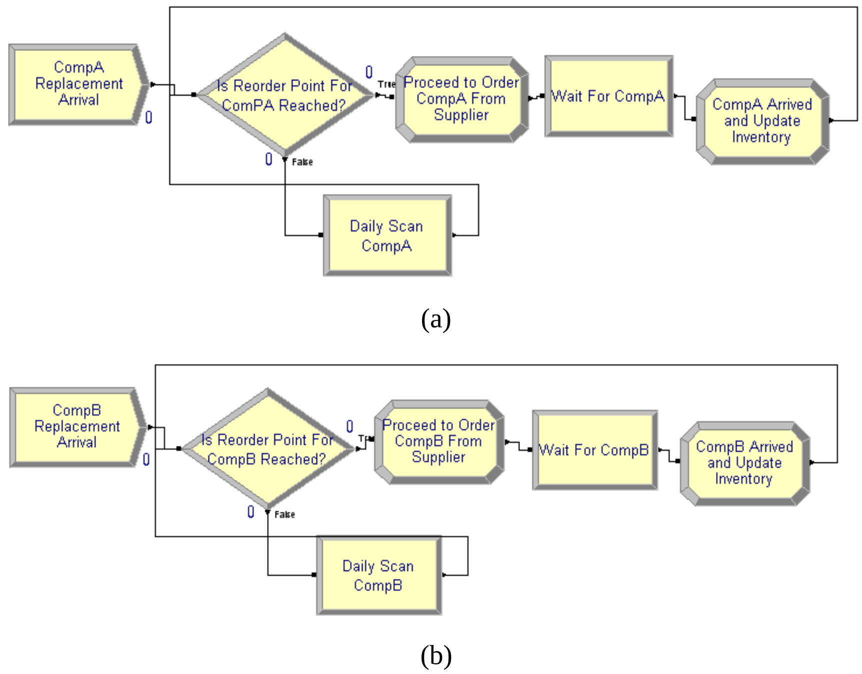


Figure G1: Architecture of the replacement components management segment for (a) component A, (b) component B (duplicated from subsection 4.5.2 of chapter 4)

In figure G1, the *Create* module called "*CompA Replacement Arrival*" generates a single control entity which monitors and manages the replacement components for component A (*CompA)*. The control's entity arrival related features (time between arrivals, number of entity per arrival, maximum number of arrivals and first time an arrival is created) are specified in this *Create* module. Components A (*CompA)* replacement related features (lotsize and delivery leadtime) are specified in a *Variable* module. Once created, the control entity proceeds to a *Decide* module, called "*Is Reorder Point For CompA Reached?*", to check whether a reorder-level for C*ompA* has just been reached. This could result in two possible outcomes.

1. If a reorder-level for *CompA* has just been reached, the control entity takes the true exit to an *Assign* module, called "*Proceed to Order CompA From Supplier*", where it updates the variable *OrderedCompA*. This variable keeps track of the number of times *CompA* has been ordered from the supplier. Next the control entity arrives at a *Delay* module, called "*Wait For CompA*", where it is held for a period equivalent to a delivery leadtime for *CompA*. Once that delivery leadtime has elapsed, the control entity is released and it proceeds to an *Assign* module, called "*CompA Arrived and Update Inventory Level*", where it updates the variable *CompARepInvLev*. Then the control entity circulates back to a *Decide* module and repeats the next cycle.

2. If a reorder-level for *CompA* has not reached, the control entity takes the false exit and proceeds to a *Delay* module, called "*Daily Scan CompA*", before circulating back to a *Decide* module, called "*Is Reorder Point For CompA Reached?*", and repeats the cycle.

APPENDIX H

Computer programs codes for the customer demand management segment of RMTS-system

In figure H1, the *Create* modules, called “*Order1”*, “*Order2”, “Order3”*, *“Order4”*, “*Order5”* and *“Order6”* generate arrivals of customer entities at the finished products warehouse. These *Create* modules generate customer entities’ arrival at the warehouse throughout the day. For any given day the first customer entity (hereafter simply called entity) is generated by the *Create* module (“*Order1”*) to arrive at the earliest hour of the day and subsequent entities are specified to arrive according to an exponential distribution. Similarly, the last customer entity is generated to arrive by a *Create* module (“*Order6”*) and time between arrivals of subsequent entities is also specified according to an exponential distribution. In all the *Create* modules, a random number from *stream1* is specified for generating the customers’ entities.

For an entity created by one of the *Create* modules, its *Attribute*, called “*Demand”* is assigned in an *Assign* module called “*Assign Demand”* and a random number from *stream2* is specified for generating the *Demand.* The *Assign* module also assigns an *Attribute* called *clock1,* a variable called *TCustomer* and an *Attribute*, called *Tolerance=*1. When the entity arrives at a *Decide* module, called “*Check Queue”*, its Attribute (*Tolerance*) is checked against the current number in queue (*NQ*) for a *Hold* module (“*Hold V”),* which resides in a *Submodel* called “*Customers Order Queue”*.

If the *Tolerance* value is smaller than current number in queue (*NQ*) for “*Hold V”* module, the entity takes the false exit, proceeds through an *Assign* module called “*Update Lost Customers”* and then goes to a *Dispose* module, called “*Disposed* 2” and is disposed off. Otherwise, the entity takes the true exit and enters a *Submodel* called “*Customers Order Queue”* where it is repeatedly held and released in a series of *Hold* modules, which represent customers queuing up while they wait for their demand to be satisfied.

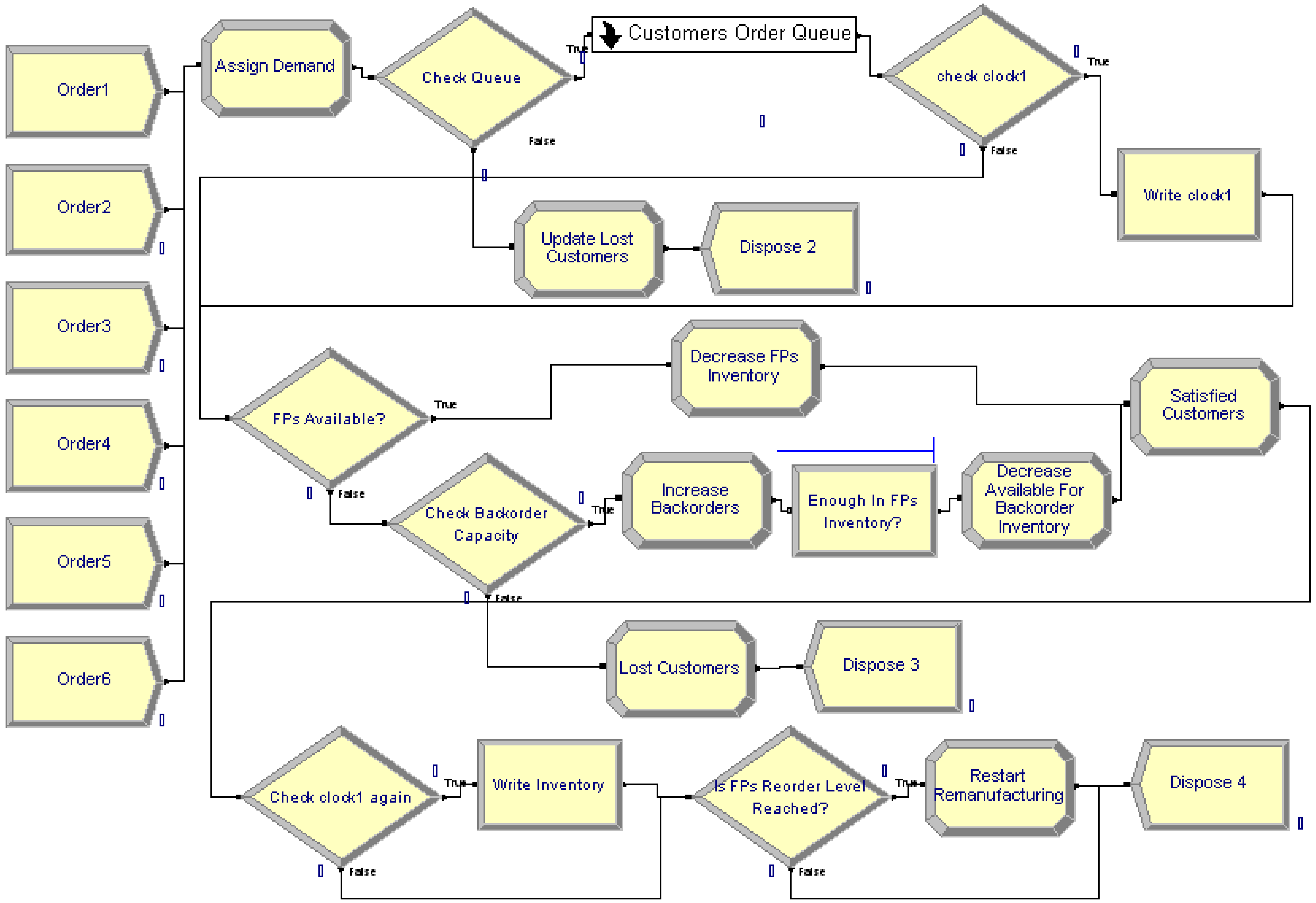


Figure H1: Architecture of the customer demand management segment of RMTS-system (duplicated from subsection 4.5.3 of chapter 4)

Once the entity reaches the last queue (*Hold* module called "*Hold A*"), it is detained until a condition [*NQ(Enough In FPs Inventory?.Queue)= =0*] becomes true and is released. Then, the entity enters a *Decide* module called "*check clock1*" to check if its attribute *clock1* equals to some specified value. If this condition is true, the entity takes the true exit and enters a *Write* module called "*Write clock1*" where it instructs its attribute *clock1* to be written to an Excel file; otherwise, it takes the false exit. Either ways, the entity comes to a *Decide* module, called "*Is FPs Available?*" to check if the warehouse has sufficient on-hand finished products inventory to satisfy a demand. This could result in two outcomes:

(a) If there are sufficient on-hand finished products inventory then the current demand is satisfied and the entity goes through the true exit into an *Assign* module, called "*Decrease FPs Inventory*", where it decrements the inventory by the demand amount.

(b) If there is insufficient on-hand finished products inventory the current demand is partially satisfied and the entity takes the false exit and proceeds to a *Decide* module called "*Backorder Capacity*" to check if the backorder capacity has been reached. This results in two possible outcomes:

- If the backorder capacity has been reached, the entity takes the false exit and enters an *Assign* module called "*Lost Customers*" where it updates the variable *LCusts* which keep tracks of the number of lost customers. Then the entity enters a *Dispose* module (*Disposed 3*) and is disposed off.

- If the backorder capacity has not been reached, the entity takes the true exit and enters an *Assign* module called "*Increase Backorders*", where it updates the variable *Backorder* which keeps track of the number of backordered demand. Furthermore, it also updates an attribute called *UnSatDemand* which keeps track of the amount of unsatisfied demand. Next the entity sets the variable *Inventory* to 0 and finally it updates the variable *BCusts* which keep tracks of the number of backordered customers.

- Then the entity proceeds to a *Hold* module called "*Enough in FPs Inventory*", where it is detained until the amount available for backorder is greater or equal to the amount of unsatisfied demand. Once the entity is released it goes to an *Assign* module, called "*Decrease Available For Backorder Inventory*", where it decrements the amount available for backorder by the unsatisfied demand.

Either way, the entity enters an *Assign* module called "*Satisfied Customers*" where it updates the variable *TotSatCusts*, which keep tracks of the number of customers whose demand has been satisfied. Next, the entity goes to a *Decide* module called "*check clock1 again*" to check if the attribute *clock1* equals to some predefined value.

If it is the case, the entity takes the true exit and enters a *Write* module called "*Write Inventory*" where it instructs the current value of the variable *Inventory* to be written to an Excel file. Otherwise, the entity takes the false exit and arrives at a *Decide* module called "*Is The Reorder Level Reached?*", to tests whether the *Reorder* variable has just been reached. If it has, the entity then proceeds to an *Assign* Module, called "*Restart Remanufacturing*", to set *Reman=1* which would promptly release the remanufacture control entity currently detained in a *Hold* module, called "*Remanufacture?*" (in the remanufacturing and inventory control segment), effectively resuming the remanufacturing process. Finally the entity proceeds to a *Decide* module called "*Dispose 4*" and is disposed off.

