

MODELLING INTERNATIONAL MANUFACTURING NETWORK

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CERTIFICATE

This is to certify that the thesis entitled "**Modelling International Manufacturing Network**" being submitted by **Shraddha Mishra** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bona fide record of original research work carried out by her. She has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which has reached the requisite standard.

The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

A generic supply chain network primarily contains all activities that change raw materials to conclusive products, and deliver it to the end customers. Advancement in communication and technology enabled the firms to extend their supply chain activities to multiple countries and cultivate the advantage of asymmetries in knowledge and capabilities. However, only extending the supply chain activities may not necessarily fulfill the local needs of a country. Thus, there is a need for the paradigm shift in manufacturing from localization to globalization to glocalization. International manufacturing network (IMN) is an integrated network of such glocal production-distribution networks. This thesis aims to study IMN with three perspectives i.e. its configuration, co-ordination and impact on the environment. Configuration includes strategic decision making for facility locations and their state of operation whereas Coordination deals with the management aspect of such network. The thesis provides the qualitative, quantitative and integrated decision making models for IMN. Most of the models proposed in the thesis are either mixed integer linear programs (MILP) or mixed integer non-linear programs (MINLP).

The qualitative study is carried out to identify and analyze the inter-relationship among various factors critical to the configuration and functioning of IMN. For this purpose, twenty nine factors have been identified from literature review and continuous deliberations from industry experts. All the factors are broadly classified under six domains viz. Political, Economic, Social, Technological, Legal and Environmental (PESTLE). Three different multi-criteria decision making techniques (MCDM) namely, a combination of PESTLE and strength, weakness, opportunity and threat (SWOT), analytic hierarchy process (AHP), and interpretive structural

modelling (ISM) have been employed to analyze the driving power and dependence of the factors. The results obtained from the above approaches are compared to identify common driving factors.

After qualitative analysis of the IMN enablers, the research then focuses on developing quantitative models for IMN. The proposed models consider a broad facility network of manufacturing plants and warehouses located in multiple countries. The model considers import export cost, loan subsidies, depreciation expense and other operating costs applicable to a specific country. Besides the novel consideration of international trade issues, the models proposed in the thesis assume significance over the traditional production-distribution models by providing country specific analysis. This enables the decision makers to monitor the operations in a particular country and devise country specific strategies within an international ecosystem. The research further attempts to extend the proposed model for IMN to include reverse logistics. A hybrid facility network is considered for cost-cutting and equipment sharing where the facilities of forward logistics are also equipped to provide reverse logistics services. Furthermore, the research attempts to address the environmental sustainability in the proposed models by quantifying carbon emissions. The carbon emissions are considered due to both FRL activities and are regulated using cap and trade policy. The research also investigates the influence of different trade policies on the total carbon emissions and total cost.

The research further attempts to develop stochastic model to balance resilience and sustainability in an uncertain market demand and product return scenario. The chance-constrained approach is used to obtain the deterministic equivalence of the stochastic demand and returns. The validation of the model has been done using randomly generated data sets. The parameters of the data sets are mapped with the 3V's of big data such as volume, velocity and variety.

After developing qualitative and quantitative models for IMN separately, the research attempts to integrate them. The results of qualitative model are provided as input to the quantitative model to support more realistic decision making. This integrated model helps to provide order of preference of facility-country pair and estimates the deviations in carbon emissions and total cost when a facility-country pair is preferred or not preferred.

Lastly, thesis is concluded by summarizing all chapters, providing major contributions, and recommendations for the future research.

Keywords: IMN, supply chain management, sustainability, resilience, reverse logistics, capacity expansion, hybrid facilities, MILP, MINLP, stochastic, AHP, ISM, IRP, PESTLE-SWOT

सार

एक सामान्य सप्लाई चेन नेटवर्क में मुख्य रूप से सभी गतिविधियाँ होती हैं जो कच्चे माल को निर्णायक उत्पादों में बदल देती हैं, और इसे अंतिम ग्राहकों तक पहुँचाती हैं। संचार और प्रौद्योगिकी में उन्नति ने फर्मों को कई देशों में अपनी सप्लाई चेन गतिविधियों का विस्तार करने और ज्ञान और क्षमताओं में विषमता का लाभ उठाने में सक्षम बनाया। हालांकि, केवल सप्लाई चेन गतिविधियों का विस्तार करना देश की स्थानीय जरूरतों को पूरा नहीं कर सकता है। इस प्रकार, स्थानीयकरण से वैश्वीकरण से ग्लोकलाइजेशन तक के निर्माण में प्रतिमान बदलाव की आवश्यकता है। अंतर्राष्ट्रीय विनिर्माण नेटवर्क (IMN) इस तरह के ग्लोकल उत्पादन-वितरण नेटवर्क का एक एकीकृत नेटवर्क है। इस थीसिस का उद्देश्य तीन दृष्टिकोणों के साथ IMN का अध्ययन करना है अर्थात् इसके कॉन्फ़िगरेशन, कोआर्डिनेशन और पर्यावरण पर प्रभाव। कॉन्फ़िगरेशन में सुविधा स्थानों और उनके संचालन की स्थिति के लिए रणनीतिक निर्णय करना शामिल है जबकि कोआर्डिनेशन ऐसे नेटवर्क के प्रबंधन पहलू से संबंधित है। थीसिस IMN के लिए गुणात्मक, मात्रात्मक और एकीकृत निर्णय लेने वाले मॉडल प्रदान करता है। थीसिस में प्रस्तावित अधिकांश मॉडल या तो मिक्स्ड इन्टिजर लीनियर (MILP) या मिक्स्ड इन्टिजर नॉन-लीनियर प्रोग्राम (MINLP) हैं।

