

**MODELING AND ANALYSIS FOR IMPLEMENTING
INDUSTRY 4.0 IN INDIAN MANUFACTURING SECTOR**

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**MODELING AND ANALYSIS FOR IMPLEMENTING
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By

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CERTIFICATE

This is to certify that the thesis titled “**Modeling and analysis for implementing Industry 4.0 in Indian manufacturing sector**”, being submitted by **Mr. Veepan Kumar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy (Ph.D.)** is a bonafide record of original research work carried out by him. He has worked under our supervision and has fulfilled the requirements for the submission of this thesis, which is in accordance with the standards required for a Ph.D. degree at this institute. The results presented 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

Over time, practitioners have adopted different manufacturing strategies to address production-related issues in order to remain globally competitive. The manufacturing industry is currently experiencing the fourth industrial revolution, which is marked by new advances in information and communication technology (ICT) infrastructure. With advancements in ICT, new technological paradigms in manufacturing such as Industry 4.0, digital manufacturing, and smart manufacturing have emerged. Industry 4.0 is a high-tech digitalization concept introduced by the German government in 2011 to digitally integrate existing production systems through the use of enabling technologies. These technologies include the Internet of Things (IoT), cloud, cybersecurity, blockchain, robots, big data analytics, simulation, augmented reality, and 3D printing (or additive manufacturing). Industry 4.0 has been recognized as a key strategy for enhancing the quality, productivity, sustainability, and efficiency of manufacturing companies. Despite the fact that Industry 4.0 implementation has become a vital factor in manufacturing industries across the developed countries, there has been little attention in the literature to examine the various relevant aspects related to Industry 4.0 implementation in the context of emerging economies like India. To address this critical gap in the literature, the present research attempts to analyze the relevant implementation variables of Industry 4.0 for the Indian manufacturing organization through undertaking six different studies.

The first study aims at proposing a conceptual framework for managing the implementation issues of Industry 4.0 using soft system methodology (SSM). According to the SSM analysis, the three target areas were identified as the most critical for managing the root causes of Industry 4.0 implementation. These areas include a digital readiness assessment system, an implementation management system (which includes a technological infrastructure system, workforce development system, and regulatory mechanism system), and Industry 4.0 enabled manufacturing system. The second study aims at investigating and validating the interrelationships for both enablers and barriers of Industry 4.0. Hierarchical structural models based on interpretive structural modeling (ISM) were developed for the identified enablers and barriers. Furthermore, PLS-SEM was used to statistically validate the

interrelationships represented by the ISM diagram, and analysis revealed that enablers and barriers with strategic orientation have the most influence on Industry 4.0 implementation. The third study proposes a framework based on a graph-theoretic approach (GTA) for evaluating the intensity of barriers in the implementation of Industry 4.0. The GTA results revealed that the considered case company is most significantly impacted by organizational, strategic, technological, and infrastructural barriers. In contrast, it is least affected by socio-cultural barriers and legal barriers. In addition, a normalized scale was developed to assess the level of preparedness of the considered case company for implementing Industry 4.0. The fourth study proposed an integrated research framework based on a modified SWARA-WASPAS methodology to prioritize the strategies for mitigating the impact of Industry 4.0 barriers. ‘Commitment from top management towards Industry 4.0 implementation’, ‘Framing of a strategic roadmap for Industry 4.0 implementation’ and ‘Align people, process and technology for effective change management’ were obtained as important strategies for Industry 4.0 implementation. The fifth study proposed a hybrid research framework based on the Neutrosophic AHP and Neutrosophic CoCoSo methodology to prioritize the Industry 4.0 performance outcomes realized due to the adoption of its enablers. ‘Improved responsiveness to market conditions in today’s competitive business environment’, ‘Enhanced competitiveness and better market share’, ‘Reduction in manufacturing waste and environment sustainability’, ‘Better product quality, through smart management of production process’ were obtained as top-ranked performance outcomes of Industry 4.0.