APPENDIX I

Computer programs codes for the customer demand management segment of RMTO-system

As shown in figure I1, the *Create* modules (“*Order*1”, “*Order2”*, “*Order3”*, “*Order4”*, “*Order5”* and “*Order6”)* generate arrivals of customers’ entities at the finished products warehouse. For any given day, the first customer entity (henceforth, called entity) is generated by the *Create* module (“*Order1”*) to arrive at the earliest hour of the day and subsequent entities are specified to arrive according to an exponential distribution. Similarly, the last customer entity is generated to arrive by the *Create* module (“*Order6”*) and time between arrivals of subsequent entities is also specified according to an exponential distribution. Also in all the *Create* modules a random number from *stream1* is specified for generating the customers’ entities.

Once a customer’s entity has been created in one of the *Create* modules it enters an *Assign* module called “*Assign Demand”*, where its *Attribute* called *Dmd* is assigned. The *Assign* module also assigns *Attributes* called *clock1*, *Tolerance* and a *Variable* called *TCusts*. When the entity arrives at a *Decide* module called “*Check Queue”*, its *Attribute* (*Tolerance*) is checked against the current number in queue (*NQ*) for a *Hold* module (*Hold V)*, residing in a *Submodel* called “*Customers Order Queue”*.

If the *Tolerance* value is smaller than the current number in queue (*NQ*) for “*Hold V”* module, the entity takes a false exit and goes to a *Dispose* module (“*Dispose 2”*) and is disposed off. Otherwise, the entity takes a true exit and enters a *Submodel* called “*Customers Order Queue”* where it is repeatedly held and released in a series of *Hold* modules. Once the entity has been released from the last *Hold* module it goes to an *Assign* module, called “*Order Arrive”* where its *Attribute* called *arrive* is assigned.

Next the entity goes through an *Assign* module called “*Increase Backorders”*, where it updates the *Variable* called *Unsatdmd* which keep tracks of a customers demand. After that the entity proceeds to another *Assign* module called “*Start Reman”* to set *Reman*=1, which would promptly release a remanufacturing control entity currently detained in a *Hold* module, called “*Remanufacture*?”, effectively initiating the remanufacturing process.

Then the entity goes to a *Hold* module, called "*Enough in FPs Inventory*" where it is detained until a condition (*Inventory==Unsatdmd)* becomes true. Once this happens, the entity is released and proceeds to a *Record* module called "*Record Waiting Time*", where its *Attribute* (*arrive*) is read. Next, the entity goes to an *Assign* module called "*Update Inventory*" where it resets the variable *Inventory* to zero and finally the entity arrives at a *Dispose* module ("*Dispose* 3") and is disposed off.

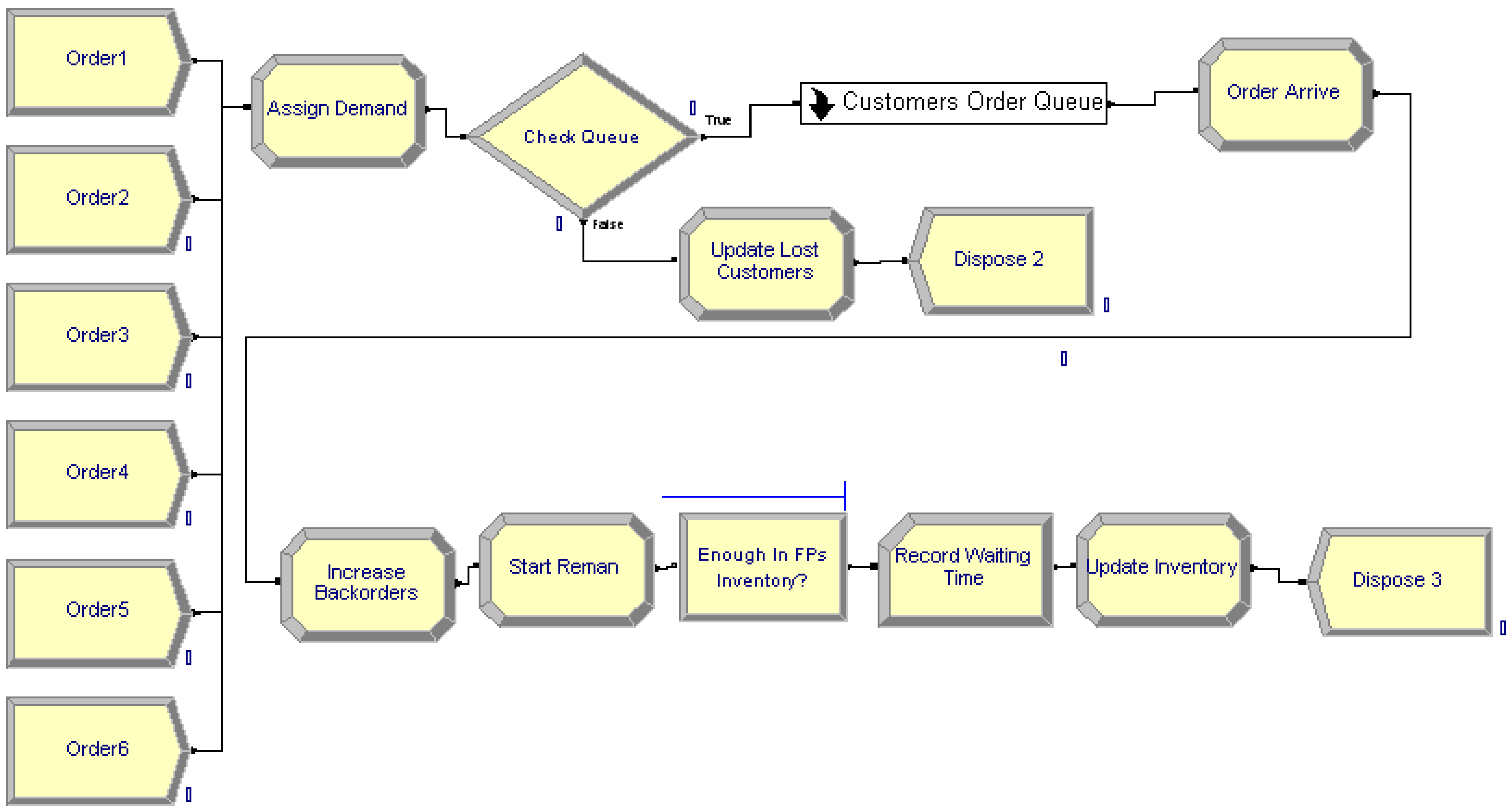


Figure I1: Architecture of the customer demand management segment of RMTO system (duplicated from subsection 4.5.3 of chapter 4)

Computer programs codes for the remanufacturing and finished products inventory control management segment of "*configA*"

In figure J1, there are four circulating control entities, two control entities (*control1*, *control2*) circulating through the UPG1 remanufacture logic and the other two (*control3* and *control4*) circulating through the UPG2 remanufacture logic. The *control1*, *control2*, *control3* and *control4* entities are created in the *Create* modules, called "*GI Remfg ProcessA*", "*GIRemfg ProcessB*", "*GII Remfg ProcessA*" and "*GII Remfg ProcessB*", respectively. After all control entities are created they go to their respective next modules, called "*AssignEntity1*", "*AssignEntity2*", "*AssignEntity3*" and "*AssignEntity4*", where their attribute *Type* are assigned. For example, for *contro1*, the *Type* attribute is assigned as 101, while for the *control4*, the *Type* attribute is assigned 104.

Then all control entities go to a *Hold* module, called "*Remanufacture?*", where they are detained until a condition (*Reman=1*) becomes true. Once this happen all control entities are released and go to an *Assign* module, called "*Assign Start Time*", where their attribute *arrival times* are assigned. Next all control entities arrive at a *Decide* module, called "*Which Route?*" to check which route they should take. If the current control entity has a *Type* attribute of 101, it would take the first true exit; if it has a *Type* attribute of 102, it would take the second true exit, if it has a *Type* attribute of 103, it would take the third true and if it has a *Type* attribute of 104, then it would take a false exit.

Considering the first true exit, the *control1* entity proceeds to a *Decide* module, called "*Check GI Inventory*", to check stock of G1 remanufacturables. If there are sufficient stocks of GI remanufacturables, the *control1* entity takes a true exit; otherwise it takes a false exit and waits in a *Hold* module ("*Wait For Incoming GI*") until there is sufficient stock of GI remanufacturables. Either ways, the *control1* entity goes to an *Assign* module, called "*Decrease GI Inventory*" where it decrements the G1 inventory level by the batch size. The *Variable batch* is defined in a V*ariable* module.

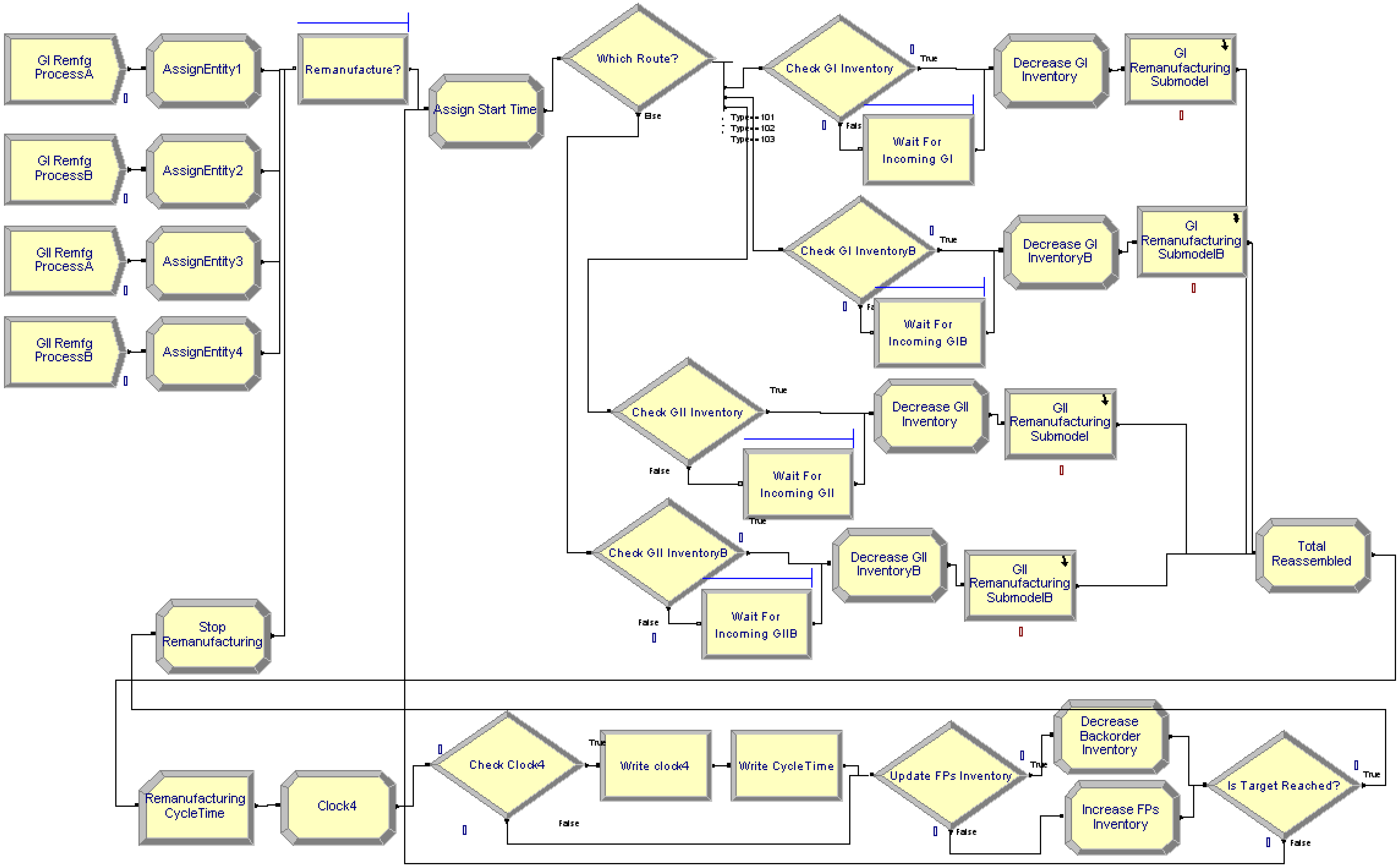


Figure J1: Architecture of the remanufacturing and inventory control management segment of "*configA*" (duplicated from subsection4.5.4 of chapter 4)

Then the *control1* entity proceeds to a *Submodel*, called *GI "Remanufacturing Submodel" (*figure J2) where it first proceeds to a *Process* module, called "*Disassembly GI Process"*, and stays there until a time equivalent to disassembly process has elapsed. Once this happens, the *control1* entity proceeds to a *Duplicate* block where it is duplicated. The number of duplicates depends on the number of type constituent component type being repaired. Since there are two component types (*CompA* and *CompB*), being remanufacture, then there is only one duplicate (i.e. there are two exit branches out of the *Duplicate* block). The top branch represents the repair logic for *CompA*, while the bottom branch represents the repair logic for *CompB*.