IMN के कॉन्फ़िगरेशन और कार्यप्रणाली के लिए महत्वपूर्ण विभिन्न कारकों के बीच अंतर-संबंधों की पहचान और विश्लेषण करने के लिए गुणात्मक अध्ययन किया जाता है। इस उद्देश्य के लिए, साहित्य विशेषज्ञों की समीक्षा और उद्योग के विशेषज्ञों से निरंतर विचार-विमर्श से उन तीस कारकों की पहचान की गई है। सभी कारकों को मोटे तौर पर छह डोमेन अर्थात् के अंतर्गत वर्गीकृत किया गया है। राजनीतिक, आर्थिक, सामाजिक, तकनीकी, कानूनी और पर्यावरण (PESTLE)। कारकों की ड्राइविंग पावर और डिपेंडेंस का विश्लेषण करने के लिए तीन अलग-अलग बहु-मापदंड निर्णय लेने की तकनीक (MCDM) अर्थात् PESTLE

और स्ट्रेथ, वीकनेस, ओपपोर्चुनिटी, थ्रेट (SWOT), एनालिटिकल हायरार्की प्रोसेस (AHP) और इंटरप्रेटिवे स्ट्रक्चरल मॉडलिंग (ISM) का संयोजन किया गया है। उपरोक्त तरीकों से प्राप्त परिणामों की तुलना आम ड्राइविंग कारकों की पहचान करने के लिए की जाती है।

आईएमएन एनबलर्स के गुणात्मक विश्लेषण के बाद, अनुसंधान फिर आईएमएन के लिए मात्रात्मक मॉडल विकसित करने पर ध्यान केंद्रित करता है। प्रस्तावित मॉडल कई देशों में स्थित विनिर्माण संयंत्रों और गोदामों की एक व्यापक सुविधा नेटवर्क पर विचार करते हैं। मॉडल एक विशिष्ट देश के लिए आयात निर्यात लागत, ऋण सब्सिडी, मूल्यहास व्यय और अन्य परिचालन लागतों पर विचार करता है। अंतरराष्ट्रीय व्यापार मुद्दों पर विचार के अलावा, थीसिस में प्रस्तावित मॉडल देश के विशिष्ट विश्लेषण प्रदान करके पारंपरिक उत्पादन-वितरण मॉडल पर महत्व देते हैं। यह निर्णय निर्माताओं को एक विशेष देश में परिचालन की निगरानी करने और एक अंतरराष्ट्रीय पारिस्थितिकी तंत्र के भीतर देश की विशिष्ट रणनीति तैयार करने में सक्षम बनाता है। अनुसंधान आगे आईएमएन के लिए रिवर्स लॉजिस्टिक्स को शामिल करने के लिए प्रस्तावित मॉडल का विस्तार करने का प्रयास करता है। एक हाइब्रिड सुविधा नेटवर्क को लागत में कटौती और उपकरणों के बंटवारे के लिए माना जाता है जहां रिवर्स लॉजिस्टिक्स सेवाएं प्रदान करने के लिए फॉरवर्ड लॉजिस्टिक्स की सुविधाएं भी सुसज्जित हैं। इसके अलावा, अनुसंधान कार्बन उत्सर्जन को निर्धारित करके प्रस्तावित मॉडलों में पर्यावरणीय स्थिरता को संबोधित करने का प्रयास करता है। कार्बन उत्सर्जन को आगे और पीछे की रसद गतिविधियों दोनों के कारण माना जाता है और कैप एंड ट्रेड नीति उपयोग करके विनियमित किया जाता है। अनुसंधान कुल कार्बन उत्सर्जन और कुल लागत पर विभिन्न व्यापार नीतियों के प्रभाव की भी जांच करता है।

अनुसंधान आगे अनिश्चित बाजार की मांग और उत्पाद वापसी परिदृश्य में रेसिलिएंस एवम सस्टेनेबिलिटी को संतुलित करने के लिए स्टोकेस्टिक मॉडल विकसित करने का प्रयास करता है। चांस-कन्स्ट्रैनेड एप्रोच का

उपयोग स्टोकेस्टिक मांग और रिटर्न के निर्धारक तुल्यता को प्राप्त करने के लिए किया जाता है। मॉडल का सत्यापन रैंडमली जनरेटेड डेटा सेट का उपयोग करके किया गया है। डेटा सेट के मापदंडों को बिग डेटा के 3V जैसे वॉल्यूम, वेलोसिटी और वैरायटी के साथ मैप किया जाता है।

