

MODELLING INDUSTRY 4.0: SELECT ISSUES

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OCTOBER 2021**

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MODELLING INDUSTRY 4.0: SELECT ISSUES

by

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Submitted in fulfillment of the requirements of the degree of
DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI,
NEW DELHI-110016, INDIA
OCTOBER 2021

CERTIFICATE

This is to certify that the thesis entitled “**Modelling Industry 4.0: Select Issues**” being submitted by **Shubhangini Rajput** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by her. She has worked under my supervision and has fulfilled the requirements for the submission of the 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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ACKNOWLEDGEMENT

I would like to express my deep sense of respect and gratitude to my thesis supervisor, Dr. S.P. Singh, for his continuous support, motivation, immense guidance, and patience throughout the study. He continually and convincingly conveyed a spirit of research, enriched my knowledge, and contributed to my personal and professional development. His words of encouragement, friendly interactions, and constructive support during the lean times of the research have always been a source of strength to go forward. I consider it a great opportunity to do my doctoral program under his guidance and learn from his experience and expertise. This thesis could not have reached to its present form without his keen interest, direction, and guidance.

I would also like to thank my Student Research Committee for their encouragement and support during various phases of the program. I gratefully acknowledge my colleagues at the Optimization lab for the numerous research discussions for enhancing my knowledge. I am also indebted to my friends Pooja, Saroj, and Ruchita for supporting me in all good and bad times.

Lastly, I owe my parents an infinite, which cannot be repaid, for their constant support and encouragement throughout my Ph.D. work. I am also grateful to my husband for his love, always being patient with me, and provided immense moral support whenever I felt low. Finally, I thank God for leading me through all difficulties, whose guidance I have experienced day by day, and to whom I trust for my future.

(Shubhangini Rajput)

ABSTRACT

Digitization and automation of manufacturing process is the need of today's industry. The manufacturing industries have changed the landscape from mass production to customized production. The rapid advancements in information technology have paved the way towards data-driven, intelligent, and networked manufacturing systems. Thus, there is a need for a paradigm shift in manufacturing industries to revamp traditional production to smart production. In this context, Industry 4.0 is assumed to be the future industrial production supported with flexible and agile manufacturing operations. This thesis aims to study Industry 4.0 and its implementation in the manufacturing sector. However, establishing an Industry 4.0 facility with IoT embedded systems in manufacturing industries is still unexplored. Therefore, the thesis provides the qualitative and quantitative models of Industry 4.0 to reap the tangible benefits and adapt to the volatile market demand and customer requirements in real-time.

The qualitative study is carried out to identify and analyze the inter-relationship among various factors critical to the successful implementation of Industry 4.0. For this purpose, twenty IoT factors for Industry 4.0 have been identified from the literature and subsequent discussion with industry experts. Two different multi-criteria decision-making techniques (MCDM), namely, ISM and DEMATEL in three variants (Average, Pessimistic, and Optimistic), have been employed to identify driving IoT enablers and establish the contextual relationship among the IoT enablers.

The thesis also identifies and examines the cause-effect relationship among different important factors for integrating circular economy (CE) and Industry 4.0. Towards this objective, twenty-six enabling factors and fifteen inhibitors have been selected from literature and subsequent discussion with experts from the industry. DEMATEL technique is applied in three variants, i.e., Average, Pessimistic, and Optimistic, to study the cause-effect relationship among the enablers and barriers. Further, ISM has also been utilized to distinguish the hierarchical

relationship among the inhibitors to achieving sustainable CE while implementing Industry 4.0. Further, common enablers/inhibitors from three variants of DEMATEL and ISM, their hierarchies, and inter-relationships have been established.