In the sixth study, the SAP-LAP (situation-actor-process and learning-action-performance) approach was employed to identify the various variables influencing Industry 4.0 implementation. The main Industry 4.0 actors and actions to be performed by them have been prioritized using an efficient interpretative ranking approach (e-IRP). Finally, a framework for establishing Industry 4.0 platform is proposed, stressing the involvement of different government agencies, industry associations, private and public companies in addressing the primary criteria of Industry 4.0.

The findings obtained from this research offer valuable insights to the practitioners, researchers, and policymakers engaged in the implementation of Industry 4.0. An integrated framework proposed in this research would enable them in understanding the prioritized sequence of strategies and performance outcomes of Industry 4.0, interrelationships of both

Industry 4.0 enablers and barriers, intensity or overall impact of different categories of barriers, and role of key stakeholders in coordinating the required activities related to Industry 4.0 implementation. A thorough understanding of each implementation variable would assist practitioners in developing a well-defined strategy roadmap for the effective implementation of Industry 4.0.

सार

समय के साथ, उत्पादकों ने विश्व स्तर पर प्रतिस्पर्धी बने रहने के लिए उत्पादन से संबंधित मुद्दों को हल करने के लिए विभिन्न विनिर्माण रणनीतियों को अपनाया है। विनिर्माण उद्योग वर्तमान में चौथी औद्योगिक क्रांति का अनुभव कर रहा है, जो सूचना और संचार प्रौद्योगिकी (आईसीटी) के बुनियादी ढांचे में नई प्रगति से चिह्नित है। आईसीटी में प्रगति के साथ, उद्योग 4.0, डिजिटल विनिर्माण और स्मार्ट विनिर्माण जैसे विनिर्माण में नए तकनीकी प्रतिमान उभरे हैं। उद्योग 4.0 एक उच्च तकनीक डिजिटलीकरण अवधारणा है जिसे जर्मन सरकार द्वारा 2011 में सक्षम प्रौद्योगिकियों के उपयोग के माध्यम से मौजूदा उत्पादन प्रणालियों को डिजिटल रूप से एकीकृत करने के लिए पेश किया गया था। इन तकनीकों में इंटरनेट ऑफ थिंग्स (IoT), क्लाउड, साइबर सुरक्षा, ब्लॉकचेन, रोबोट, बिग डेटा एनालिटिक्स, सिमुलेशन, संवर्धित वास्तविकता और 3D प्रिंटिंग (या एडिटिव मैन्युफैक्चरिंग) शामिल हैं। उद्योग 4.0 को विनिर्माण कंपनियों की गुणवत्ता, उत्पादकता, स्थिरता और दक्षता बढ़ाने के लिए एक प्रमुख रणनीति के रूप में मान्यता दी गई है। इस तथ्य के बावजूद कि उद्योग 4.0 का कार्यान्वयन विकसित देशों में उद्योगों के निर्माण में एक महत्वपूर्ण कारक बन गया है; भारत जैसी उभरती अर्थव्यवस्थाओं के संदर्भ में उद्योग 4.0 कार्यान्वयन से संबंधित विभिन्न प्रासंगिक पहलुओं की जांच करने के लिए साहित्य में बहुत कम ध्यान दिया गया है। साहित्य में इस महत्वपूर्ण अंतर को दूर करने के लिए, वर्तमान शोध छह अलग-अलग अध्ययनों के माध्यम से भारतीय विनिर्माण संगठन के लिए उद्योग 4.0 के प्रासंगिक कार्यान्वयन के विश्लेषण करने का प्रयास करता है।