अलग से IMN के लिए गुणात्मक और मात्रात्मक मॉडल विकसित करने के बाद, अनुसंधान उन्हें एकीकृत करने का प्रयास करता है। गुणात्मक मॉडल के परिणाम अधिक यथार्थवादी निर्णय लेने का समर्थन करने के लिए मात्रात्मक मॉडल के इनपुट के रूप में प्रदान किए जाते हैं। यह एकीकृत मॉडल फैसिलिटी कंट्री पेअर को रैंक प्रदान करने में मदद करता है और कार्बन उत्सर्जन और कुल लागत में विचलन का अनुमान लगाता है जब फैसिलिटी कंट्री पेअर को प्राथमिकता दी जाती है या नहीं दी जाती है।

अन्त में, थीसिस का समापन सभी अध्यायों को संक्षेप में करके, प्रमुख योगदान प्रदान करके और भविष्य के शोध के लिए कुछ दिशाओं का सुझाव देकर किया जाता है।

कीवर्ड: IMN, सप्लाय चैन मैनेजमेंट, सस्टेनेबिलिटी, फ्लेक्सिबिलिटी, रिवर्स लॉजिस्टिक्स, क्षमता विस्तार, हाइब्रिड फैसिलिटी, MILP, MINLP, स्टोकेस्टिक, AHP, ISM, IRP, PESTLE-SWOT

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
TABLE OF CONTENT	ix
LIST OF FIGURES	xvi
LIST OF TABLES	xix
LIST OF INDICES, VARIABLES AND PARAMETERS	xxi
LIST OF ABBREVIATIONS	xxviii

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND	1
1.2 WHAT IS IMN?	2
1.3 IMN CONFIGURATION AND COORDINATION	3
1.3.1 Configuration	3
1.3.2 Coordination	4
1.4 SUSTAINABLE IMN	6
1.4.1 Carbon trading	6
1.4.2 Reverse logistics	7
1.5 THESIS ORGANIZATION	10
1.6 CONCLUDING REMARKS	13

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION	14
2.2 REVIEW ON MANUFACTURING NETWORKS EVOLUTION	15
2.2.1 Literature related to plant-level analysis	16
2.2.2 Literature related to the evolution of IMN	16
2.2.3 Literature related to production-distribution network	17
2.3 REVIEW ON CONFIGURATION AND COORDINATION	18

2.3.1 Literature related to IMN configuration	18
2.3.2 Literature related to IMN coordination	20
2.4 REVIEW ON REVERSE LOGISTICS	21
2.5 REVIEW ON SUSTAINABLE AND RESILIENT MANUFACTURING NETWORKS	22
2.5.1 Literature on sustainable manufacturing networks	23
2.5.2 Literature on resilient manufacturing networks	24
2.6 REVIEW ON BIG DATA IN MANUFACTURING NETWORKS	26
2.7 RESEARCH GAPS	29
2.8 RESEARCH OBJECTIVES	29
2.9 CONCLUDING REMARKS	30

CHAPTER 3: MODELLING ENABLERS FOR INTERNATIONAL MANUFACTURING NETWORK

3.1 INTRODUCTION	31
3.2 PROPOSED FRAMEWORK	32
3.3 IMN ANALYSIS USING PCA, PESTLE-SWOT, AHP AND ISM	38
3.4 COMPARATIVE ANALYSIS OF RESULTS	55
3.5 CONCLUDING REMARKS	59

CHAPTER 4: MODELLING DYNAMIC PRODUCTION-DISTRIBUTION NETWORK

4.1 INTRODUCTION	60
4.2 PROBLEM STATEMENT AND MODEL FORMUALTION	61
4.2.1 Problem statement	61
4.2.2 Linking big data with the proposed model	62
4.2.3 Model assumptions	63
4.2.4 Dynamic IMN model	64
4.3 NUMERICAL ILLUSTRATION	65
4.3.1 Illustration for 2C-3P-2I-5J-3K-5T	65
4.3.2 Illustration for 5C-10P-3I-5J-7K-10T	66

4.4 RESULTS	66
4.4.1 Illustration for 2C-3P-2I-5J-3K-5T	66
4.4.2 Illustration for 5C-10P-3I-5J-7K-10T	70
4.5 CONCLUDING REMARKS	76

CHAPTER 5: MODELLING SUSTAINABLE PRODUCTION- DISTRIBUTION NETWORK

5.1 INTRODUCTION	77
5.2 PROBLEM STATEMENT AND MODEL FORMULATION	78
5.2.1 Problem statement	78
5.2.2 Model assumptions	79
5.2.3 Sustainable IMN model	80
5.3 NUMERICAL ILLUSTRATION	83
5.4 RESULTS	88
5.5 CONCLUDING REMARKS	92