After qualitative modeling, the thesis also proposes few quantitative models for Industry 4.0. The proposed models consider the three machine variants, i.e., high precision, medium precision, and low precision machines for multi-product in a multi-time period, which is the novelty of the study. Besides this, the model presents the trade-off between the machine processing costs and energy consumption of the machines through product machine allocation in Industry 4.0 ecosystem. The model also includes the machine costs, sensors cost comprising unit cost, installation cost, calibration, and maintenance cost of sensors, and second is the transportation cost of the multi-products. The sensors were deployed in Industry 4.0 manufacturing environment to provide real-time production data, which is further used for predictive or cognitive analytics. The proposed model optimizes the energy consumption ethically through product-machine allocation in Industry 4.0 environment to achieve CE and cleaner production at different plant locations. It optimizes the overall cost considering the cost of high precision, medium precision, and low precision machines, the cost of sensors deployed over the entire planning horizon, and the transportation cost of multi-products from the warehouses to different markets. The thesis provides a novel attempt considering multi-machines, plants, warehouses, multi-products, markets, and multi-time periods to reduce the energy consumption of machines in terms of data transmission over a period of time.

The thesis further attempts to extend the proposed model for Industry 4.0 to include reverse logistics (RL). The proposed model has considered the remanufacturing and disposal facilities to achieve the integrated CE-RL in Industry 4.0. The model is also analyzed to investigate the effect of the product's return rates and disposal rates on the total cost. This significant contribution makes the study unique, which is relevant from the viewpoint of manufacturing

industry practitioners optimizing the cost in producing the high-end products and also monitors the end-of-life (EoL) of the product in real-time.

This thesis further proposes the cyber-physical fusion architecture integrated with disruptive technologies to be implemented in the manufacturing industry. The cyber-physical fusion architecture better manages the physical and virtual world operation collaboratively, effectively, and efficiently. It has paved the way for optimizing the manufacturing process, logistics, supply chain, and customized products. Achieving cyber-physical fusion requires higher semantic interoperability, interfacing, and networking capabilities for improved productivity and real-time optimization. This fusion provides an innovative, dynamic supply chain that can control the real-time device manipulations, real-time status, and information view of the complex system. The thesis has also proposed six-leveled architecture which meets all currently identified CPS requirements and characteristics and includes customization features in Industry 4.0 5C architecture. The conceptual framework for Container Supply Chain (CSC) aligned with the cyber-physical fusion architecture of Industry 4.0 has been proposed. It has also developed recent CSC advances, including smart analytics, IoT, and big data.

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

Keywords Industry 4.0, sustainable production and consumption, circular economy, reverse logistics, energy consumption, cyber-physical fusion, IoT, MILP, DEMATEL, PCA, ISM.

सार

मैन्युफैक्चरिंग प्रोसेस का डिजिटाइजेशन और ऑटोमेशन आज के उद्योग की जरूरत है। विनिर्माण उद्योगों ने परिदृश्य को बड़े पैमाने पर उत्पादन से अनुकूलित उत्पादन में बदल दिया है। सूचना प्रौद्योगिकी में तेजी से प्रगति ने डेटा-संचालित, बुद्धिमान और नेटवर्क निर्माण प्रणालियों की ओर मार्ग प्रशस्त किया है। इस प्रकार, पारंपरिक उत्पादन को स्मार्ट उत्पादन में बदलने के लिए विनिर्माण उद्योगों में एक आदर्श बदलाव की आवश्यकता है। इस संदर्भ में, उद्योग 4.0 को लचीला और चुस्त निर्माण कार्यों के साथ समर्थित भविष्य का औद्योगिक उत्पादन माना जाता है। इस थीसिस का उद्देश्य उद्योग 4.0 और विनिर्माण क्षेत्र में इसके कार्यान्वयन का अध्ययन करना है। हालाँकि, विनिर्माण उद्योगों में IoT एम्बेडेड सिस्टम के साथ एक उद्योग 4.0 सुविधा स्थापित करना अभी भी अस्पष्ट है। इसलिए, थीसिस उद्योग 4.0 के गुणात्मक और मात्रात्मक मॉडल प्रदान करती है ताकि वास्तविक लाभ प्राप्त किया जा सके और वास्तविक समय में अस्थिर बाजार की मांग और ग्राहकों की आवश्यकताओं को अनुकूलित किया जा सके।

उद्योग 4.0 के सफल कार्यान्वयन 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, उद्योग 4.0 के लिए बीस IoT कारकों की पहचान साहित्य से की गई है और बाद में उद्योग विशेषज्ञों के साथ चर्चा की गई है। दो अलग-अलग बहु-मापदंड निर्णय लेने की तकनीक (एमसीडीएम), अर्थात् आईएसएम और डीमैटेल तीन प्रकारों (औसत,