पहले अध्ययन का उद्देश्य सॉफ्ट सिस्टम पद्धति (एसएसएम) का उपयोग करके उद्योग 4.0 के कार्यान्वयन के मुद्दों के प्रबंधन के लिए एक वैचारिक ढांचे का प्रस्ताव करना है। इन क्षेत्रों में एक डिजिटल तत्परता मूल्यांकन प्रणाली, कार्यान्वयन प्रबंधन प्रणाली (जिसमें तकनीकी बुनियादी ढांचा प्रणाली, कार्यबल विकास प्रणाली और नियामक तंत्र प्रणाली शामिल है), और उद्योग 4.0 सक्षम विनिर्माण प्रणाली शामिल हैं। दूसरे अध्ययन का उद्देश्य उद्योग 4.0 के प्रवर्तकों और बाधाओं दोनों के लिए अंतर्संबंधों की जांच और सत्यापन करना है। व्याख्यात्मक संरचनात्मक मॉडलिंग (आईएसएम) पर आधारित पदानुक्रमित संरचनात्मक मॉडल पहचाने गए एनबलर्स और बाधाओं के लिए विकसित किए गए थे। इसके अलावा, PLS-SEM का उपयोग ISM आरेख द्वारा दर्शाए गए अंतर्संबंधों को

सांख्यिकीय रूप से मान्य करने के लिए किया गया था, विश्लेषण से पता चला कि रणनीतिक अभिविन्यास वाले इनेबलर्स और बाधाओं का उद्योग 4.0 कार्यान्वयन पर सबसे अधिक प्रभाव है। तीसरा अध्ययन उद्योग 4.0 के कार्यान्वयन में बाधाओं की तीव्रता के मूल्यांकन के लिए ग्राफ-सैद्धांतिक दृष्टिकोण (जीटीए) पर आधारित एक रूपरेखा का प्रस्ताव करता है। GTA के परिणामों से पता चला है कि विचाराधीन केस कंपनी संगठनात्मक, रणनीतिक, तकनीकी और अवसंरचनात्मक बाधाओं से सबसे अधिक प्रभावित है। इसके विपरीत, यह सामाजिक-सांस्कृतिक बाधाओं और कानूनी बाधाओं से कम से कम प्रभावित होता है। इसके अलावा, उद्योग 4.0 को लागू करने के लिए विचाराधीन कंपनी की तैयारी के स्तर का आकलन करने के लिए एक सामान्यीकृत पैमाना विकसित किया गया था। चौथे अध्ययन में उद्योग 4.0 बाधाओं के प्रभाव को कम करने के लिए रणनीतियों को प्राथमिकता देने के लिए संशोधित स्वरा-वासपास पद्धति पर आधारित एक एकीकृत अनुसंधान ढांचे का प्रस्ताव रखा। उद्योग 4.0 कार्यान्वयन के लिए शीर्ष प्रबंधन से प्रतिबद्धता', 'उद्योग 4.0 कार्यान्वयन के लिए एक रणनीतिक रोडमैप तैयार करना' और 'लोगों को संरेखित करना, प्रभावी परिवर्तन प्रबंधन के लिए प्रक्रिया और प्रौद्योगिकी' उद्योग 4.0 कार्यान्वयन के लिए महत्वपूर्ण रणनीतियों के रूप में प्राप्त किए गए थे। पांचवें अध्ययन ने उद्योग 4.0 के प्रदर्शन परिणामों को प्राथमिकता देने के लिए न्यूट्रोसोफिक एएचपी और न्यूट्रोसोफिक कोकोसो पद्धति पर आधारित एक हाइब्रिड शोध ढांचे का प्रस्ताव दिया, जो इसके समर्थकों को अपनाने के कारण प्राप्त हुआ। 'आज के प्रतिस्पर्धी कारोबारी माहौल में बाजार की स्थितियों के लिए बेहतर प्रतिक्रिया', 'बढ़ी हुई प्रतिस्पर्धा और बेहतर बाजार हिस्सेदारी', 'विनिर्माण अपशिष्ट और पर्यावरण स्थिरता में कमी', 'उत्पादन प्रक्रिया के स्मार्ट प्रबंधन के माध्यम से बेहतर उत्पाद की गुणवत्ता' उद्योग 4.0 के शीर्ष क्रम के प्रदर्शन परिणामों के रूप में प्राप्त किए गए थे।