The original *control1* entity takes the top exit and proceeds to an *Assign* module called "*AssignCompAGI"*, where it is assigned an attribute *Entity.SerialNumber*. Next, the *control1* entity proceeds to a *Decide* module ("*CompAGI Inspection1"*) to check which exit it would take. The probability it would take the true exit is specified in a *Variable* called *FracAIre* which is specified in the *Variable* module, while the probability it would take the false exit is defined as *100* **-** *FracAIre*. The true exit represents the route for the repair process while the false exit represents the route for the replacement process (in this case the disassembled components are considered as scrap).

Considering the true exit, the *control1* entity proceeds to a *Process* module, called "*Repair CompAGI Process"*, where it is detained for a time equivalent to the repair period. Once this time has elapsed the *control1* entity goes to an *Assign* module, called "*Total Remanufactured CompAGI"*, where it updates the variable *RemfgA* which keeps track of the total number of component A that has undergone the repair process.

Next the *control1* entity proceeds to a *Batch* module, called "*Batch for Reassembly Process 1"*, where it waits for the duplicated control entity. The duplicated *control1* entity also proceeds through a similar series of modules as that of the original *control1* entity. However, the specifications for these modules ("*CompBGI Inspection1"* and "*Repair BGI Process"*) are different from those modules undergone by the *control1* entity. At the *Batch* module the duplicated control entity is merged with the original *control1* entity into a single *control1* entity.

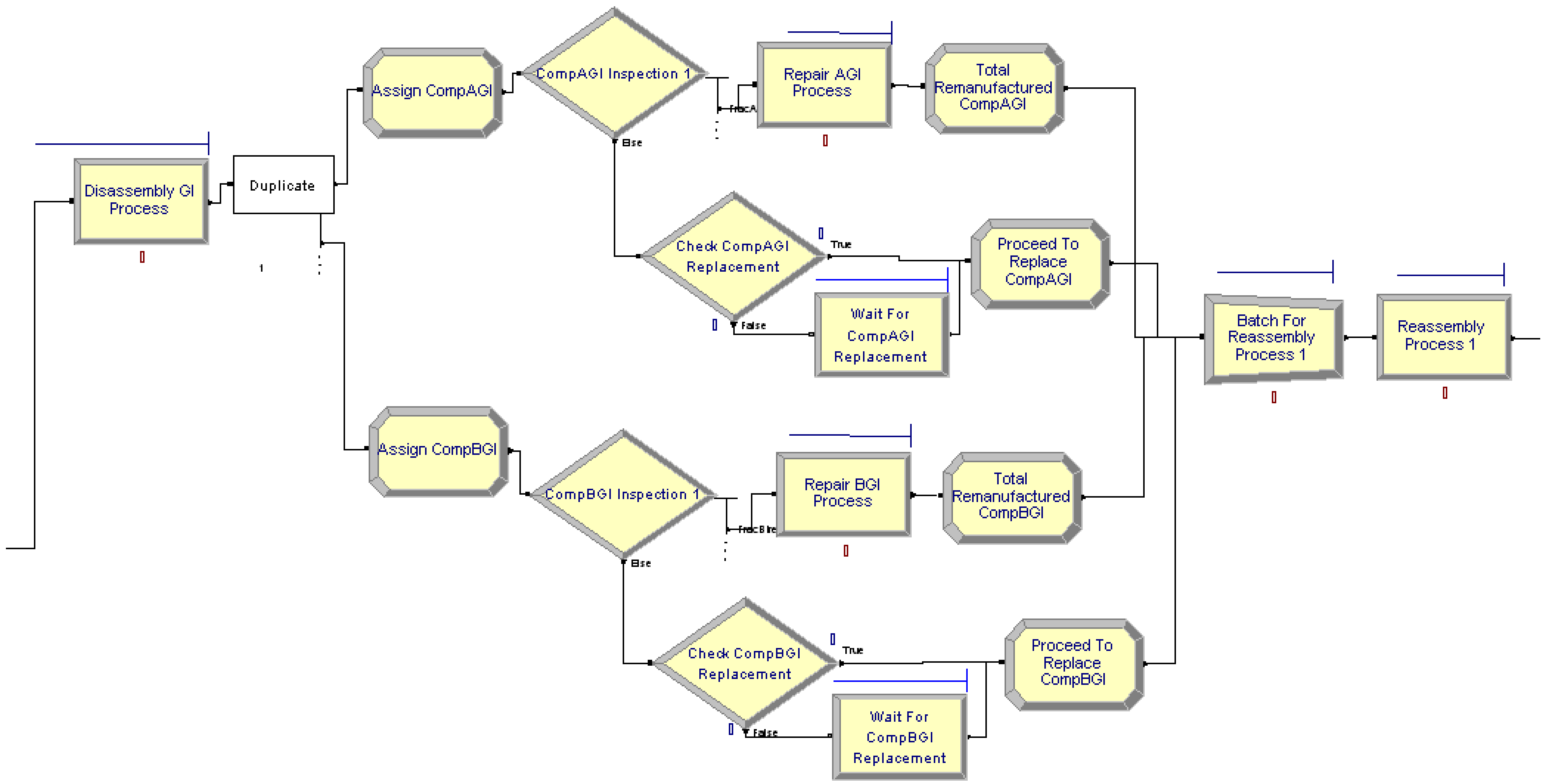


Figure J2: Architecture of the *submodel* called "*GI Remanufacturing Submodel*"

The *control1* entity then proceeds to a *Process* module, called "*Reassembly Process 1"*, where it is held for a time equivalent to the reassembly period. After this time has elapsed the *control1* entity is released and proceeds to an *Assign* module, called "*Total Reassembled"*, where it updates the variable *Reassembled* which keeps track of the total number of finished products that have been reassembled

Next the *control1* entity proceeds to a *Record* module, called "*Remanufacturing CycleTime"*, where its attribute (*Time*) is recorded. This time equals to the time that has elapsed since the *control1* entity's arrival at the "*Assign Start Time* module". The *control1* entity then proceeds to an *Assign* module called "*Clock4"*, where its arrival time attribute (*clock4*) is assigned. Next the control entity arrives at a *Decide* module called "*Check Clock4"* to check if a condition specify in the *Decide* module is true. If this is the case, the *control1* entity takes the true exit and goes through a series of *Write* modules ("*Write clock4", "Write CycleTime"*) where it instructs some information to be written to Excel files. For instance, the "*Write clock4"* module is specified to write the arrival time attribute (*clock4*) and the "*Write CycleTime"* module is specified to write the remanufacturing cycletime.

Next the *control1* entity proceeds to a *Decide* module called "*Update FPs Inventory",* where it checks if there are any pending backorders. This could result in two possible outcomes. If there are any pending backorders, the *control1* entity takes the true exit for the *Assign* module called "*Decrease Backorder Inventory"*, where a pending backorder is satisfied by decrementing the *Variable Backorder* by *batch* and incrementing the *Variable AvailBackorder* by *batch.* Otherwise, if no backorders are pending, the control entity takes the false exit for the *Assign* module called "*Increase FPs Inventory"*, where it updates the finished products inventory by incrementing the *Variable Inventory* by *batch*.

Either way the control entity proceeds to a *Decide* module called "*Is Target Reached?"* to check if the finished products inventory level has reached a target level. This could result in two possible outcomes. If the finished products inventory level has reached a target level the *control1* entity takes the true exit and proceeds to an *Assign* module called "*Stop Remanufacturing"* where it sets *Reman=0,* which would change the condition in the *Hold* module ("*Remanufacture*?") such that any incoming control entities are detained. Other wise, the control entity takes the false exit and proceeds to an *Assign* module ("*Assign Start Time"*) and repeats the cycle.

For *control2* entity, it takes the second true exit at the *Decide* module ("*Which Route?"*) and proceeds through a series of four modules which are unique to this *control2* entity. Then it proceeds through the series of common modules (starting with "*Total Reassembled"* module and ending with "*Which Route*?" module). For the *control3* entity, it takes the third true exit at the *Decide* module ("*Which Route?"*) and enters a series of four modules which are also unique to this *control3* entity. It also proceeds through a series of common modules. As for the *control4* entity, it takes the false exit, proceeds through its series of unique modules, as well as through the series of common modules.

APPENDIX J-b

Computer programs codes for the remanufacturing and finished products inventory control management segment of "*configC*"

In figure J3, there are two circulating control entities (*control1* and *control2*) that go through either the GI or GII remanufacture logic. Both control entities go through one common inventory control logic. The *control1* and *control2* entities are created in the *Create* modules, called "*GI Remfg Process*" and "*GII Remfg Process*" respectively. After the control entities are created they go to their respective next modules, called *Assign* "*Entity1*" and "*Assign Entity2*" where their attribute *Type* is assigned. For example, for the *control1* entity, the *Type* attribute is assigned as 101, while for the *control2* entity, the *Type* attribute is assigned 102.

Then both control entities go to a *Hold* module, called "*Remanufacture?*", where they are detained until a condition (*Reman=1*) becomes true. Once this happens both control entities are released and proceed to an *Assign* module called "*Assign Start Time*", where the entities' attribute (*arrival times*) are assigned. Next both control entities arrive at a *Decide* module called "*GI or GII?*" to check if a specified condition (*Inventory <= Threshold*) is true. This could result in two outcomes. If the specified condition is true, the control entities take the true exit and arrive at another *Decide* module called "*Which Route?*" to check which route they should take. If the current control entity has an attribute *Type*=101, then it would take the true exit, otherwise it would take the false exit.

Assuming that the current entity is of *Type*=101, it arrives at another *Decide* module called "*Check GI Inventory*" to check if there is sufficient GI remanufacturables. If this is the case, the control entity takes the true exit. Other wise, the control entity goes to a *Hold* module called "*Wait for Incoming GI*" where it is detained until a specified condition becomes true. Either ways, the control entity goes to an *Assign* module called "*Decrease GI Inventory*" where it decrements the variable *UPGI* by the variable *batch*. Next the control entity arrives at a *Submodel* called "*GI Remanufacturing Submodel*".

If the control entity is of *Type*=102, it takes the false exit of the "*Which Route?*" *Decide* module, and proceeds through a set of modules ("*Check GI InventoryB*", "*Decrease GI InventoryB*", "*GI Remanufacturing SubmodelB*"). Then the control entity arrives at an *Assign* Module called "*Total Reassembled*".

If the specified condition (*Inventory<=Threshold*) in a *Decide* module called "*GI or GII*?" is not true, the control entities take the false exit to arrive at a *Decide* module called "*Which Route2?*" to check which route they should take. If the control entity is *Type*=101, it takes the true exit and proceeds through a set of modules ("*Check GII Inventory*", "*Decrease GII Inventory*" and "*GII Remanufacturing Submodel*") until it arrives at an *Assign* module called "*Total Reassembled*". If the control entity has attribute *Type*=102, it takes the false exit and also proceeds through a set of modules ("*Check GII InventoryB*", "*Decrease GII InventoryB*" and "*GII Remanufacturing SubmodelB*") until it arrives at an *Assign* module "*Total Reassembled*".

The architecture and simulation logic of *Submodels ("GI Remanufacturing Submodel", "GI Remanufacturing SubmodelB", "GII Remanufacturing Submodel"* and *"GII Remanufacturing SubmodelB"*) are identical to those already described for "*configA*"; hence these architecture and simulation logic are not described again. Once the control entities have exited the *Assign* module ("*Total Reassembled*") they go through a set of common modules which are also identical to those described for "*configA*", thus the architecture and simulation logic are not described.