निराशावादी, और आशावादी) में, ड्राइविंग आईओटी एनबलर्स की पहचान करने और आईओटी इनबलर्स के बीच प्रासंगिक संबंध स्थापित करने के लिए नियोजित किया गया है।

थीसिस सर्कुलर इकोनॉमी (सीई) और उद्योग 4.0 को एकीकृत करने के लिए विभिन्न महत्वपूर्ण कारकों के बीच कारण-प्रभाव संबंधों की पहचान और जांच भी करती है। इस उद्देश्य के लिए, छब्बीस सक्षम करने वाले कारकों और पंद्रह अवरोधकों को साहित्य से चुना गया है और बाद में उद्योग के विशेषज्ञों के साथ चर्चा की गई है। DEMATEL तकनीक को तीन प्रकारों में लागू किया जाता है, अर्थात्, औसत, निराशावादी और आशावादी, प्रवर्तकों और बाधाओं के बीच कारण-प्रभाव संबंध का अध्ययन करने के लिए। इसके अलावा, आईएसएम का उपयोग उद्योग 4.0 को लागू करते समय स्थायी सीई प्राप्त करने के लिए अवरोधकों के बीच पदानुक्रमित संबंधों को अलग करने के लिए भी किया गया है। इसके अलावा, DEMATEL और ISM के तीन प्रकारों से सामान्य प्रवर्तक / अवरोधक, उनके पदानुक्रम, और अंतर-संबंध स्थापित किए गए हैं।

गुणात्मक मॉडलिंग के बाद, थीसिस उद्योग 4.0 के लिए कुछ मात्रात्मक मॉडल भी प्रस्तावित करता है। प्रस्तावित मॉडल मल्टी-टाइम अवधि में मल्टी-प्रोडक्ट के लिए तीन मशीन वेरिएंट, यानी उच्च परिशुद्धता, मध्यम परिशुद्धता और कम सटीक मशीनों पर विचार करते हैं, जो अध्ययन की नवीनता है। इसके अलावा, मॉडल उद्योग 4.0 पारिस्थितिकी तंत्र में उत्पाद मशीन आवंटन के माध्यम से मशीन प्रसंस्करण लागत और मशीनों की ऊर्जा खपत

के बीच व्यापार-बंद प्रस्तुत करता है। मॉडल में मशीन की लागत, सेंसर की लागत जिसमें इकाई लागत, स्थापना लागत, अंशांकन और सेंसर की रखरखाव लागत शामिल है, और दूसरा बहु-उत्पादों की परिवहन लागत है। वास्तविक समय उत्पादन डेटा प्रदान करने के लिए उद्योग 4.0 विनिर्माण वातावरण में सेंसर तैनात किए गए थे, जिसका उपयोग भविष्य कहनेवाला या संज्ञानात्मक विश्लेषण के लिए किया जाता है। प्रस्तावित मॉडल उद्योग 4.0 पर्यावरण में उत्पाद-मशीन आवंटन के माध्यम से विभिन्न संयंत्र स्थानों पर सीई और क्लीनर उत्पादन प्राप्त करने के लिए नैतिक रूप से ऊर्जा खपत को अनुकूलित करता है। यह उच्च परिशुद्धता, मध्यम परिशुद्धता, और कम परिशुद्धता मशीनों की लागत, संपूर्ण नियोजन क्षितिज पर तैनात सेंसर की लागत, और गोदामों से विभिन्न बाजारों में बहु-उत्पादों की परिवहन लागत पर विचार करते हुए समग्र लागत का अनुकूलन करता है। थीसिस समय की अवधि में डेटा ट्रांसमिशन के मामले में मशीनों की ऊर्जा खपत को कम करने के लिए बहु-मशीनों, संयंत्रों, गोदामों, बहु-उत्पादों, बाजारों और बहु-समय अवधियों पर विचार करने के लिए एक नया प्रयास प्रदान करती है।