CHAPTER 6: MODELLING SUSTAINABLE REVERSE LOGISTICS NETWORK

6.1 INTRODUCTION	93
6.2 RL-IMN MODEL	94
6.2.1 Model formulation	95
6.2.2 Linearization of MINLP model	99
6.3 NUMERICAL ILLUSTRATION	100
6.3.1 Illustration for 2C-2P-2I-3J-2K-3T	101
6.4 SUSTAINABLE RL-IMN MODEL	109
6.5 NUMERICAL ILLUSTRATION	111
6.5.1 Illustration for 2C-2P-2I-3J-2K-3T	111
6.5.2 Illustration for 3C-5P-3I-5J-7K-3T	117
6.6 TRADE POLICIES	121
6.6.1 Case I: If country C2 adopts protectionist policy	121
6.6.2 Case II: If country C1 also adopts protectionist policy	123

6.6.3 Case II: Free trade agreement	124
6.7 CONCLUDING REMARKS	125

CHAPTER 7: STOCHASTIC MODELLING FOR RESILIENT AND SUSTAINABLE REVERSE LOGISTICS NETWORK

7.1 INTRODUCTION	126
7.2 RESEARCH FRAMEWORK	127
7.3 STOCHASTIC IMN MODEL	128
7.3.1 Model Assumptions	129
7.3.2 Model Formulation	129
7.4 LINKING BIG DATA WITH IMN MODEL	133
7.5 NUMERICAL ILLUSTRATION	134
7.5.1 Supply Disruption	148
7.5.2 Demand Disruption	151
7.6 CONCLUDING REMARKS	152

CHAPTER 8: MODELLING INTEGRATED RE-MANUFACTURING NETWORK

8.1 INTRODUCTION	153
8.2 RESEARCH FRAMEWORK	154
8.2.1 Problem Characteristics	154
8.2.2 Research framework	155
8.3 PREFERENCE-BASED SUSTAINABLE AND STOCHASTIC IMRN MODEL	157
8.3.1 Phase I: Prioritizations of Plant-country/warehouse country pair using weighted IRP	157
8.3.2. Phase II: Sustainable and stochastic international manufacturing- remanufacturing network (SSIMRN) model	162
8.3.3. Phase III: Preference-based SSIMRN model	166
8.4 NUMERICAL ILLUSTRATION (3C-3P-3I-5J-5K-3T)	167
8.5 MODIFIED MILP-2 MODEL	175
8.6 CONCLUDING REMARKS	179

CHAPTER 9: DISCUSSION AND CONCLUSION

9.1 OVERALL SUMMARY	180
9.2 MAJOR CONTRIBUTIONS	182
9.3 RESEARCH IMPLICATIONS	184
9.3.1 Implications for Academicians	185
9.3.2 Implications for Practitioners	186
9.3.3 Implications for Policy makers	187
9.4 RECOMMENDATIONS FOR FUTURE RESEARCH	188
REFERENCES	189
APPENDICES	
Appendix 4.1: Lingo Code to solve dynamic IMN model	207
Appendix 4.2: Transportation Cost from Plant to Warehouse (I-J)	209
Appendix 4.3: Transportation Cost from Plant to Plant (I-I)	222
Appendix 4.4: Transportation Cost from Plant to Market (I-K)	232
Appendix 4.5: Transportation Cost from Warehouse to Warehouse (J-J)	250
Appendix 4.6: Transportation Cost from Warehouse to Market (J-K)	277
Appendix 4.7: Market Demand and Data for other cost parameters	310
Appendix 4.8: Market Demand and Data for other cost parameters	313
Appendix 5.1: Lingo Code to solve sustainable IMN model	327
Appendix 5.2: Transportation Cost from Plant to Plant (I-I)	331
Appendix 5.3: Transportation Cost from Plant to Warehouse (I-J)	332
Appendix 5.4: Transportation Cost from Warehouse to Warehouse (J-J)	333
Appendix 5.5: Transportation Cost from Plant to Market (I-K)	335
Appendix 5.6: Transportation Cost from Warehouse to Market (W-M)	337

Appendix 5.7: Market Demand and Data for other cost parameters	339
Appendix 6.1: Lingo Code to solve RL-IMN model	343
Appendix 6.2: Data for 2C-2P-2I-3J-2K-3T case	346
Appendix 6.3: Lingo Code to solve sustainable RL-IMN model	349
Appendix 6.4: Data for 2C-2P-2I-3J-2K-3T case	
Data for 3C-5P-3I-5J-7K-3T case	355
Appendix 7.1: Lingo code to solve sustainable and stochastic IMN model	363
Appendix 7.2: Transportation cost from plant to plant (I-I)	366
Appendix 7.3: Transportation cost from plant-warehouse(I-J)	368
Appendix 7.4: Transporattion cost from warehouse-warehouse (J-J)	370
Appendix 7.5: Transporattion cost from warehouse-market (J-K)	373
Appendix 7.6: Transporattion cost from plant-market (I-K)	375
Appendix 7.7: Stochastic Demand Data	376
Appendix 7.8: Stochastic Return Data	379
Appendix 7.9: Distance data from one facility to other	382
Appendix 7.10: Data for other cost parameters	385
Appendix 8.1: Lingo Code for Preference based IMRN model	387
Appendix 8.2: Stochastic Demand and Return data	392
Appendix 8.3: Transportation cost from plant to plant (I-I)	393
Appendix 8.4: Transportation cost from plant to warehouse (I-J)	394
Appendix 8.5: Transportation Cost from Plant to market (I-K)	395
Appendix 8.6: Transportation Cost from warehouse to warehouse (J-J)	396
Appendix 8.7: Transportation Cost from warehouse to market (J-K)	397