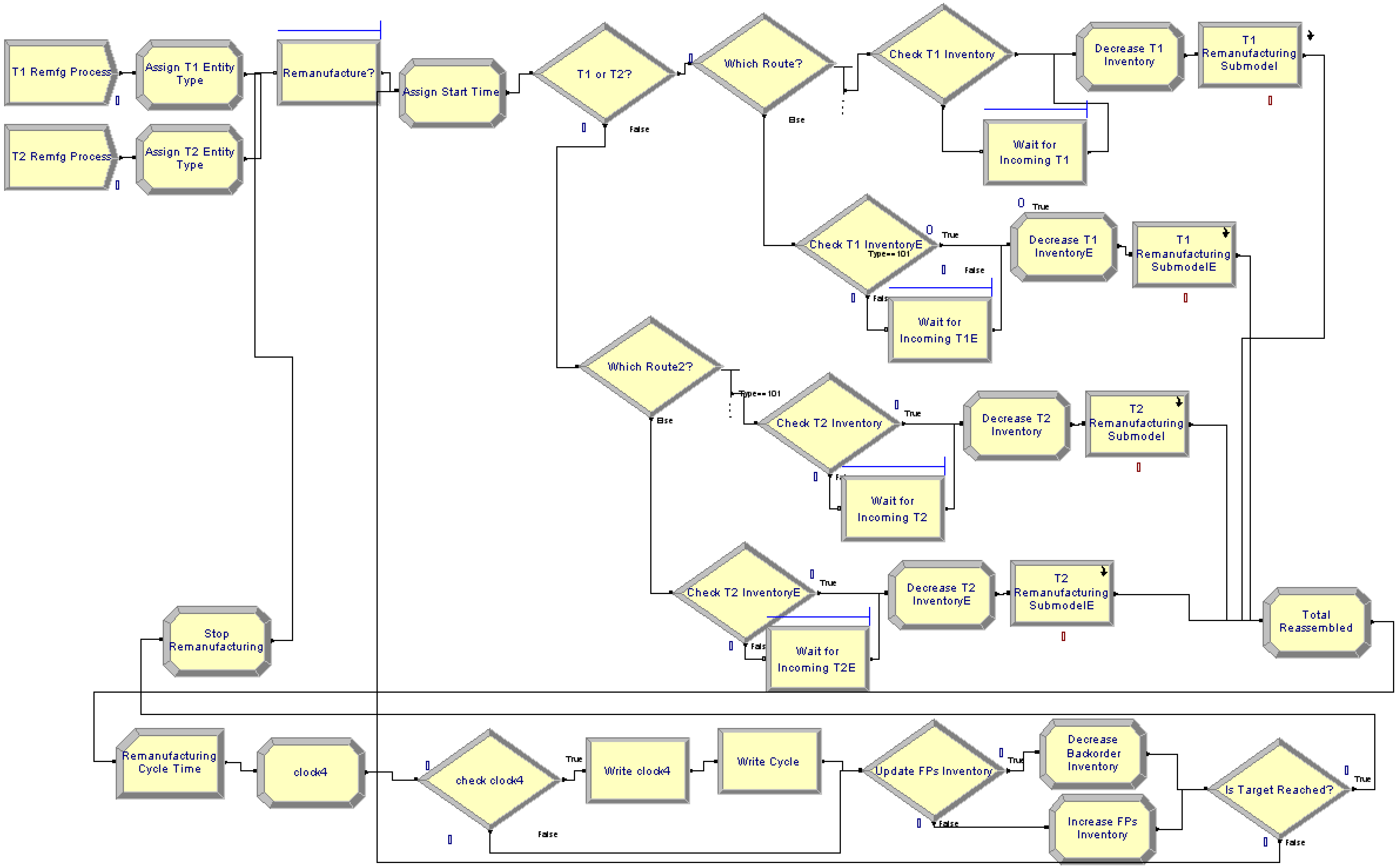


Figure J3: Architecture of the remanufacturing and inventory control management segment of "*configC*" (duplicated from subsection 4.5.4 of chapter 4)

APPENDIX J-c

Computer programs codes for the remanufacturing and finished products inventory control management segment of *“configD”*

The architecture and simulation logic of this configuration (figure J4) are slightly different to those in “*configC”*. The difference is in terms of the simulation logic for the false exit of the *Decide* modules (“*Check GI Inventory”*, *“Check GI InventoryB”*, *“Check GII Inventory”* and *“Check GII InventoryB”*).

For example, considering a *Decide* module called “*Check GI Inventory”*, a control entity taking its false exit would be directed to another *Decide* module called *“Check GII Inventory”*. So, whenever a control entity arrives at one of the *Decide* modules, it is directed to another *Decide* module. The matching modules for redirection are: (1) “*Check GI Inventory”* redirected to “*Check GII Inventory”* and vice-versa, (2) “*Check GI InventoryB”* redirected to “*Check GII InventoryB”* and vice-versa. Since the architecture of this configuration are similar to those already described for “*configC”*, they are not described here.

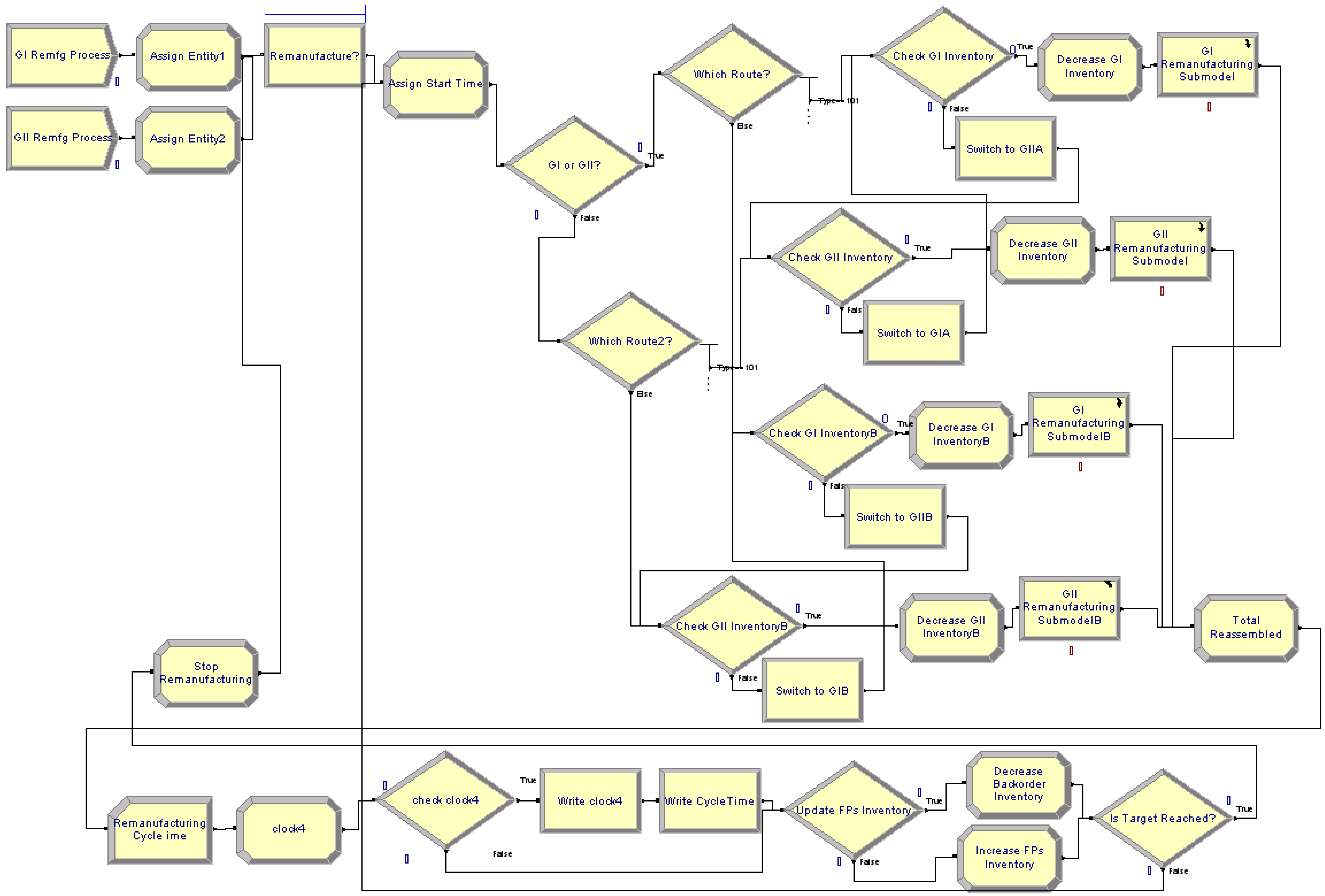


Figure J4: Architecture of the remanufacturing and inventory control management segment of "*configD*" (duplicated from subsection 4.5.4 of chapter 4)

APPENDIX K-a

Computer programs codes for the remanufacturing and finished products inventory control management segment of "*configE*"

In figure K1, after being created in a *Create* module called "*GI Remfg Process*" the control entity proceeds to the next module called "*Assign Entity*", where its attribute *Type* is assigned. Then it goes to a *Hold* module, called "*Remanufacture?*", where it is detained until the condition (*Reman=1*) becomes true. Once this happens it is released and proceeds to an *Assign* module called "*Assign Start Time*", where its attribute *arrival times* are assigned. Next the control entity arrives at a *Decide* module, called "*Check GI Inventory*" to check if a specified condition is true. This could result in two possible outcomes.

If the specified condition is true, the control entity takes the true exit, otherwise it takes the false exit and goes to a *Hold* module called "*Wait for Incoming GI*" until a specified condition becomes true. Either ways, the control entity arrives at an *Assign* module called "*Decrease GI Inventory*", where it decrements the variable *UPT1* by one unit. This *UPT1* variable keeps tracks off the number of GI remanufacturables in inventory. Then it proceeds to a *Submodel* called "*GI Remanufacturing Submodel";* this *Submodel* has identical structures and simulation logic to those described for "*configA*".

Once the control entity has emerged from the *Submodel* it proceeds through a series of modules ("*Total Reassembled*", "*Remanufacturing CycleTime*", "*clock4*", "*check clock4*", "*Write clock4*" and "*Write CycleTime*") that are also identical to those already described for "*configA*". After proceeding through a *Write* module, called "*Write CycleTime*", the control entity goes to an *Assign* module, called "*Increase FPs Inventory*", where it updates the variable *Inventory* by one unit.

Then it goes to a *Decide* module, called "*Is Demand Satisfied?*" to check if the current inventory level is equal to a customer's demand. This could result in two possible outcomes. If the current inventory level is equal to a customer's demand the control entity takes the true exit and proceeds to an *Assign* module called "*Stop Remanufacturing*" where it sets *Reman=0* which would change a condition in *Hold* module ("*Remanufacture*?") such that it would be detained when it arrives at the *Hold* module. Other wise, the control entity takes the false exit and proceeds to an *Assign* module ("*Assign Start Time*") and repeats the cycle.

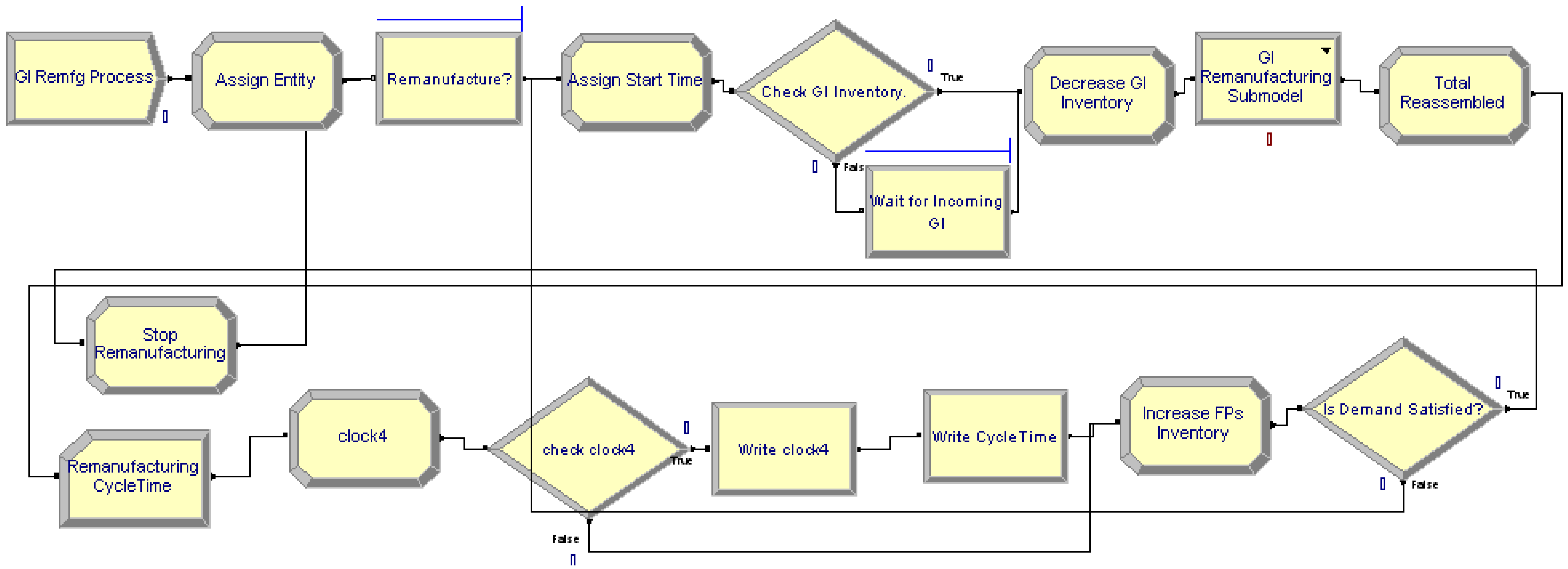


Figure K1: Architecture of the remanufacturing and inventory control management segment of *"configE"* (duplicated from subsection 4.5.5 of chapter 4)

APPENDIX K-b

Computer programs codes for the remanufacturing and finished products inventory control management segment of "*configF*"

As shown in figure K2, the architectures of *configF* are more complex than those of *configE* because remanufacturables from both the GI & GII quality groups are considered for remanufacture. When the control entity takes a false exit at a *Decide* module say, "*Check GI Inventory*", it would be redirected to another *Decide* module, called "*Check GII Inventory*". Similarly, if the control entity takes a false exit at the *Decide* module called "*Check GII Inventory*", it would be redirected to another *Decide* module, called "*Check GII Inventory*".