छठे अध्ययन में, SAP-LAP दृष्टिकोण को उद्योग 4.0 कार्यान्वयन को प्रभावित करने वाले विभिन्न चरों की पहचान करने के लिए नियोजित किया गया था। मुख्यतः उद्योग 4.0 पेशेवरों और उनके द्वारा किए जाने वाले कार्यों को एक कुशल व्याख्यात्मक रैंकिंग दृष्टिकोण (ई-आईआरपी) का उपयोग करने को प्राथमिकता दी गई है। अंत में, उद्योग 4.0 के प्राथमिक मानदंडों को संबोधित करने में विभिन्न सरकारी एजेंसियों, उद्योग संघों, निजी और सार्वजनिक कंपनियों की भागीदारी पर बल देते हुए, उद्योग 4.0 मंच की स्थापना के लिए एक रूपरेखा प्रस्तावित है।

इस शोध से प्राप्त निष्कर्ष उद्योग 4.0 के कार्यान्वयन में लगे पेशेवरों, शोधकर्ताओं और नीति निर्माताओं को मूल्यवान अंतर्दृष्टि प्रदान करते हैं। इस शोध में प्रस्तावित एक एकीकृत ढांचा उन्हें

उद्योग 4.0 की रणनीतियों और प्रदर्शन परिणामों के प्राथमिकता क्रम को समझने में सक्षम बनाएगा। उद्योग 4.0 सक्षमकर्ताओं और बाधाओं दोनों के अंतर्संबंधों, बाधाओं की विभिन्न श्रेणियों की तीव्रता या समग्र प्रभाव और समन्वय में प्रमुख हितधारकों की भूमिका को समझने में सक्षम होगा। प्रत्येक कार्यान्वयन चर की गहन समझ से व्यवसायियों को उद्योग 4.0 के प्रभावी कार्यान्वयन के लिए एक अच्छी तरह से परिभाषित रणनीति रोडमैप विकसित करने में सहायता मिलेगी।

TABLE OF CONTENTS

CERTIFICATE.....	i
ACKNOWLEDGEMENTS.....	ii
ABSTRACT.....	iv
श्री.....	vii
TABLE OF CONTENTS.....	x
LIST OF FIGURES	xx
LIST OF TABLES.....	xxii
LIST OF ABBREVIATIONS.....	xxvi
CHAPTER 1 INTRODUCTION.....	1
1.1 Overview	1
1.2 Background of the study.....	1
1.3 Evolution of Industry 4.0.....	4
1.4 Technologies of Industry 4.0	5
1.5 Scope of the Study.....	8
1.6 Motivations behind the present research work	9
1.7 Research questions	11
1.8 Research objectives	12
1.9 Research methodology.....	13
1.10 Organization of the Thesis	14
1.11 Concluding remarks	17
CHAPTER 2 LITERATURE REVIEW.....	18
2.1 Overview	18

2.2	Introduction	18
2.3	Systematic literature review (SLR) analysis of Industry 4.0	20
2.3.1	Collection of the research articles	20
2.3.2	Refinement of the selected research articles	21
2.3.3	Descriptive analysis for bibliographic details.....	21
2.3.4	Selection of categories	22
2.3.5	Categorical analysis of the selected articles.....	22
2.3.6	Results and conclusions.....	22
2.4	Findings based on descriptive analysis for Industry 4.0	23
2.4.1	Year-wise publication trends of Industry 4.0 articles	23
2.4.2	Journal wise distribution of research papers	24
2.4.3	Author wise distribution	25
2.4.4	Country-wise distribution of research articles	26
2.5	Review of various variables/factors influencing the implementation of Industry 4.0.....	28
2.5.1	Review of Industry 4.0 enablers/ critical success factors (CSFs) for sustainable manufacturing	28
2.5.2	Review of Industry 4.0 critical success factors (CSFs) /enablers	34
2.5.3	Review of Industry 4.0 barriers	37
2.5.4	Review of Industry 4.0 strategies	46
2.5.5	Review of Industry 4.0 performance outcomes.....	49
2.6	Research gaps.....	56
2.7	Concluding remarks	58
CHAPTER 3 RESEARCH DESIGN AND METHODOLOGY.....		59
3.1	Overview	59
3.2	Introduction	59