Appendix 8.8: Transportation Cost from market to warehouse (K-J)	398
Appendix 8.9: Transportation Cost from warehouse to plant (J-I)	399
Appendix 8.10: Data for other cost parameters	400
PUBLICATIONS FROM THE THESIS	402
PROFILE OF THE SCHOLAR	404

LIST OF FIGURES

Figure 1.1: Network classification based on their size	4
Figure 1.2: Network configurations based on coordination level	5
Figure 1.3: Flowchart of the thesis	9
Figure 3.1: Framework for identifying driving factors for IMN	33
Figure 3.2: PESTLE – SWOT Framework	35
Figure 3.3: Grouping of factors	42
Figure 3.4: The hierarchy of IMN factors	46
Figure 3.5: MICMAC Analysis	54
Figure 4.1: Big data framework for IMN	63
Figure 4.2: Products distribution across two geographical regions (C1 and C2) for the T1 for products (P1, P2, P3)	69
Figure 4.3: Plants operating for manufacturing Product 1 in all the time periods	71
Figure 4.4: Plants operating for manufacturing Product 2 in all the time periods	71
Figure 4.5: Plants operating for manufacturing Product 3 in all the time periods	72
Figure 4.6: Plants operating for manufacturing Product 4 in all the time periods	72
Figure 4.7: Plants operating for manufacturing Product 5 in all the time periods	73
Figure 4.8: Plants operating for manufacturing Product 6 in all the time periods	73
Figure 4.9: Plants operating for manufacturing Product 7 in all the time periods	74
Figure 4.10: Plants operating for manufacturing Product 8 in all the time periods	74
Figure 4.11: Plants operating for manufacturing Product 9 in all the time periods	75

Figure 4.12: Plants operating for manufacturing Product 9 in all the time periods	75
Figure 5.1: Proposed MILP Model Framework	80
Figure 5.2: Carbon emission (for 3C-5P-3I-5J-7K-3T)	88
Figure 5.3: Product flow diagram for P1	91
Figure 6.1: FRL distribution network for 2C-2P-2I-3J-2K-3T	103
Figure 6.2: Fluctuation in total cost with plant and warehouse capacity	107
Figure 6.3: Variation in plant capacity over time	107
Figure 6.4: Variation in warehouse capacity over time	109
Figure 6.5: Variation in Remanufacturing, Repairing and Total cost	108
Figure 6.6: Variation in costs for all cases of 2P-2C-2I-2J-2K-3T	117
Figure 6.7: Variation in total cost and emissions with varying carbon price	117
Figure 6.8: Quantity of Product P1 manufactured at each plant	119
Figure 6.9: Quantity of Product P2 manufactured at each plant	119
Figure 6.10: Quantity of Product P3 manufactured at each plant	120
Figure 6.11: Quantity of Product P4 manufactured at each plant	120
Figure 6.12: Quantity of Product P5 manufactured at each plant	120
Figure 6.13. Product Flow Diagram for P1 for FRL	122
Figure 6.14. Variation in C2 import cost.	123
Figure 6.15. Variation in both C1 and C2 import cost.	124
Figure 7.1. Flowchart representation of the proposed model.	128
Figure 7.2. Big data framework for sustainable and resilient IMN	134
Figure 7.3. Carbon emissions in each country for all three time periods.	144

Figure 7.4. Forward Distribution of product (P1) for all time periods	145
Figure 7.5 Quantity of Product 1 manufactured at Plants in all time periods	147
Figure 7.6 Quantity of Product 2 manufactured at Plants in all time periods	147
Figure 7.7 Quantity of Product 3 manufactured at Plants in all time periods	147
Figure 7.8 Quantity of Product 4 manufactured at Plants in all time periods	148
Figure 7.9 Quantity of Product 5 manufactured at Plants in all time periods	148
Figure 7.10. Production Level in country C2 and C4 when the disruption occurs in C1 and C3	150
Figure 7.11. Change is Carbon emission level due to supply disruption in C1 and C3	150
Figure 7.12(a). Distribution of P1 in Base case for all periods	151
Figure 7.12(b). Distribution of P1 when demand increases suddenly due to disaster	151
Figure 8.1. Research framework for the integrated model	157
Figure 8.2(a). Carbon emissions in the base model SSIMRN model (MILP-1)	171
Figure 8.2(b). Carbon emissions in preference-based SSIMRN model (MILP-2)	172
Figure 8.3. Forward logistics network flow for products P1, P2, and P3 for T=1	172
Figure 8.4. Reverse logistics network flow for products P1, P2, and P3 for T=1	174
Figure 8.5. Total cost and total emissions comparison in different warranty periods	178