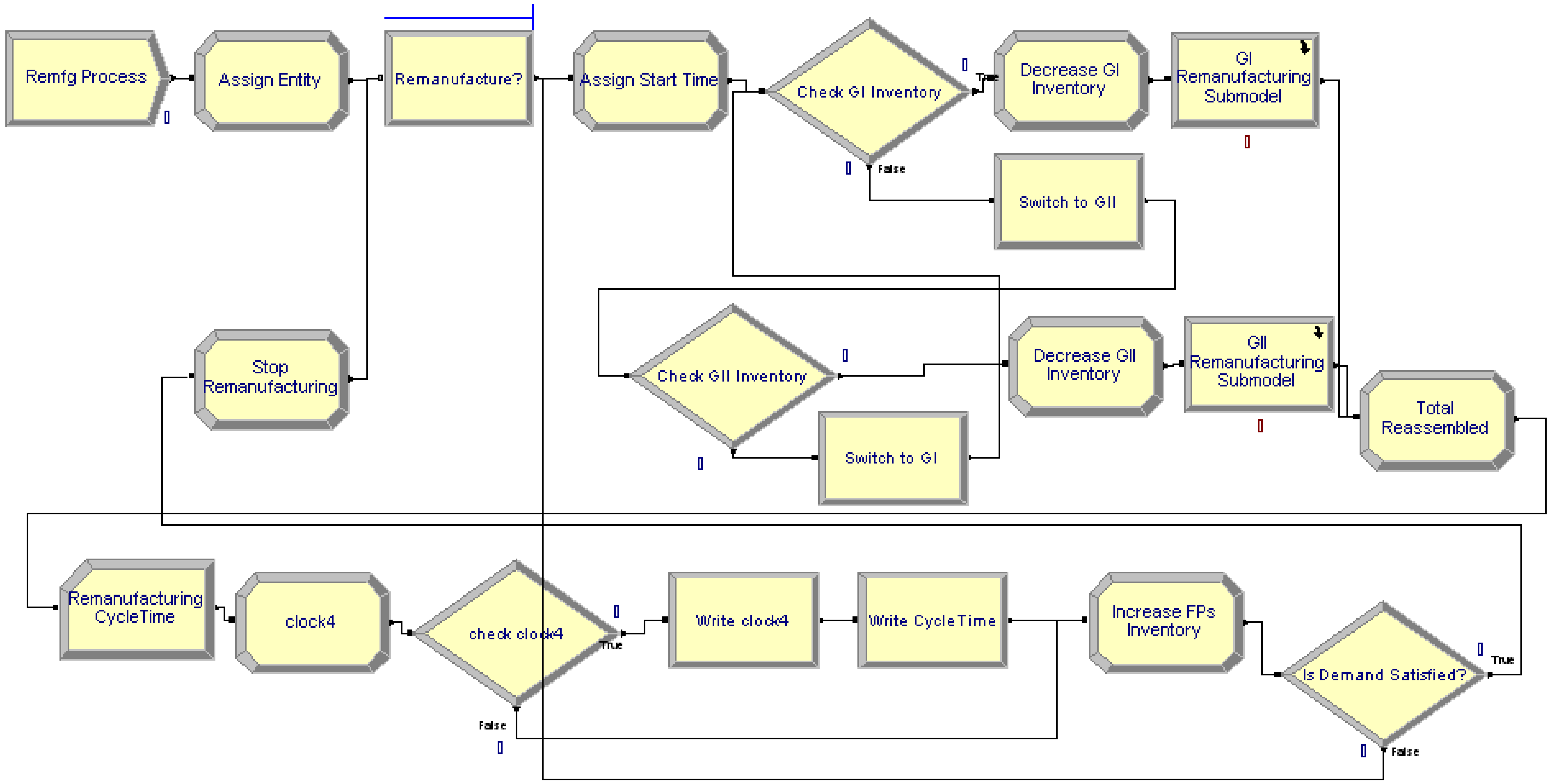


Figure K2: Architecture of the remanufacturing and inventory control management segment of "*configF*" (duplicated from subsection 4.5.5 of chapter 4)

APPENDIX L

Publications

1. Andrew-Munot, M., Ibrahim, R.N. and Lochert, P.B., 2008. An inventory lot-sizing model for a manufacturing/remanufacturing environment with variable remanufacturing lot-sizes. Proceedings of the 15th International Conference on Life Cycle Engineering, The University of New South Wales: Sydney.

2. Andrew-Munot, M., Ibrahim, R.N. and Lochert, P.B., 2008. An Economic Lot-Sizing Model in a Manufacturing/Remanufacturing Environment. Proceedings of International Conference on Mechanical and Manufacturing Engineering 2008. Universiti Tun Hussein Onn Malaysia: Johor Bahru.

An Inventory Lot-Sizing Model for a Manufacturing/Remanufacturing Environment with Variable Remanufacturing Lot-Sizes.

Magdalene Andrew - Munot[1], Raafat N Ibrahim[1], Paul B Lochert[1]
[1]Department of Mechanical Engineering, Building 31, Monash University, Melbourne, Australia

Abstract
More manufacturers are involved in remanufacturing of used items due to the economical benefit of reusing used items and strict environmental regulation. Consequently, manufacturers have to determine the remanufacturing and manufacturing lot-sizes that minimise the total cost per unit time. Existing lot-sizing models are developed assuming a constant lot-size for both manufacturing and remanufacturing. However, a constant lot-size for remanufacturing could lead to excess inventory of remanufacturable items, resulting in high inventory holding cost. This paper develops a new lot-sizing model that considers variable remanufacturing lot-sizes. It has been established that the new model could lead to savings in total cost per unit time. This is mainly due to a reduction in the inventory holding cost of remanufacturable items. A sensitivity analysis has been carried out to test the robustness of the new model.

Keywords:
Used Items; Inventory; Lot-sizing; Remanufacturing;

1 INTRODUCTION

Increasingly, manufacturers are remanufacturing their post-used items/products due to the economic attractiveness of reusing products, subassemblies or components instead of disposing them [1-3]. In addition, new, more rigid environmental legislation, increased public awareness, and extended manufacturer's responsibility have fuelled the remanufacturing efforts [4-5]. The automotive sector, in particular, has a strong history of remanufacturing [6]. Several pioneering companies such as Xerox, Canon and Kodak have expanded the scope of their core business operations with remanufacturing [7]. Recently remanufacturing is gaining scientific significance in a variety of industry sectors, such as photocopier [8], cellular telephone [9] or single-use camera remanufacturing [10]. In [11], remanufacturing is defined as a process of restoring used items to a like new condition, providing them with performance characteristics and durability at least as good as those of the original product.

Remanufacturing cycle starts when used items are returned from the users or customers back to the manufacturer. These used items provide an alternative input resource in the production of new products. Considering this situation (shown in Figure 1), an appropriate control mechanism is required to integrate the return flow of used items into the manufacturer's material planning [12]. As depicted in Figure 1, the manufacturer meets demand for new products and also receives used items returned from the market. The manufacturer has two options to fulfil the demand for the new products. Firstly, he can orders the required raw materials externally and manufactures the new products. Secondly, since remanufacturing of used products is, in general cheaper than manufacturing new products [13], he can remanufactures the used items and bring them back to "as new" conditions.

It is important to note that the return rate of used item varies throughout the item's life cycle [14]. As reported in [15] the proportion of demand that is met by remanufactured items is typically between 0.25 and 0.75. Unless the product is in the process of being phased out, the return rate of used items is typically less than the end-user demand rate, then, it is necessary to manufacture some of the new products in order to satisfy the demand. Therefore, in this case, the problem is to balance the quantity of remanufactured items and newly manufactured products so that the total cost per unit time is minimised. This involves determining the optimal lot-sizes for remanufacturing of used items and manufacturing/procuring of new products that minimizes the total cost per time unit.

Referring to Figure 1, when information, particularly for demand and returns are assumed to be known with certainty, the economic order quantity (EOQ) model can be employed to manage and control the inventory of remanufacturables (used items) and serviceables (remanufactured and newly manufactured items). The earliest study on EOQ model with remanufacturing was found in [16]. In [16], it is argued that it is better to hold inventory as remanufacturable items rather than as serviceable items. This is because the cost of remanufacturable items after being remanufactured is still cheaper than the cost of newly manufactured products. Therefore, it is assumed that a control policy supplies 100% of demand from the remanufactured items until the supplies of remanufacturable items drop to zero. This policy also considered one manufacturing/procurement lot alternating with several remanufacturing lots n, i.e. policy of $P(1,n)$.

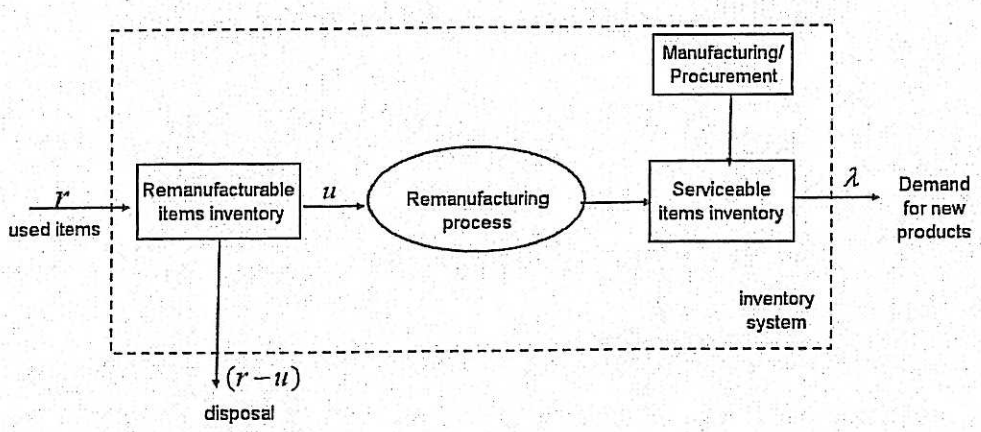


Figure 1: A simple inventory system with remanufacturing

The assumptions are constant rate for both demand and returns, infinite rate for both manufacturing/procurement and remanufacturing, fixed leadtime for both manufacturing/procurement and remanufacturing and remanufacture all returned items. The cost structure comprised of manufacturing/procurement cost per unit time, remanufacturing cost per unit time and holding cost per unit time, for both the remanufactured item and newly manufactured product.

In [17], the model developed in [16] was extended in two ways. Firstly, it was considered that for a single item model, a shortage or stockout of the serviceable items inventory is allowed. Secondly, the single item model (with no shortage) is modified to take into account multiple items competing for a common remanufacturing capacity, in particular remanufacturing capacity allocation and manufacturing/procurement and remanufacturing lot-size determination. For both models, a numerical solution is proposed for obtaining the optimal value.

A different model from [16] was analysed in [18-19]. It is assumed that there is no continuous flow of used items to the manufacturer. The used items are collected in a 'second shop' and brought back to the 'first shop' (the manufacturer) at the end of each 'collection interval'. This collection interval coincides with a production cycle in the first shop. The remanufacturing of used items is postponed until the end of the collection interval. In addition, a constant disposal rate of returned products is allowed. The formula for the total average cost is determined, however, simple expressions for the optimal lot sizes are not obtained.

The model developed in [16] was generalized in two ways in [20]. Firstly, it is considered that several manufacturing lots m alternate with several remanufacturing lots n , i. e. policy P (m,n). It is also considered that the variable disposal rate for used items takes place after the nth remanufacturing lot and over a certain period of time. Secondly, it is assumed that different holding cost rate applies for remanufactured and newly manufactured items. The closed form expressions for optimal manufacturing and remanufacturing lot is obtained for a given remanufacturing fraction for two types of policies, P $(1,n)$ and P $(m,1)$.