थीसिस आगे रिवर्स लॉजिस्टिक्स (आरएल) को शामिल करने के लिए उद्योग 4.0 के लिए प्रस्तावित मॉडल का विस्तार करने का प्रयास करती है। प्रस्तावित मॉडल ने उद्योग 4.0 में एकीकृत सीई-आरएल प्राप्त करने के लिए पुनः निर्माण और निपटान सुविधाओं पर विचार किया है। कुल लागत पर उत्पाद की वापसी दरों और निपटान दरों के प्रभाव की जांच के लिए मॉडल का भी विश्लेषण किया जाता है। यह महत्वपूर्ण योगदान अध्ययन को अद्वितीय बनाता है, जो उच्च अंत उत्पादों के उत्पादन में लागत को अनुकूलित करने वाले विनिर्माण

उद्योग के चिकित्सकों के दृष्टिकोण से प्रासंगिक है और वास्तविक समय में उत्पाद के जीवन के अंत (ईओएल) की निगरानी भी करता है।

यह थीसिस आगे विनिर्माण उद्योग में लागू की जाने वाली विघटनकारी प्रौद्योगिकियों के साथ एकीकृत साइबर-भौतिक संलयन वास्तुकला का प्रस्ताव करती है। साइबर-भौतिक प्यूजन आर्किटेक्चर भौतिक और आभासी दुनिया के संचालन को सहयोगात्मक, प्रभावी और कुशलता से बेहतर ढंग से प्रबंधित करता है। इसने विनिर्माण प्रक्रिया, रसद, आपूर्ति श्रृंखला और अनुकूलित उत्पादों के अनुकूलन का मार्ग प्रशस्त किया है। साइबर-भौतिक प्यूजन को प्राप्त करने के लिए बेहतर उत्पादकता और रीयल-टाइम ऑप्टिमाइजेशन के लिए उच्च सिमेंटिक इंटरऑपरेबिलिटी, इंटरफेसिंग और नेटवर्किंग क्षमताओं की आवश्यकता होती है। यह प्यूजन एक अभिनव, गतिशील आपूर्ति श्रृंखला प्रदान करता है जो वास्तविक समय डिवाइस जोड़तोड़, वास्तविक समय की स्थिति और जटिल प्रणाली के सूचना दृश्य को नियंत्रित कर सकता है। थीसिस ने छह-स्तरीय वास्तुकला का भी प्रस्ताव किया है जो वर्तमान में पहचानी गई सभी सीपीएस आवश्यकताओं और विशेषताओं को पूरा करता है और इसमें उद्योग 4.0 5 सी वास्तुकला में अनुकूलन सुविधा शामिल है। उद्योग 4.0 के साइबर-भौतिक संलयन वास्तुकला के साथ संरेखित कंटेनर आपूर्ति श्रृंखला (सीएससी) के लिए वैचारिक ढांचा प्रस्तावित किया गया है, और स्मार्ट एनालिटिक्स, आईओटी और बड़े डेटा सहित हाल ही में सीएससी अग्रिमों को विकसित किया है।

अंत में, थीसिस का समापन सभी अध्यायों को सारांशित करके और भविष्य के शोध के लिए महत्वपूर्ण योगदान और सिफारिशें प्रदान करके किया गया है।

कीवर्ड इंडस्ट्री 4.0, टिकाऊ उत्पादन और खपत, सर्कुलर इकोनॉमी, रिवर्स लॉजिस्टिक्स, ऊर्जा खपत, साइबर-फिजिकल फ्यूजन, IoT, MILP, DEMATEL, PCA, ISM

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LIST OF INDICES, VARIABLES AND PARAMETERS

List of indices

cc=index for collection center

dc=index for disassembly center

h= index for high precision machine

i= index for plant

j= index for warehouse

k= index for market

l= index for low precision machine

m= index for medium precision machine

r= index for product

t= index for time period

List of parameters

CAH_{irht} Calibration cost of sensors in i^{th} plant for product 'r' for h^{th} high precision machine for t^{th} time period.

CAM_{irmt} Calibration cost of sensors in i^{th} plant for product 'r' for m^{th} medium precision machine for t^{th} time period.

CAL_{irlt} Calibration cost of sensors in i^{th} plant for product 'r' for l^{th} low precision machine for t^{th} time period.

D_{rkt} Demand for r^{th} product at k^{th} market for t^{th} time period.