LIST OF TABLES

Table 1.1: Characteristics of different manufacturing networks	3
Table 2.1: Number of reputed journal citations	14
Table 2.2: Summary of literature review	28
Table 3.1: List of Factors	39
Table 3.2: KMO and Bartlett test for cluster formation	40
Table 3.3: Percentage of variance of each component	40
Table 3.4: Correlation matrix using PCA	41
Table 3.5: PESTLE-SWOT Analysis for IMN	43
Table 3.6: Priority vectors for IMN Factors from AHP	47
Table 3.7: Structural self-interaction matrix (SSIM)	49
Table 3.8: Initial Reachability Matrix	50
Table 3.9: Final Reachability Matrix inclusive of transitive links	51
Table 3.10: Level Partition	52
Table 3.11: Shortlisted Factors	55
Table 3.12: List of common IMN Factors across ISM, AHP and PESTLE	56
Table 3.13: Weights of common factors	58
Table 4.1: Solution corresponding to facility location decision.	68
Table 5.1: Instances and Results	83
Table 5.2: Detailed solution for 3C-5P-3I-5J-7K-3T instance.	85

Table 6.1. Results for case instances	100
Table 6.2. Detailed solution for 2C-2P-2I-3J-2K-3T	102
Table 6.3. Experimental results for varying capacity (plant, warehouse)	105
Table 6.4. Results for 2C-3P-3I-3J-2K-3T (10% case)	115
Table 7.1. Detailed solution for the 4C-5P-3I-5J-7K-3T case	136
Table 8.1 Reference variables for plant and warehouse and their weights	158
Table 8.2 Comparison of plant-country pair with respect to each criteria	159
Table 8.3 Dominance matrix for plant-country pair obtained using weighted IRP	159
Table 8.4 Ranking of plant-country pair obtained using weighted IRP	160
Table 8.5 Comparison of warehouse-country pair with respect to each criteria	160
Table 8.6 Dominance matrix for warehouse-country pair obtained using weighted IRP	161
Table 8.7 Ranking of warehouse-country pair using weighted IRP	162
Table 8.8 Hybrid Plant allocation in the base model (MILP-1) and preference-based model(MILP-2)	169
Table 8.9 Hybrid warehouse allocation in the base model(MILP-1) and preference-based model(MILP-2)	170
Table 8.10 The objective function and carbon emissions for different reformulated strategies	175

LIST OF INDICES, VARIABLES AND PARAMETERS

List of Indices

b, c	indices for countries	C	number of countries
i	index for plants	I	number of plants
j	index for warehouses	J	number of warehouses
k	index for markets	K	number of markets
p	index for products	P	number of products
t	index for time period	T	number of time periods

List of Parameters

CP_{pict}	Cost of producing a unit of p^{th} product in i^{th} plant in c^{th} country for t^{th} period
CR_{pict}	Remanufacturing cost of p^{th} product in i^{th} plant in c^{th} country for t^{th} period
C_{ct}	Carbon price in c^{th} country for t^{th} period
DP_{pict}	Depreciation expense per unit of p^{th} product in i^{th} plant located at c^{th} country for t^{th} period
DR_{pict}	Depreciation expense due to remanufacturing per unit of p^{th} product at i^{th} plant located in c^{th} country in t^{th} period
$d1_{ici'bt}$	Distance between i^{th} plant in c^{th} country to i'^{th} plant in b^{th} country in t^{th} period
$d2_{icjbt}$	Distance between i^{th} plant in c^{th} country to j^{th} warehouse in b^{th} country in t^{th} period
$d3_{ickbt}$	Distance between i^{th} plant in c^{th} country to k^{th} market in b^{th} country in t^{th} period
$d4_{jcj'bt}$	Distance between j^{th} warehouse in c^{th} country to j'^{th} warehouse in b^{th} country in t^{th} period
$d5_{ijkbt}$	Distance between j^{th} warehouse in c^{th} country to k^{th} market in b^{th} country in t^{th} period

$E1_{pt}$	Carbon emission caused when p^{th} product is manufactured in t^{th} period
$E2_{pt}$	Carbon emission caused in holding a unit of p^{th} product in warehouse for t^{th} period
Ef	Variable emission factor corresponding to the load carried, fuel type, distance traveled and mileage of the carrier.
$F1_{ict}$	Setup/Maintenance cost of i^{th} plant in c^{th} country for t^{th} period
$F2_{jct}$	Setup/Maintenance cost of j^{th} warehouse in c^{th} country for t^{th} period
FPN_{ict}	Setup cost of i^{th} plant in c^{th} country for t^{th} period
FPE_{ict}	Fixed Expansion cost of i^{th} plant in c^{th} country for t^{th} period
FWN_{jct}	Setup cost of j^{th} warehouse in c^{th} country for t^{th} period
FWE_{jct}	Fixed Expansion cost of j^{th} warehouse in c^{th} country for t^{th} period
$F_{QS_{pkct}}^{-1}$	Constant inverse cumulative function for random demand for given ρ_{pkct} having mean (μ) and standard deviation (σ)
$F_{Rp_{kct}}^{-1}$	Constant inverse cumulative function for random product returns for given α_{pkct} having mean (μ) and standard deviation (σ)
FEf	Fixed emission factor corresponding to the number of carriers/trips required irrespective of the load carried.
H_{pjct}	Unit holding cost of p^{th} product in c^{th} country for t^{th} period
LA_{ct}	Loan granted to c^{th} country in t^{th} period for setting up facilities in that country
$LI_{ct}(r, T)$	Interest rate calculation factor for loan granted to c^{th} country with interest rate r to be repaid in time T
LN_{ct}	Interest payments on loan amount given to c^{th} country in t^{th} period