3.3	Research design	60
3.4	Research methodology.....	63
3.4.1	Soft system methodology (SSM)	63
3.4.2	Interpretive structural modeling (ISM).....	66
3.4.3	Partial least square-structural equation modeling (PLS-SEM)	66
3.4.4	Modified stepwise weight assessment ratio analysis (SWARA) method	67
3.4.5	Weighted aggregated sum product assessment (WASPAS).....	68
3.4.6	Graph-theoretic approach (GTA)	68
3.4.7	Situation actors processes-learning actions performances	69
3.4.8	Efficient-Interpretive Ranking Process (e-IRP)	70
3.4.9	Neutrosophic-AHP (N-AHP).....	70
3.4.10	Neutrosophic combined compromised solution (N-CoCoSo).....	71
3.4.11	Stakeholder theory.....	71
3.5	Mapping of research objective to research methodology.....	72
3.6	Justification for using qualitative and quantitative approaches.....	73
3.6.1	Rationale for employing different research methodologies catering to each research objective	74
3.6.1.1	Soft system methodology for research objective one (RO1).....	75
3.6.1.2	An integrated approach based on questionnaire survey, ISM and PLS-SEM methods for research objective two (RO2)	75
3.6.1.3	Graph theoretic approach for research objective three (RO3).....	76
3.6.1.4	An integrated approach based on modified SWARA and WASPAS for research objective four (RO4)	77
3.6.1.5	An integrated approach based on Neutrosophic AHP and CoCoSo for research objective five (RO5).....	77
3.6.1.6	An integrated approach based on stakeholder theory, SAP-LAP and e-IRP for research objective six (RO6).....	78

3.7	Justification for case examination of Indian auto-component manufacturing organization.....	80
3.8	Concluding remarks	81

CHAPTER 4 A CONCEPTUAL FRAMEWORK FOR THE MANAGEMENT OF INDUSTRY 4.0 IMPLEMENTATION ISSUES..... 82

4.1	Overview	82
4.2	Introduction and Problem Description.....	82
4.3	Solution Methodology	86
4.4	Application of Soft System Methodology for Industry 4.0 implementation in Indian auto-component manufacturing organization	89
4.4.1	Case analysis	92
4.4.1.1	Phase I: Developing a symptom map to analyse the current problem scenario for the considered case organization	92
4.4.1.2	Phase II: Developing a rich picture to highlight the challenges among the functional domains of the considered case organization while implementing Industry 4.0.....	95
4.4.1.3	Phase III: Identification of root causes of the current problem scenario of the considered case company	96
4.4.1.4	Phase V: Development of an initial conceptual model and final implementable model for Industry 4.0 in the case company under consideration	105
4.4.1.5	Phase VI: Development of implementation management system framework for Industry 4.0 in the case company under consideration.....	110
4.5	Discussions	111
4.6	Concluding remarks	116