Dfr_r Disposal rate per unit of product

DLC_{rt} Disposal cost of r^{th} product in t^{th} time period.

EC_{irht}	Energy consumption in i^{th} plant for product 'r' for h^{th} high precision machine for t^{th} time period.
ECL_{irlt}	Energy consumption in i^{th} plant for product 'r' for l^{th} low precision machine for t^{th} time period.
ECM_{irmt}	Energy consumption in i^{th} plant for product 'r' for m^{th} medium precision machine for t^{th} time period.
INH_{irht}	Installation cost of sensors in i^{th} plant for product 'r' for h^{th} high precision machine for t^{th} time period.
INL_{irlt}	Installation cost of sensors in i^{th} plant for product 'r' for l^{th} low precision machine for t^{th} time period.
INM_{irmt}	Installation cost of sensors in i^{th} plant for product 'r' for m^{th} medium precision machine for t^{th} time period.
LM_{irmt}	Fixed setup cost in i^{th} plant for product 'r' for l^{th} low precision machine for t^{th} time period.
MAH_{irht}	Maintenance cost of sensors in i^{th} plant for product 'r' for h^{th} high precision machine for t^{th} time period.
MAL_{irlt}	Maintenance cost of sensors in i^{th} plant for product 'r' for l^{th} low precision machine for t^{th} time period.
MAM_{irmt}	Maintenance cost of sensors in i^{th} plant for product 'r' for m^{th} medium precision machine for t^{th} time period.
MC_{irht}	Fixed setup cost in i^{th} plant for product 'r' for h^{th} high precision machine for t^{th} time period.
MM_{irmt}	Fixed setup cost in i^{th} plant for product 'r' for m^{th} medium precision machine for t^{th} time period.
PC_{irt}	Production cost of i^{th} plant for r^{th} product in t^{th} time period.

PQ_{irt}	Maximum production capacity in i^{th} plant for r^{th} product for t^{th} time period.
PTH_{irht}	Processing time in i^{th} plant for product 'r' for h^{th} high precision machine for t^{th} time period.
PTL_{irlt}	Processing time in i^{th} plant for product 'r' for l^{th} low precision machine for t^{th} time period.
PTM_{irmt}	Processing time in i^{th} plant for product 'r' for m^{th} medium precision machine for t^{th} time period.
QM_{rit}	Unit of r^{th} product remanufactured at i^{th} plant in t^{th} time period.
$RM C_{rit}$	Remanufacturing cost of r^{th} product at i^{th} plant in t^{th} time period.
RR_r	Rate of return per unit of product
SCH_{irht}	IoT sensors deployment cost in i^{th} plant for r^{th} product for h^{th} high precision machine in t^{th} time period.
SCL_{irlt}	Fixed setup machine cost in i^{th} plant for r^{th} product for l^{th} low precision machine in t^{th} time period.
SCM_{irmt}	IoT sensors deployment cost in i^{th} plant for r^{th} product for m^{th} medium precision machine in t^{th} time period.
$TC1_{irjt}$	Transportation cost for shipping a unit of product 'r' from i^{th} plant to j^{th} warehouse for t^{th} time period.
$TC2_{jrkt}$	Transportation cost for shipping a unit of product 'r' from j^{th} warehouse to k^{th} market for t^{th} time period.
$TC3_{rkcct}$	Transportation cost for shipping a unit of product 'r' from k^{th} market to cc^{th} collection center in t^{th} time period
$TC4_{rccdct}$	Transportation cost for shipping a unit of product 'r' from cc^{th} collection center to dc^{th} disassembly center in t^{th} time period

$TC5_{rdcit}$	Transportation cost for shipping a unit of product ‘r’ from dc^{th} disassembly center to i^{th} plant in t^{th} time period
$TC6_{rdct}$	Transportation cost for shipping a unit of product ‘r’ from dc^{th} disassembly center for disposal in t^{th} time period.
UPH_{irht}	Unit cost of sensors in i^{th} plant for product ‘r’ for h^{th} high precision machine for t^{th} time period.
UPL_{irlt}	Unit cost of sensors in i^{th} plant for product ‘r’ for l^{th} low precision machine for t^{th} time period.
UPM_{irmt}	Unit cost of sensors in i^{th} plant for product ‘r’ for m^{th} medium precision machine for t^{th} time period.