QS_{pkct}	Demand for p^{th} product at k^{th} market in c^{th} country for t^{th} period
QP_{pict}^{max}	Existing maximum capacity of i^{th} plant at c^{th} country for p^{th} product in t^{th} period
QW_{pjct}^{max}	Existing maximum capacity of j^{th} warehouse located in c^{th} country for p^{th} product in t^{th} period
RF_{pjct}	Refurbishing cost per unit of p^{th} product at j^{th} warehouse in c^{th} country in t^{th} period
R_{pkct}	Product returns of p^{th} type product from k^{th} market in c^{th} country in t^{th} time period
$T1_{picibt}$	Shipment cost of a unit of p^{th} product from i^{th} plant located in c^{th} country to i^{th} plant in b^{th} country for t^{th} period
$T2_{picjbt}$	Shipment cost of a unit of p^{th} product from i^{th} plant located in c^{th} country to j^{th} warehouse in b^{th} country for t^{th} period
$T3_{pickbt}$	Shipment cost of a unit of p^{th} product from i^{th} plant located in c^{th} country to k^{th} market in b^{th} country for t^{th} period
$T4_{pjci'bt}$	Shipment cost of a unit of p^{th} product from j^{th} warehouse located in c^{th} country to j^{th} warehouse in b^{th} country for t^{th} period
$T5_{pjckbt}$	Shipment cost of a unit of p^{th} product from j^{th} warehouse located in c^{th} country to k^{th} market in b^{th} country for t^{th} period
$T6_{pcbt}$	Unit Import/Export cost of p^{th} product shipped from c^{th} country to b^{th} country for t^{th} period
$T7_{pkcjct}$	Shipment cost of a unit of p^{th} product from k^{th} market to j^{th} warehouse in c^{th} country for t^{th} period (includes to and fro shipments)
$T8_{pjci ct}$	Shipment cost of a unit of p^{th} product from j^{th} warehouse to i^{th} plant in c^{th} country

	for t^{th} period (includes to and fro shipments)
UA_{ict}	Maximum limit of capacity expansion of i^{th} plant in c^{th} country for t^{th} period
UB_{jct}	Maximum limit of capacity expansion of j^{th} warehouse in c^{th} country for t^{th} period
VPE_{ict}	Variable Expansion cost of i^{th} plant in c^{th} country for t^{th} period
VWE_{jct}	Variable Expansion cost of j^{th} warehouse in c^{th} country for t^{th} period
Vp	Packaged volume of p^{th} product
ρ_{pkct}	Level of probability that demand of the p^{th} product in k^{th} market in c^{th} country in t^{th} period having mean (μ) and standard deviation (σ)
α_{ct}	Carbon emission quota in c^{th} country for t^{th} period
α_{pkct}	Level of probability that warranty period returns of p^{th} type product from k^{th} market in c^{th} country in t^{th} period having mean (μ) and standard deviation (σ)
Ω	Maximum load capacity of carrier in volume

List of Variables

$CE1_{ct}$	Carbon emissions due to transportation of all the products in c^{th} country for t^{th} period
$CE2_{ct}$	Carbon emissions due to production of all the products in c^{th} country for t^{th} period
$CE3_{ct}$	Carbon emissions due to storage of all the products in c^{th} country for t^{th} period
$CE4_{ct}$	Carbon emissions due to repairing of all the products in c^{th} country for t^{th} period
$CE5_{ct}$	Carbon emissions due to remanufacturing of all the products in c^{th} country for t^{th} period
DP_{ct}	Depreciation expense in production of all the products at all the plant in c^{th} country for t^{th} period
FC_{ict}	Setup cost of all the plant and warehouses in c^{th} country for t^{th} period

