# MODELLING INTERNATIONAL MANUFACTURING NETWORK

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**by**

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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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**Shraddha Mishra**

# 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 उनतीस कारकों की पहचान की गई है। सभी कारकों को मोटे तौर पर छह डोमेन अर्थात 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 स्ट्रेंथ, वीकनेस, ओप्पोर्चुनिटी, 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, मूल्यह्रास 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 रैंडम्ली 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, सप्लाई चेन मैनेजमेंट, सस्टेनेबिलिटी, फ्लेक्सिबिलिटी, रिवर्स लॉजिस्टिक्स, क्षमता विस्तार, हाइब्रिड फैसिलिटी , MILP, MINLP, स्टोकेस्टिक, AHP, ISM, IRP, PESTLE-SWOT

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|---|---|---|---|
| *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

$F^{-1}_{QS_{pkct}}$ Constant inverse cummulative function for random demand for given $\rho_{pkct}$ having mean mean (μ) and standard deviation (σ)

$F^{-1}_{R_{pkct}}$ Constant inverse cummulative function for random product returns for given $\alpha_{pkct}$ 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 cthcountry 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 kth market in $c^{th}$ country in $t^{th}$ time period

$T1_{pici'bt}$ 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 $b^{th}$ countryfor $t^{th}$ 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 $b^{th}$ countryfor $t^{th}$ period

$T4_{pjcj'bt}$ Shipment cost of a unit of $p^{th}$ product from $j^{th}$ warehouse located in $c^{th}$ country to $j'^{th}$ warehouse in $b^{th}$ countryfor $t^{th}$ 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 $b^{th}$ countryfor $t^{th}$ period

$T6_{pcbt}$ Unit Import/Export cost of pth 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)

$T8_{pjcict}$ Shipment cost of a unit of $p^{th}$ product from $j^{th}$ warehouse to ith 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

V$p$ Packaged volume of $p^{th}$ product

$\rho_{pkct}$ Level of probability that demand of the $p^{th}$ product in $k^{th}$ market in $cth$ country in $t^{th}$ period having mean mean (μ) and standard deviation (σ)

$\alpha_{ct}$ Carbon emission quota in $c^{th}$ country for $t^{th}$period

$\alpha_{pkct}$ 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

***<u>List of Variables</u>***

$CE1_{ct}$ Carbon emissions due to trasnportation 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

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

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

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

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

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

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

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

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

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

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

$Z_{ct}$ Carbon trading cost in $c^{th}$ country for $t^{\text{th}}$ 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 ABBREVATIONS

| | |
|---|---|
| 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 |