In [16-20] it was assumed that used items are accumulated and stored for a certain period of time prior to processing the first remanufacturing lot. This is necessary in order to achieve a number of constant lot-size remanufacturing processes. However, in [21-22], it is shown that it is not optimum to implement constant remanufacturing lot-sizes. The results from [21-22] show that the optimal timing of manufacturing lots (the time distance between consecutive manufacturing lots) has equal length, thus indicating identical manufacturing lot-sizes. Also, the time distance between consecutive remanufacturing lots has equal length, thus suggesting identical remanufacturing lot-sizes. However, for the final remanufacturing lot, it is shown that this final remanufacturing lot-size is smaller than the previous ones. And, if the amount of remanufacturable items available for remanufacturing is limited, the remanufacturing lot-sizes would decrease monotonically.

Implementing a constant remanufacturing lot-size resulted in delaying the remanufacturing process and also after each remanufacturing process (except the final lot) the remanufacturables inventory always carries some stock of used items. Delaying the remanufacturing process leads to a loss of responsiveness to demand and as such a higher safety stock is required [23]. Additionally, carrying some remanufacturables stock after processing each remanufacturing lot could lead to excess inventory, which could be costly to store especially when there is limited floor space available. Another resulting problem is, used items returned after the final remanufacturing lot processing have to be stored over the entire manufacturing interval until the next remanufacturing batch is started [21-22]. Therefore, there is a cost incentive to reduce the lot-size of the final remanufacturing lot, so that the time interval between the final remanufacturing lot and the next remanufacturing lot is shortened.

Based on the above argument, this paper focuses on developing a new inventory lot-sizing model for a manufacturing/remanufacturing environment with variable remanufacturing lot-sizes. In such a manufacturing/remanufacturing environment, the number of lots for manufacturing and remanufacturing during a cycle characterizes the policy used to control such an environment.

It is acknowledged that the optimal policy might vary the number of manufacturing and remanufacturing lots in a cycle. For instance, the optimal policy might be P $(m=2, n=5)$, however, as argued in [24] such a complex policy would be difficult to implement in practice. Additionally, as shown in [20], the optimal policy for P $(1,n)$ will be near optimal. Consequently, this paper restricts its attention to the policy where one manufacturing lot alternates with a variable number of remanufacturing lots, i.e. policy P $(1,n)$.

The paper is organised as follows. The assumptions of the new model are given in Section 2. In Section 3, the development of the new model is presented. The numerical example illustrating the application of the model and the results obtained is given in Section 4. A sensitivity analysis to test the robustness of the new model is provided in Section 5. Finally, the conclusion for the study is given in Section 6.

2 MODEL ASSUMPTIONS

The common underlying assumptions made in [16-20, 24] are use in developing the new model and are given below:

- Planning horizon of the system is infinite, i.e. time is modelled as a continuous variable $t \in [0,\infty]$.
- Demand and return of items are continuous (infinitely divisible items) and deterministic. The demand rate is $\lambda > 0$ and the return rate is $r\lambda$, where $r < 1$. The returned items may be either disposed of or remanufactured at a rate of $u\lambda$, where $0 \le u \le r$.
- Both serviceable and remanufacturable items are held in stock. In order to increase the stock of serviceable items, additional new products may be manufactured or used items may be remanufactured at any time $t \in [0,\infty]$. Manufacturing and the remanufacturing processes are assumed to be instantaneous. Shortages are not permitted.

The following costs are incurred:

- Setup costs for manufacturing (K_m) and remanufacturing (K_r). There is no setup cost for disposal.
- Disposal cost (c_d) for returned item.
- Manufacturing cost (c_m) for newly manufactured product and remanufacturing cost (c_r) for used items.
- Holding costs per item per unit time for remanufacturable items (h_n), remanufactured items (h_r) and newly manufactured products (h_m).
- All costs are assumed to be non-negative except where disposing the returned items may provide some revenue.

3 MODEL DEVELOPMENT

3.1 Model description

The evolution of the remanufacturable and serviceable inventory levels are illustrated in Figures 2 and 3 respectively. For both remanufacturable and serviceable inventory, the end of one cycle is reached at time $t = T$.

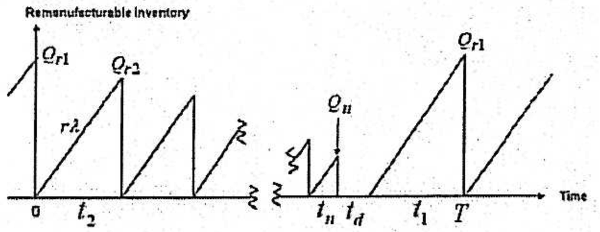


Figure 2: Remanufacturable inventory level.

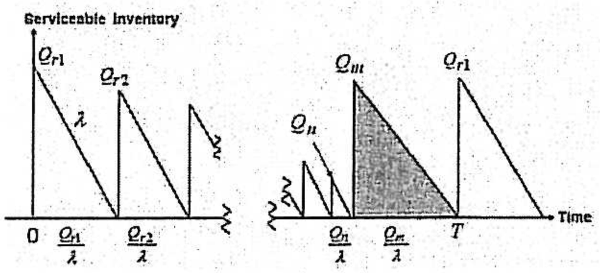


Figure 3: Serviceable inventory level.

Referring to Figure 3, assume that at time $t = 0$, the first lot of remanufactured items, Q_{r1} arrives at the serviceable inventory. This quantity was accumulated at the remanufacturable inventory at a rate $r\lambda$ for a period t_1. This first lot will be used as the serviceable stock to meet the demand at a rate of λ, thus depleting Q_{r1} to zero would take a time of $\frac{Q_{r1}}{\lambda}$. When Q_{r1} is used as the serviceable stock, the second lot of used items grow at the remanufacturable inventory at a rate $r\lambda$ for a period t_2 to an amount of $Q_{r2} = r\lambda t_2$. After the remanufacturing process, this second lot of remanufactured item arrives at the serviceable inventory when Q_{r1} is fully depleted to zero. In this case, the time taken for Q_{r1} to deplete to zero must equal to the time taken for the second lot of used items to grow at the remanufacturable inventory. Substituting t_2 with $\frac{Q_{r1}}{\lambda}$, the second lot of remanufactured items can also be expressed as $Q_{r2} = r^2\lambda t_1$. Therefore the relationship between t_2 and t_1 is given as $t_2 = rt_1$. It can be shown that the relationship between Q_{r2} and Q_{r1} is given by $Q_{r2} = rQ_{r1}$.

Assuming that the number of remanufacturing lots per cycle are n, it is proved that $t_n = r^{n-1}t_1$ and $Q_n = r^{n-1}Q_{r1}$. When the last lot of remanufactured items Q_n is depleted to zero, a lot of newly manufactured products Q_m arrives at the serviceable inventory. This newly manufactured product will be used to meet the demand over a period of $\frac{Q_m}{\lambda}$.

The disposal of used items takes place after the nth remanufacturing lot is started and the disposal period is $t_d = \frac{r-u}{u}T$. At the end of the disposal period, used items start to accumulate again at the remanufacturable inventory for a period of t_1 resulting in quantity of $Q_{r1} = r\lambda t_1$.

3.2 Model formulation

In order to have a balance of the material flow at the serviceable inventory, the following relation (Equation 1) must hold.

$$u = \frac{Q_{r1} + Q_{r2} + Q_{r3} + \ldots + Q_n}{Q_{r1} + Q_{r2} + Q_{r3} + \ldots + Q_n + Q_m} \tag{1}$$

From Figure 3 it is easily shown that the system cycle time is:

$$T = \frac{Q_m}{\lambda(1-u)} \tag{2}$$

Analysing Figure 2, during t_d and t_1, Q_n and Q_m must be used as stock of serviceable to meet the demand. Mathematically this situation can be expressed as:

$$\frac{Q_n}{\lambda} + \frac{Q_m}{\lambda} = \frac{r-u}{r}T + t_1 \tag{3}$$

Substituting for Q_n and T and after an algebraic manipulation gives:

$$t_1 = \frac{u(r-1)Q_m}{r\lambda(1-u)(r^n-1)} \tag{4}$$

Analysing Figure 3, it can be seen that the average number of remanufactured and newly manufactured items in the serviceable inventory over a period of one cycle is represented by the area under the curve, which is given as the sum of n unshaded triangles plus 1 shaded triangle. After an algebraic manipulation, the average inventory level for remanufactured items, A_{rm} and newly manufactured items, A_m in the serviceable inventory over a period of one cycle are represented by Equations 5 and 6.

$$A_{rm} = \frac{Q_m^2}{2\lambda}\left(\frac{u}{1-u}\right)^2\left(\frac{r-1}{r^n-1}\right)\left(\frac{r^n+1}{r+1}\right) \tag{5}$$

$$A_m = \frac{Q_m^2}{2\lambda} \tag{6}$$

Likewise, from Figure 2 it can be seen that the average number of used items in the remanufacturable inventory over a period of one cycle is represented by the area under the curve. After an algebraic manipulation the average inventory level for used items in the remanufacturable inventory over a period of one cycle is given by Equation 7.

$$A_r = \frac{Q_m^2(r^n+1)(r-1)}{2r\lambda(r+1)(r^n-1)}\left(\frac{u}{1-u}\right)^2 \tag{7}$$

The total cost per unit time for policy P(1,n) for a manufacturing/remanufacturing environment consists of eight (8) cost terms, namely setup cost for manufacturing, setup cost for remanufacturing, holding cost for remanufacturable items, holding cost for remanufactured items, holding cost for newly manufactured products, manufacturing cost for new products, remanufacturing cost for used items and disposal cost for non remanufacturable items. Therefore, the cost expression for the total cost per unit time, TC is given by Equation 8.

$$\begin{aligned} TC = {} & \frac{K_m\lambda(1-u)}{Q_m} + \frac{nK_r\lambda(1-u)}{Q_m} + \\ & \frac{h_nQ_m}{2r}\left[\left(\frac{u^2}{1-u}\right)\left(\frac{r-1}{r^n-1}\right)\left(\frac{r^n+1}{r+1}\right)\right] + \\ & \frac{h_rQ_mu^2(r-1)(r^n+1)}{2(1-u)(r^n-1)(r+1)} + \\ & \frac{h_mQ_m(1-u)}{2} + \lambda c_m(1-u) + \\ & \lambda c_r u + \lambda c_d(r-u) \end{aligned} \tag{8}$$

In this case, the problem is to determine the optimum values for n, u and Q_m that minimise the total cost per unit time. Subsequently, the optimum values for Q_{r1} and Q_n can be determined as well. To solve this problem, this paper proceeds as follows: First, consider setting the partial derivatives of Equation 8 with respect to n, u and Q_m to zero and solving would give values of n, u and Q_m to optimise the total cost per unit time. This resulted in a system of equations that had no simple solution. Then, consider setting the partial derivatives of Equation 8 with respect to n and Q_m to zero and solving would give the values for n and Q_m to optimise the total cost per unit time for a given value of u. Even, in this case, a simple expressions for optimal n and Q_m cannot be obtained from the system of equations. Consequently, the Excel Solver tool was utilised to determine the optimal values for n and Q_m for given values of u and the parameters of the system.

4 NUMERICAL ILLUSTRATION

The parameters setting is taken from Teunter (2001) and is used to highlight the technique and result obtained:

$r = 0.8$; $K_m = 100$; $K_r = 100$; $\lambda = 100$; $h_r = 9$; $h_m = 10$; $h_n = 5$; $c_r = 50$; $c_m = 60$; $c_d = -10$; $u = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8$

4.1 Examining behaviour of Q_m, n, Q_{r1} and Q_n with u

The computational results are given in Table 1. Analysing Table 1, it can be observed that Q_m, n and Q_{r1} change with the remanufacturing fraction u. Specifically, n and Q_{r1} increases as the remanufacturing fraction increases, while Q_m decreases as u increases. This observation is as expected; higher value of u means that more remanufacturable items are transformed to serviceable items to meet the demand (however, this resulted in more remanufacturing lots) and therefore the manufacture of new items can be decreased. It is important to note that, the remanufacturing lot-size is constrained by the number of used items available for remanufacturing. For example, when $u = 0.1$, n is 1 and the remanufacturing lot-size is 7 items.