CHAPTER 5	EXAMINING AND VALIDATING THE CAUSAL	
RELATIONSHIPS OF INDUSTRY 4.0 ENABLERS AND BARRIERS		118
5.1	Overview	118
5.2	Introduction	119
5.3	Problem Description.....	124
5.4	Identification of Industry 4.0 enablers and barriers and hypothesis development	125
5.5	Solution methodology.....	127
5.5.1	Interpretive structural modeling (ISM).....	128
5.5.2	Questionnaire-based survey	129
5.5.3	PLS-SEM.....	129
5.6	Analyzing the relationships of Industry 4.0 enablers and barriers in the manufacturing organization	130
5.6.1	Identification of Industry 4.0 factors (i.e., enablers and barriers) through literature and validation using a questionnaire-based survey	130
5.6.1.1	Design of the questionnaire.....	130
5.6.1.2	Administration of the questionnaire.....	131
5.6.2	Modeling the interrelationships of Industry 4.0 factors (enablers and barriers) through the development of a hierarchical structural model using ISM.....	133
5.6.2.1	ISM model development	133
5.6.3	Validation of interrelationships of Industry 4.0 enablers and barriers established through ISM based model using PLS-SEM	146
5.6.3.1	Determining the underlying constructs among the finalized Industry 4.0 enablers and barriers using exploratory factor analysis	146
5.6.3.2	Formulation of hypotheses for constructs of Industry 4.0 enablers and barriers obtained using EFA.....	150
5.6.3.3	Evaluation of measurement model.....	155
5.6.3.4	Assessment of structural model.....	159

5.7	Discussion of the results	169
5.8	Concluding remarks	176

CHAPTER 6 AN EVALUATION FRAMEWORK TO QUANTIFY THE IMPACT OF INDUSTRY 4.0 BARRIERS 179

6.1	Overview	179
6.2	Introduction	179
6.3	Problem Description.....	183
6.4	Identification and finalization of Industry 4.0 barriers.....	185
6.5	Solution Methodology	187
6.6	An application of the proposed framework.....	188
6.6.1	Problem identification and background of the case company.....	188
6.6.2	Case analysis	190
6.7	Discussion.....	205
6.7.1	A normalized scale for Industry 4.0 barrier intensity index	209
6.8	Concluding remarks	212

CHAPTER 7 PRIORITIZING THE STRATEGIES TO OVERCOME THE BARRIERS IN INDUSTRY 4.0 214

7.1	Overview	214
7.2	Introduction	215
7.3	Problem Description.....	218
7.4	Solution Methodology	220
7.4.1	Modified Stepwise Weight Assessment Ratio Analysis (SWARA) Method	221
7.4.2	WASPAS methodology	223
7.5	Proposed research framework.....	225

7.6	Application of the proposed research framework to an Indian auto component manufacturing company	226
7.6.1	Problem identification and background of case company	226
7.6.2	Case analysis	228
7.6.2.1	Phase 1: Identification and finalization of barriers and strategies of Industry 4.0 implementation	228
7.6.2.2	Phase 2: Determining the relative weights of barriers of Industry 4.0 using the modified SWARA method	232
7.6.2.3	Phase 3: Obtaining the rank of Industry 4.0 implementation strategies using WASPAS method.....	234
7.7	Discussion of the results	242
7.8	Concluding remarks	251

CHAPTER 8 PRIORITIZING THE PERFORMANCE OUTCOMES REALIZED DUE TO ADOPTION OF INDUSTRY 4.0 ENABLERS..... 253

8.1	Overview	253
8.2	Introduction	254
8.3	Problem Description.....	258
8.4	Solution Methodology	260
8.4.1	Fundamental concepts of Neutrosophic sets and their preliminaries	260
8.4.2	Neutrosophic-AHP (N-AHP).....	264
8.4.3	Neutrosophic combined compromised solution (N-CoCoSo).....	268
8.5	Proposed research framework.....	273
8.6	Application of the proposed research framework to an Indian auto component manufacturing company	275
8.6.1	Problem identification and background of the case company	275
8.6.2	Analysis of the case company with concern to the proposed research framework	277