List of Decision Variables

$P1_{irht}$	Unit of r^{th} product produced in i^{th} plant from h^{th} high precision machine for t^{th} time period.
$P2_{irmt}$	Unit of r^{th} product produced in i^{th} plant from m^{th} medium precision machine for t^{th} time period.
$P3_{irlt}$	Unit of r^{th} product produced in i^{th} plant from l^{th} low precision machine for t^{th} time period.
$Q1_{irjt}$	Unit of r^{th} product shipped from i^{th} plant to j^{th} warehouse for t^{th} time period.
$Q2_{jrkt}$	Unit of r^{th} product shipped from j^{th} warehouse to k^{th} market in t^{th} time period
$Q3_{rkct}$	Unit of r^{th} product shipped from k^{th} market to cc^{th} collection center in t^{th} time period
$Q4_{rccdct}$	Unit of r^{th} product shipped from cc^{th} collection center to dc^{th} disassembly center in t^{th} time period

- $Q5_{rdcit}$ Unit of r^{th} product shipped from dc^{th} disassembly center to i^{th} plant in t^{th} time period
- $Q6_{rdct}$ Unit of r^{th} product shipped from dc^{th} disassembly center for disposal in t^{th} time period

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
AM	Additive Manufacturing
ANP	Analytical Network Process
AR	Augmented Reality
BDA	Big data analytics
BDBA	Big data business analytics
BWM	Best Worst Method
CAD	Computer Aided Design
CC	Cloud Computing
CE	Circular Economy
CE-SEM	Circular Economy-Supply Chain
CIoT	Consumer Internet of Things
CMfg	Cloud Manufacturing
CPS	Cyber-Physical System
CPPS	Cyber-Physical Production System
CSC	Container Supply Chain
DEMATEL	Decision Making Trial and Evaluation Laboratory
DMDI	Digital Manufacturing and Design Innovation
DT	Digital Twins
EFA	Exploratory Factor Analysis
ElIoT	Environment Internet of Things
ELECTRE	ELimination and Choice Expressing Reality
EoL	End-of-Life
ERP	Enterprise Resource Planning
FA	Factor Analysis
FEM	Finite Element Method
FEM ¹	Fuzzy Evaluation Method
GIWSNs	Group-based Industrial Wireless Sensor Network

I&PP	Inventory & Production Planning
IaaS	Infrastructure as a Service
IIoT	Industrial Internet of Things
IMS	Intelligent Manufacturing System
IoT	Internet of Things
ISM	Interpretive Structural Modeling
IT	Information Technology
IVFS	Interval-Valued Fuzzy Sets
KMO	Kaiser-Meyer-Olkin
LISA	Line Information System Architecture
LSCM	Logistics and Supply Chain Management
LWCM	Light Weight Collaborative Manufacturing
M2M	Machine to Machine
MCDM	Multi-Criteria Decision Making
MES	Manufacturing Execution System
MICMAC	Matriced' Impacts Croised-Multiplication Applique and Classment
MILP	Mixed Integer Linear Programming
MOILP	Multi-Objective Integer Linear Programming
NIST	National Institute of Standards and Technology
PaaS	Platform as a Service
PCA	Principal Component Analysis
PLM	Product Lifecycle Management
PLS-SEM	Partial Least Square- Structural Equation Modeling
PSA	Product Service Architecture
PSS	Product Service System
QoS	Quality of Service
RAMI4.0	Reference Architecture Model Industrie 4.0
RBV	Resource Based View
RCS	Resilience Control System
RFID	Radio-frequency Identification

RL	Reverse Logistics
SaaS	Software as a Service
SCs	Supply Chains
SCA	Supply Chain Analytics
SCM	Supply Chain Management
SEM	Structural Equation Modelling
SDN	Software Defined Networking
SLR	Systematic Literature Review
SPC	Sustainable Production and Consumption
SSIM	Structural Self-Interaction Matrix
SWOT	Strength Weakness Opportunites Threat
TBL	Triple Bottom Line
TOE	Technology-Organization-Environment
VR	Virtual Reality
WSAN	Wireless Sensor Actuator Network
WSN	Wireless Sensor Network