4.2 Benefit of the variable remanufacturing lot-sizes

The benefit of the new model with variable remanufacturing lot-sizes is illustrated in comparison to a model with constant remanufacturing lot-sizes [20]. From this point forward, this is referred as the base-cost model. The computational result for the comparison study is illustrated in Table 2. Analysing Table 2, it is clear that, the new model with variable remanufacturing lot-sizes is superior to the base-cost model, particularly at a higher remanufacturing fraction. At a remanufacturing fraction of 0.5, there is only 1 remanufacturing lot n per time period for both models, i.e. both models have policy of P $(m=1, n=1)$. In this case, the two models are almost equivalent, thus the benefit of the new model of not having any carryover stock to the next remanufacture lot will not be achieved. This observation is as expected and also suggests that the benefit of the new model will be significant at policies of P $(m>1, n>1)$.

Table 2 also shows that n as well as the benefit (% saving) of the new model increases as u increases. These observations are as expected and support the argument presented earlier. As argued earlier on, it is not optimal (in terms of holding cost) to implement a constant remanufacturing lot-size because used items received after the final remanufacturing lot processing have to be stored over the entire manufacturing interval until the next remanufacturing lot processing is started. Therefore, there is a cost incentive to reduce the time interval between the final remanufacturing lot and the next remanufacturing lot. This can only be achieved by implementing variable remanufacturing lot-sizes, where the lot-sizes decrease monotonically.

5 Sensitivity analysis

A sensitivity analysis was conducted to test the robustness of the new model facing uncertainties in the given parameters. The analysis examines two cases: (1) the sensitivity of Q_m and Q_{r1} estimates to changes in K_m, K_r, h_m, h_n, h_r and λ at low values of K_m, K_r, h_m, h_n, h_r and λ; (2) the sensitivity of Q_m and Q_{r1} estimates to changes in K_m, K_r, h_m, h_n, h_r and λ at high values of K_m, K_r, h_m, h_n, h_r and λ. The results of the sensitivity analysis show that for both cases Q_m and Q_{r1} are generally insensitive to changes in K_m, K_r, h_m, h_n, h_r and λ.

	Remanufacturing fraction (u)							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Q_m	63	60	56	49	40	47	46	37
n	1	1	1	1	1	2	3	4
Q_{r1}	7	15	24	33	40	39	44	50
Q_n	7	15	24	33	40	31	28	25
$TC^{(1,n)}$	5775	5730	5701	5692	5702	5713	5727	5747

Table 1: The solution for Q_m, n, Q_{r1}, Q_n and $TC^{(1,n)}$ for a given u.

	Remanufacturing fraction (u)			
	0.5	0.6	0.7	0.8
Number of remanufacturing lots (n) for the new model	1	2	3	4
Cost per unit time for the new model	502.49	513.58	527.07	547.73
Cost per unit time for the base-cost model	503.17	526.00	555.64	579.92
Saving (%)	0.14[a]	2.36	5.14	5.56
0.14[a]=(503.17-502.49)/503.17				

Table 2: Comparison of cost per unit time.

6 CONCLUSION

This paper has investigated a new inventory lot-sizing model for a manufacturing/remanufacturing environment with variable remanufacturing lot-sizes. In this manufacturing/remanufacturing environment the constant demand rate can be satisfied by newly manufactured products and by remanufactured items. For given values of the model's parameters the optimal solutions are numerically determined. The new model is shown to be beneficial as it could lead to saving in cost per unit time. In addition, the new model is shown to be insensitive to changes in costs and demand parameters. The new model could be extended to consider finite manufacturing and remanufacturing rate and permitting shortages in serviceable items.

7 REFERENCES

[1] Aras, N., Boyaci, T., Verter, V., 2004, The effect of categorizing returned products in remanufacturing, IIE Transactions (Institute of Industrial Engineers), 36/4:319-331.

[2] Ferrer, G., 2006, Managing new and remanufactured products, Management science, 52/1:15-26.

[3] Ketzenberg, M. E., Souza, G. C., Guide, V. D. R., 2003, Mixed assembly and disassembly operations for remanufacturing, Production and operations management, 12/3:320-335.

[4] McGovern, S. M., Gupta, S. M., 2004, Demanufacturing strategy based upon metaheuristics, Proceedings of the 2004 Institute of Industrial Engineering Research Conference, (CD-ROM). Houston, Texas.

[5] Ferrer, G., Whybark, D. C., 2000, From garbage to goods: Successful remanufacturing systems and skills, Business Horizons, 43/6:55-64.

[6] Seitz, M. A., 2007, A critical assessment of motives for product recovery: the case of engine remanufacturing, Journal of Cleaner Production, 15/11-12:1147-1157.

[7] Akcalı, E., Morse, M. A., 2004, Seeding strategies in remanufacturing, Proceedings of the IIE Research Conference, Houston, Texas.

[8] Kerr, W., Ryan, C., 2001, Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia, Journal of Cleaner Production, 9/1:75-81.

[9] Guide Jr, V. D. R., Teunter, R. H., Van Wassenhove, L. N., 2003a, Matching Demand and Supply to Maximize Profits from Remanufacturing, Manufacturing & service operations management, 5/4:303-316.

[10] Guide, V. D. R., Jayaraman, V., Linton, J. D., 2003b, Building contingency planning for closed-loop supply chains with product recovery, Journal of operations management, 21/3:259-279.

[11] Lund, R. T., 1984, Remanufacturing Technology Review, 87/2:18-23.

[12] Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., Van der Laan, E., Van Nunen, J. A. E. E., Van Wassenhove, L. N., 1997, Quantitative models for reverse logistics: A review. European Journal of Operational Research, 103/1:1-17.

[13] Dowlatshahi, S., 2000, Developing a theory of reverse logistics, Interfaces, 30/3:143-155.

[14] Flapper, S. D. P., Van Nunen, J. A. E. E., Van Wassenhove, L. N. (eds.), 2005, Managing Closed-Loop Supply Chains, Springer, New York.

[15] Geyer, R., Van Wassenhove, L. N., 2000, Product take back and component reuse, INSEAD Report France, 2000/34/TM/CIMSO 12.

[16] Schrady, D. A., 1967, A deterministic model for reparable items, Naval Research Logistics Quarterly, 14:391-398.

[17] Mabini, M. C., Pintelon, L. M., Felders, L. F., 1992, EOQ type formulations for controlling repairable inventories, International Journal of Production Economics, 28/1:21-33.

[18] Richter, K., 1996a, The EOQ repair and waste disposal model with variable setup numbers, European Journal of Operational Research, 95/2:313-324.

[19] Richter, K., 1996b, The extended EOQ repair and waste disposal model, International Journal of Production Economics, 45/1-3:443-447.

[20] Teunter, R. H., 2001, Economic ordering quantities for recoverable item inventory systems, Naval research logistics, 48/6:484-495.

[21] Minner, S., 2001, Economic Production and Remanufacturing Lot-sizing Under Constant Demands and Returns, In Operations Research Proceedings 2000, Springer, Berlin Heidelberg New York:pp328-332.

[22] Minner, S., Lindner, G., 2004, Lot Sizing Decisions in Product Recovery Management, In: Dekker, R., Fleischmann, M., Inderfurth, K., Van Wassenhove, L. N., (Eds.), Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains, Springer-Verlag Berlin, 157-179.

[23] Fleischmann, M., 2001, Quantitative Models for Reverse Logistics, Lecture Notes in Economics and Mathematical Systems,

[24] Teunter, R., 2004, Lot-sizing for inventory systems with product recovery, Computers & Industrial Engineering, 46/3:431-441.

Proceedings of International Conference on Mechanical & Manufacturing Engineering (ICME2008), 21– 23 May 2008, Johor Bahru, Malaysia.
© Faculty of Mechanical & Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia.
ISBN: 97–98 –2963–59–2

An Economic Lot-Sizing Model in a Manufacturing/Remanufacturing Environment

Magdalene Andrew-Munot*, Raafat N Ibrahim, Paul B Lochert

Department of Mechanical Engineering,
Building 31, Monash University,
Victoria, 3800,
Australia

*Magdalene.Andrew-Munot@eng.monash.edu.au

Abstract

Many manufacturers are involved in the remanufacture of used items because of the economic benefit of reusing items and the need to meet new environmental regulation. A key problem in the manufacturing/remanufacturing environment is to determine the economic lot-sizes. Existing lot-sizing models assume a constant lot-size for both manufacturing and remanufacturing. A constant lot-size for remanufacturing could lead to holding excess inventory of remanufacturable items. This paper presents a model that determines a set of variable remanufacturing lot-sizes that minimize the total cost per unit time. It has been established that the model leads to savings in total cost per unit time due to a reduction in the average inventory per unit time of remanufacturable items. A sensitivity analysis was conducted to test the robustness of the model.

Keywords: Lot-sizing, Remanufacturing, Product returns, EOQ, Inventory,

1. Introduction

In the recent past, remanufacturing of post-used items is becoming popular amongst various industries such as the automotive [1], photocopier [2], cellular telephone [3] and single-used camera [4]. This is mainly due to the economic benefits [5], increased public awareness, more rigid environmental legislation and extended manufacturer's responsibility [6].

According to [7], remanufacturing is a process that involves restoring used items to a like new condition, providing them with performance characteristics and durability at least as good as those of the original product. Used items provide an alternative input resource in the production of new products. Then, according to [8] an appropriate control mechanism is required to integrate the return flow of used items into the manufacturer's materials planning. However, as highlight in [9], the return rate of used items is typically less than the demand rate of new products, then, it is necessary for the manufacturer to manufacture some of the new products in order to satisfy the demand. In this situation (also shown in Fig 1.) the problem is to determine the economic manufacturing and remanufacturing lot-sizes. In Fig. 1, when demand and returns are known with certainty, the economic order quantity model has been proposed for managing the inventory of remanufacturables (used items) and serviceables (remanufactured and newly manufactured items).

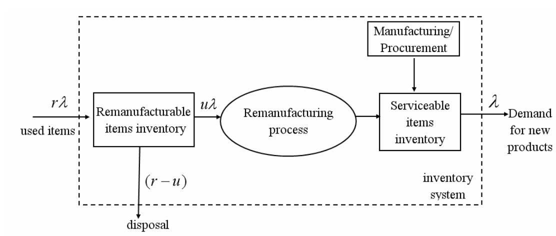


Fig.1 A simple inventory system with remanufacturing

The earliest work on determining the economic manufacturing and remanufacturing lot-sizes was carried out in [10]. The author considers a policy that supplies 100% of demand from remanufactured items until the supplies of remanufacturable items drop to zero, resulting in a policy that alternates several

Proceedings of International Conference on Mechanical & Manufacturing Engineering (ICME2008), 21– 23 May 2008, Johor Bahru, Malaysia.
© Faculty of Mechanical & Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia.
ISBN: 97–98 –2963–59–2

remanufacturing lots (n) with one manufacturing lot $(m=1)$. In [11-12] a different model (from [10]) is analysed, whereby (1) the flow of used items to the manufacturer is not continuous. Used items are collected in a 'second shop' and brought back to the 'first shop' (the manufacturer) at the end of each 'collection interval'. This collection interval coincides with a production cycle in the first shop and (2) emanufacturing of the used items is postponed until the end of the collection interval and constant disposal rate of used products.

The model introduced by [10] is generalized by [13]. The author considers a model characterizes by (1) several manufacturing lots (m) alternating with several remanufacturing lots (n); (2) variable disposal rates taking place after the (n^{th}) remanufacturing and (3) different holding cost rates for remanufactured and newly manufactured items. The author considers two types of policies ($P(1,n)$ and $P(m,1)$) and for a given remanufacturing fraction, obtains the closed form expressions for the optimal lot-size for manufacturing and remanufacturing.

Previous models employ a constant/fixed remanufacturing lot-size; a strategy that requires a certain level of remanufacturable items inventory, before processing the first remanufacturing lot. This results in delay of remanufacturing process; also after each remanufacturing process (except the final lot), there are still some stock of remanufacturable items. As emphasized by [14], delay of remanufacturing process results in a loss of responsiveness to demand and thus a higher safety stock is required. Carrying remanufacturables stock after each remanufacturing process could lead to excess inventory, which would be costly to store especially if there is a constraint on the available floor space.

It is important to note that used items collected after the final remanufacturing lot processing have to be stored over the entire manufacturing interval until the next remanufacturing lot is started. Therefore, [15-16] argue that there is a cost incentives to shorten the time interval between the final remanufacturing lot and the next remanufacturing lot. The results of their work provide further evidence that constant lot-size does not necessarily apply for the remanufacturing model. Specifically, for the optimum conditions they found that (1) the lot-size for all manufacturing lots are identical, (2) the lot-size for the first to the (n-1) remanufacturing lots are identical, (3) the lot-size for the final remanufacturing lot is smaller than the previous ones and (4) the remanufacturing lot-sizes will decrease monotonically in the case of limited remanufacturable items.