8.6.2.1	Phase 1: Identification and finalization of enablers and performance outcomes of Industry 4.0 implementation	278
8.6.2.2	Phase 2: Calculation of the relative weights of Industry 4.0 enablers using Neutrosophic Analytical Hierarchy Process (N-AHP).....	282
8.6.2.3	Phase 3: Prioritization of the Performance outcomes, realized due to adoption of Industry 4.0 enablers using Neutrosophic Combined Compromise Solution (N-CoCoSo)	285
8.7	Results and discussions.....	286
8.8	Concluding remarks	299

CHAPTER 9 A FRAMEWORK FOR ESTABLISHING INDUSTRY 4.0 PLATFORM FOR THE INDIAN MANUFACTURING ORGANIZATION 305

9.1	Overview	305
9.2	Introduction	306
9.3	Problem description	310
9.4	Solution methodology.....	311
9.4.1	Stakeholder (SH) Theory.....	312
9.4.2	SAP-LAP methodology.....	313
9.4.3	Efficient-Interpretive Ranking Process (e-IRP)	317
9.5	Steps for integrated SAP-LAP and e-IRP approach	318
9.6	Application of the proposed framework to establish Industry 4.0 Platform for the manufacturing organization.....	321
9.6.1	Review of elements of SAP-LAP model for Industry 4.0 based on the literature.....	322
9.6.1.1	Situation.....	322
9.6.1.2	Actors	323
9.6.1.3	Process	324
9.6.1.4	Learning.....	325

9.6.1.5	Actions	327
9.6.1.6	Performance	329
9.7	Framework for developing Industry 4.0 Platform.....	334
9.7.1	Need of Platform for Industry 4.0	336
9.7.2	Regulating bodies for proposed Industry 4.0 Platform	337
9.8	Discussions	341
9.8.1	Actors w.r.t processes	342
9.8.2	Actions w.r.t performances	347
9.9	Concluding remarks	353
CHAPTER 10 RESEARCH SUMMARY AND CONCLUSIONS		361
10.1	Overview	361
10.2	Introduction	361
10.3	Summary of research findings	367
10.4	Significant research contributions: Theoretical and Managerial Implications & Recommendations	374
10.4.1	Theoretical implications of the research.....	374
10.4.2	Managerial implications of the research.....	377
10.5	Limitations of the research.....	380
10.6	Scope for future research.....	382
REFERENCES.....		385
APPENDICES		412-436
APPENDIX-I Questionnaire for Industry 4.0 enablers and barriers		412
APPENDIX-II Questionnaire for evaluating the intensity of Industry 4.0 barriers		417
APPENDIX-III Questionnaire for prioritizing the strategies to overcome Industry 4.0 barriers		421

APPENDIX-IV Questionnaire for Industry 4.0 performance outcomes realized due to adoption of its enablers	427
APPENDIX-V Working details for dominance relation analysis as per efficient-interpretive ranking process for Industry 4.0 implementation variables (i.e. Actors' w.r.t. Processes and actions w.r.t. Performance).....	433
LIST OF PUBLICATIONS BASED ON THESIS.....	437
BIODATA OF THE AUTHOR	438

LIST OF FIGURES

Figure 1.1	Overview of different phases of Industrial Revolution	4
Figure 1.2	The nine emerging technologies of Industry 4.0	8
Figure 2.1	Year-wise distribution of Industry 4.0 research articles	24
Figure 3.1	Research design for different studies	62
Figure 3.2	Research flow diagram of the thesis	65
Figure 4.1	Seven-stage involved in Soft System Methodology (SSM)	88
Figure 4.2	A symptom map illustrating Industry 4.0 implementation issues related to each functional domain of the considered case company	98
Figure 4.3	A rich picture depicting the implementation issues of Industry 4.0 across various functional domains in relation to one another	99
Figure 4.4	Initial conceptual model for implementing Industry 4.0	108
Figure 4.5	Final implementable model for Industry 4.0	109
Figure 4.6	Proposed implementation management system framework for Industry 4.0	112
Figure 5.1	Research design adopted for the present study	133
Figure 5.2	ISM model for Industry 4.0 enablers	144
Figure 5.3	ISM model for Industry 4.0 barriers	145
Figure 5.4	Hypothesized model for Industry 4.0 enablers	152
Figure 5.5	Hypothesized model for Industry 4.0 barriers	154
Figure 5.6	Measurement model for Industry 4.0 enablers, illustrating outer loadings values	157
Figure 5.7	Measurement model for Industry 4.0 barriers, illustrating outer loadings values	158
Figure 5.8	Structural model for Industry 4.0 enablers, illustrating path coefficient (β) and adjusted R^2 values	167