G_{ct}	Carbon bought/purchased in c^{th} country for t^{th} period
IE_{ct}	Import-export cost of all the products in c^{th} country for t^{th} period
IH_{ct}	Inventory holding cost of all the products at all the warehouses located in c^{th} country for t^{th} period
IN_{pjct}	Balance inventory of p^{th} product at j^{th} warehouse located in c^{th} country for t^{th} period
$K1_{jct}$	Capacity expansion of j^{th} warehouse in c^{th} country in t^{th} period
$K2_{ict}$	Capacity expansion of i^{th} plant in c^{th} country in t^{th} period
PC_{ct}	Cost of producing all the product at all the plants in c^{th} country for t^{th} period
$Q1_{pici'bt}$	Unit of p^{th} product shipped from i^{th} plant located in c^{th} country to i^{th} plant located in b^{th} country for t^{th} period
$Q2_{picjbt}$	Unit of p^{th} product shipped from i^{th} plant in c^{th} country to j^{th} warehouse in b^{th} country for t^{th} period
$Q3_{pickbt}$	Unit of p^{th} product shipped from i^{th} plant in c^{th} country to market k in b^{th} country for t^{th} period
$Q4_{pjcj'bt}$	Unit of p^{th} product shipped from j^{th} warehouse located in c^{th} country to j'^{th} warehouse located in b^{th} country for t^{th} period
$Q5_{pjckbt}$	Unit of p^{th} product shipped from j^{th} warehouse in c^{th} country to market k in b^{th} country for t^{th} period
$Q6_{pkjct}$	Unit of p^{th} product shipped from k^{th} market to j^{th} warehouse in c^{th} country for t^{th} period
$Q6_{pkcjct}$	Unit of p^{th} product shipped from k^{th} market to j^{th} warehouse in c^{th} country for t^{th} period
QP_{pict}	Quantity produced at i^{th} plant at c^{th} country for p^{th} product in t^{th} period
QRF_{pkjct}	Quantity of p^{th} product refurbished at j^{th} warehouse returned from k^{th} market located in c^{th} country in t^{th} period

QRF_{pkcjt} Quantity of p^{th} product refurbished at j^{th} warehouse in c^{th} country returned from k^{th} market located in c^{th} country in t^{th} period

QRM_{pkjict} Quantity of p^{th} product remanufactured at i^{th} plant returned from k^{th} market via j^{th} warehouse at c^{th} country for in t^{th} period

$QRM_{pkjcict}$ Quantity of p^{th} product remanufactured at i^{th} plant in c^{th} country returned from k^{th} market in c^{th} country via j^{th} warehouse at c^{th} country for in t^{th} period

RMC_{ct} Remanufacturing cost of all the returned products in c^{th} country for t^{th} period

RC_{ct} Repairing cost of all the products in c^{th} country in t^{th} period

TC_{ct} Transportation cost of all the product in c^{th} country for t^{th} period

$U_{jct} = \begin{cases} 1 & \text{if warehouse } j \text{ is to be expanded in country } c \text{ for period } t \\ 0 & \text{otherwise} \end{cases}$

$V_{ict} = \begin{cases} 1 & \text{if plant } i \text{ is to be expanded in country } c \text{ for period } t \\ 0 & \text{otherwise} \end{cases}$

$X_{ict} = \begin{cases} 1 & \text{if plant } i \text{ open in country } c \text{ for period } t \\ 0 & \text{otherwise} \end{cases}$

$Y_{jct} = \begin{cases} 1 & \text{if warehouse } j \text{ is open in country } c \text{ for period } t \\ 0 & \text{otherwise} \end{cases}$

Z_{ct} Carbon trading cost in c^{th} country for t^{th} period

$\eta 1_{ici'bt}$ Number of carriers required by i^{th} plant in c^{th} country to ship to i'^{th} plant in b^{th} country in t^{th} period

$\eta 2_{icjbt}$ Number of carriers required by i^{th} plant in c^{th} country to ship to j^{th} warehouse in b^{th} country in t^{th} period

$\eta 3_{ickbt}$ Number of carriers required by i^{th} plant in c^{th} country to ship to k^{th} market in b^{th} country in t^{th} period

- $\eta 4_{jcj'bt}$ Number of carriers required by j^{th} warehouse in c^{th} country to ship to j'^{th} warehouse in b^{th} country in t^{th} period
- $\eta 5_{ijkbt}$ Number of carriers required by j^{th} warehouse in c^{th} country to ship to k^{th} market in b^{th} country in t^{th} period
- $\eta 6_{kcjct}$ Number of carriers required to collect return products from the k^{th} market and ship to j^{th} warehouse in c^{th} country in t^{th} period
- $\eta 7_{jcict}$ Number of carriers required by j^{th} warehouse to ship products for remanufacturing to i^{th} plant in c^{th} country in t^{th} period

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
CSR	Corporate Social Responsibility
CLSC	Closed Loop Supply Chain
EA	Elimination Algorithm
EPR	Extended Producer Responsibility
FDI	Foreign Direct Investment
FRL	Forward and Reverse Logistics
FTA	Free Trade Agreement
GDP	Gross Domestic Product
GHGs	Green House Gasses
GSCM	Global Supply Chain Management
IMN	International Manufacturing Network
IMRN	International Manufacturing-Remanufacturing Network
IoT	Internet of Things
IRP	Interpretive Ranking Process
ISM	Interpretive Ranking Process
JIT	Just-in-Time
MCDM	Multi-Criteria Decision Making
MILP	Mixed Integer Linear Program
MINLP	Mixed Integer Non-Linear Program
OEM	Original Equipment Manufacturer
PCA	Principal Component Analysis
PESTLE	Political Economic Social Technological Legal Environment
RFID	Radio Frequency Identification
RL-IMN	Reverse Logistics International Manufacturing Network
SSIMRN	Sustainable and Stochastic International Manufacturing-Remanufacturing

Network

SWOT Strength Weakness Opportunities Threat

WEEE Waste Electrical and Electronic Equipment