Therefore, this paper considers variable remanufacturing lot-size for the manufacturing/remanufacturing environment for policy $P(1,n)$. The paper is organised as follows. The assumptions for our work are given in Section 2. In Section 3, the development of the model considering variable remanufacturing lot-sizes is presented. A numerical example to illustrate the model's application and the results obtained are provided in Section 4. In Section 5, the result of the sensitivity analysis is given and Section 6 provides the conclusion for the study.

2. Model assumptions

The assumptions are similar to previous works which are (1) infinite planning horizon; (2) continuous and deterministic demand and return (infinitely divisible items). Demand rate is λ, return rate is $r\lambda$ and remanufacturing rate is $u\lambda$, where $0<u<r$; (3) additional new products may be manufactured or returned items may be remanufactured at any time $t\in[0,\infty]$ to increase the stock of serviceables; (4) instantaneous manufacturing and remanufacturing process and (5) no shortages.

The costs incurred are (1) setup costs for manufacturing (K_m) and remanufacturing (K_r); (2) disposal cost (c_d) for used item; (3) manufacturing cost (c_m) for newly manufactured product; (4) remanufacturing cost (c_r) for used items; (5) holding costs per item per unit time for remanufacturable items (h_n), remanufactured items (h_r) and newly manufactured products (h_m).

Proceedings of International Conference on Mechanical & Manufacturing Engineering (ICME2008), 21– 23 May 2008, Johor Bahru, Malaysia.
© Faculty of Mechanical & Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia.
ISBN: 97–98 –2963–59–2

3. Model development

3.1 Model description

This paper considers a situation shown in Fig. 2. In Fig. 2, the subsequent remanufacturing lot-size is smaller than the previous one and all stock of remanufacturables are depleted to zero after each remanufacturing process. The first remanufacturing lot-size is represented by Q_{r1}, the second by Q_{r2} and the final by Q_n. These Q_{r1}, Q_{r2} and Q_n have been accumulated in the remanufacturable inventory for a period of t_1, t_2 and t_n respectively. There is only one m and the size is represented by Q_m. Consequently, the corresponding serviceable inventory level can be shown in Fig. 3. For both figures the end of one cycle is denoted by the time $t = T$.

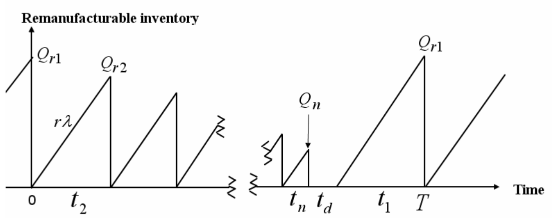


Figure 2: Remanufacturable inventory level.

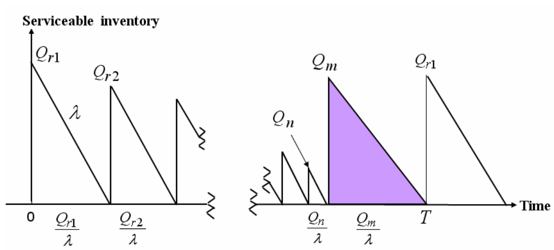


Figure 3: Serviceable inventory level.

3.2 Model formulation

In order to have a balance of the material flow at the serviceable inventory, the following relation (Eqn. 1) must hold.

$$u = \frac{Q_{r1} + Q_{r2} + Q_{r3} + \ldots + Q_n}{Q_{r1} + Q_{r2} + Q_{r3} + \ldots + Q_n + Q_m} \quad (1)$$

From Fig. 2 it is easily shown that the system cycle time is:

$$T = \frac{Q_m}{\lambda(1-u)} \quad (2)$$

From Fig. 2 and after an algebraic manipulation the average number of used items (A_r) in the remanufacturable inventory over a period of one cycle is:

$$A_r = \frac{(Q_m)^2 (r^n + 1)(r-1)}{2r\lambda(r+1)(r^n - 1)} \left(\frac{u}{1-u}\right)^2 \quad (3)$$

Likewise from Fig. 3 and after an algebraic manipulation the average number of remanufactured items (A_{rm}) and newly manufactured products (A_m) in the serviceable inventory over a period of one cycle are represented by Eqns. 4 and 5.

$$A_{rm} = \frac{(Q_m)^2}{2\lambda} \left(\frac{u}{1-u}\right)^2 \left(\frac{r-1}{r^n - 1}\right) \left(\frac{r^n + 1}{r+1}\right) \quad (4)$$

$$A_m = \frac{(Q_m)^2}{2\lambda} \quad (5)$$

Therefore, the cost expression for the total cost per unit time is:

$$TC = \frac{K_m \lambda(1-u)}{Q_m} + \frac{nK_r \lambda(1-u)}{Q_m} + \frac{h_n Q_m}{2r} \left[\left(\frac{u^2}{1-u}\right) \left(\frac{r-1}{r^n - 1}\right) \left(\frac{r^n + 1}{r+1}\right) \right] + \frac{h_r Q_m u^2 (r-1)(r^n + 1)}{2(1-u)(r^n - 1)(r+1)} + \frac{h_m Q_m (1-u)}{2} + \lambda c_m (1-u) + \lambda c_r u + \lambda c_d (r-u) \quad (6)$$

The problem is to determine the optimum values for n, u and Q_m that minimises the total cost per unit time. The optimum values for Q_{r1}, $Q_{r2} \ldots\ldots Q_n$ follow from Q_m. To solve this problem, this paper proceeds as follows: First, consider setting the partial derivatives of Eqn. (6) with respect to n, u and Q_m to zero and solving to give values of n, u and Q_m to optimise the total cost per unit time. This resulted in a system of equations that had no simple solution.

Then, consider setting the partial derivatives of Eqn. (6) with respect to n and Q_m to zero and solving will give the values for n and Q_m to optimise the total cost per unit time for a given value of u. Even, in this case, a simple expressions for optimal n and Q_m cannot be obtained from the system of equations. Consequently, we consider determine the optimal values for n and Q_m numerically for given values of u and the

Proceedings of International Conference on Mechanical & Manufacturing Engineering (ICME2008), 21– 23 May 2008, Johor Bahru, Malaysia.
© Faculty of Mechanical & Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia.
ISBN: 97–98 –2963–59–2

parameters of the system using the Excel Solver tool.

4. Results and Discussion

The parameters values are taken from [13]: $r = 0.8$; $K_m = 100$; $K_r = 100$; $\lambda = 100$; $h_r = 9$; $h_m = 10$; $h_n = 5$; $c_m = 60$; $c_r = 50$; $c_d = -10$; $u = 0.5, 0.6, 0.7, 0.8$.

Table 1 shows the % of potential saving from the model when compared to the base-cost model. The base-cost model is the model introduced by [13] for policy $P(1,n)$ considering fixed remanufacturing lot-sizes. From Table 1, it is clear that the model is superior to the base-cost model. Specifically, at remanufacturing fraction of 0.5, both models have optimum policy of $P(m=1, n=1)$. In this case there is no difference between the two models, as indicated by almost the same cost per unit time. Therefore at $u = 0.5$, we would not achieve the benefit of having no carryover of any remanufacturable items to the next remanufacturing lot processing (as indicated by 0.14% of saving).

On the other hand, as u becomes higher, more remanufacturable items would be available for the remanufacturing process, and this resulted in having more than one n per cycle. Thus, for the base-cost model, there would always be carryover of remanufacturable items after processing each remanufacturing lot. The amount of carryover would increase as n increases. However, for our model there is no carryover of remanufacturable items because the remanufacturables inventory is depleted to zero after processing each remanufacturing lot.

Based on the preceding paragraphs, it is expected that the % of potential saving achieved from our model would increase as u is increased. This is established by the fact that the % of potential saving shown in Table 1 increases as u is increased and highest amount of potential saving (5.39%) is achieved at $u = 0.8$.

5. Sensitivity analysis

Sensitivity analysis was conducted to test the robustness of our model facing uncertainties in the given parameters K_m, K_r, h_m, h_n, h_r, and λ on Q_m and Q_{r1}. The analysis examines two cases : (1) the sensitivity of Q_m and Q_{r1} estimates to changes in K_m, K_r, h_m, h_n, h_r, and λ at low values of K_m, K_r, h_m, h_n, h_r, and λ; (2) the sensitivity of Q_m and Q_{r1} estimates to changes in K_m, K_r, h_m, h_n, h_r and λ at high values of K_m, K_r, h_m, h_r, h_n and λ. The results of the sensitivity analysis show that for both cases, Q_m and Q_{r1} are generally insensitive to changes in K_m, K_r, h_m, h_n, h_r, h_n and λ.

Table 1
Comparison of cost per unit time[a]

	Remanufacturing fraction (u)			
	0.5	0.6	0.7	0.8
Number of remanufacturing lots (n) for the model with variable remanufacturing lot-sizes	1	2	3	4
Cost per unit time for the model with variable remanufacturing lot-sizes	502.49	513.58	527.07	547.73
Cost per unit time for the model with fixed remanufacturing lot-sizes[b]	503.17	526.00	555.64	578.92
Saving (%)	0.14[c]	2.36	5.14	5.39

[a] Cost per unit time refers to the total cost for setup and holding cost terms for both models.
[b] The model was adjusted using the method proposed by Teunter (2004).
[c] 0.14=(503.17-502.49)/503.17

6. Conclusion

Manufacturing/remanufacturing environment is becoming more common as more manufacturers are involved in remanufacturing of used items. In this environment, a key problem is the determination of the economic manufacturing and remanufacturing lot-sizes. This paper has presented a model to determine a set of remanufacturing lot-sizes that minimises the total cost per unit time. For a range of values of the parameters optimal solutions are determined numerically. The model is shown to be beneficial as it leads to saving in cost per unit time in all cases. In addition, the model is shown to be relatively insensitive to changes in costs and demand parameters, consequently the model obtains robust estimates for the set of lot sizes. The model could be extended to consider finite manufacturing and remanufacturing rate and permitting shortages in serviceable items.

References

[1] M.A. Seitz, A critical assessment of motives for product recovery:the case of engine remanufacturing, Journal of Cleaner Production, 15(11-12), pp. 1147-1157, 2007.

[2] E. Akcalı and M.A. Morse, Seeding strategies in remanufacturing, Proceedings of the IIE Research Conference, Houston, Texas, 2004.

[3] Jr V.D.R. Guide, R.H. Teunter and L.N. Van Wassenhove, Matching Demand and Supply to Maximize Profits from Remanufacturing, Manufacturing & service operations management 5,(4), pp.303-316, 2003b.

[4] V.D.R. Guide, V. Jayaraman and J.D. Linton, Building contingency planning for closed-loop supply chains with product recovery, Journal of Operations Management, 21(3), pp. 259-279, 2003c.

[5] G. Ferrer, Managing new and remanufactured products, Management science, 52(1), pp.15-26, 2006.

[6] S.M. McGovern and S.M. Gupta, Demanufacturing strategy based upon metaheuristics, Proceedings of the 2004 Institute of Industrial Engineering Research Conference, (CD-ROM). Houston, Texas, 2004.

[7] R.T. Lund, Remanufacturing, Technology Review, 87(2), pp.18-23, 1984.

[8] M. Fleischmann, J.M. Bloemhof-Ruwaard, R. Dekker, E. Van der Laan, J.A.E.E. Van Nunen, and L.N. Van Wassenhove, Quantitative models for reverse logistics:A review, European Journal of Operational Research, 103(1), pp.1-17, 1997.

[9] R. Geyer and L.N. Van Wassenhove, Product take back and component reuse. INSEAD Report France, 2000/34/TM/CIMSO 12, 2000.

[10] D.A. Schrady, A deterministic model for reparable items, Naval Research Logistics Quarterly, 14,pp.391-398, 1967.

[11] K. Richter, The EOQ repair and waste disposal model with variable setup numbers, European Journal of Operational Research, 95(2), pp.313-324, 1996a.

[12] K. Richter, The extended EOQ repair and waste disposal model, International Journal of Production Economics, 45(1-3), pp.443-447,1996b.

[13] R.H. Teunter, Economic ordering quantities for recoverable item inventory systems, Naval research logistics 48(6), pp.484-495, 2001.

[14] M. Fleischmann, Quantitative Models for Reverse Logistics, Lecture Notes in Economics and Mathematical Systems, 2001.

[15] S. Minner, Economic Production and Remanufacturing Lot-sizing Under Constant Demands and Returns, In Operations Research Proceedings 2000, Berlin Heidelberg New York, Springer pp 328-332, 2001.

[16] S. Minner and G. Lindner, Lot Sizing Decisions in Product Recovery Management. In: Dekker, R., Fleischmann, M., Inderfurth, K., Van Wassenhove, L. N., (Eds.). Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains. Berlin: Springer-Verlag, pp.157-179, 2004.