Figure 5.9	Structural model for Industry 4.0 barriers, illustrating path coefficient (β) and adjusted R^2 values.....	168
Figure 6.1	Schematic diagram of the proposed research flow	189
Figure 6.2	Schematic representation of Industry 4.0 Barriers.....	194
Figure 6.3	Digraph of main criteria barriers of Industry 4.0.....	194
Figure 6.4	Digraph of strategic barriers	195
Figure 6.5	Digraph of organizational barriers.....	195
Figure 6.6	Digraph of technological and infrastructural barriers.....	196
Figure 6.7	Digraph of legal barriers	196
Figure 6.8	Digraph of Socio-cultural barriers	197
Figure 6.9	I4.0BII value comparison for the case company with the best-case scenario	208
Figure 7.1	Proposed research framework for prioritizing the implementation strategies of Industry 4.0 to overcome its barriers.....	227
Figure 7.2	Results of sensitivity analysis	251
Figure 8.1	Proposed research framework for prioritizing the performance outcomes of Industry 4.0, realized due to adoption of its enablers	274
Figure 8.2	(a) Result of sensitivity analysis (Ki Value) (b) Result of sensitivity analysis (Ki Value) (c) Result of sensitivity analysis (Ki Value).....	301
Figure 9.1	Framework for developing Industry 4.0 Platform	343

LIST OF TABLES

Table 2.1	Top twenty journals of published literature on Industry 4.0.....	24
Table 2.2	Authors wise distribution of the research papers.....	26
Table 2.3	Country-wise distribution of Industry 4.0 research articles.....	27
Table 2.4	List of enablers identified for Industry 4.0 implementation to achieve sustainability in manufacturing.....	32
Table 2.5	List of enablers finalized for Industry 4.0.....	38
Table 2.6	List of barriers finalized for Industry 4.0.....	43
Table 2.7	List of finalized Industry 4.0 strategies	50
Table 2.8	The performance outcomes (POs) derived due to adoption of Industry 4.0 enablers.....	54
Table 3.1	Mapping of research objectives with research methodology.....	72
Table 4.1	Identification of the root causes based on the critical issues of Industry 4.0 that exist in relation to one another across the various functional domains.....	100
Table 4.2	CATWOE approach for determining root definition for developing Industry 4.0 enabled manufacturing ecosystem.....	103
Table 5.1	Initial reachability matrix for Industry 4.0 enablers	137
Table 5.2	Initial reachability matrix for Industry 4.0 barriers	138
Table 5.3	Final reachability matrix for Industry 4.0 enablers.....	139
Table 5.4	Final reachability matrix for Industry 4.0 barriers.....	140
Table 5.5	A summary of all iterations related to FRM level partitioning of Industry 4.0 enablers.....	141
Table 5.6	A summary of all iterations related to FRM level partitioning of Industry 4.0 barriers.....	142
Table 5.7	Results of Exploratory Factor Analysis (EFA) for Industry 4.0 enablers	148

Table 5.8	Results of Exploratory Factor Analysis (EFA) for Industry 4.0 barriers... 149
Table 5.9	Statistics results of the measurement model for Industry 4.0 enablers..... 160
Table 5.10	Statistics results of the measurement model for Industry 4.0 barriers..... 161
Table 5.11	Fornell-Larcker Criterion analysis for examining discriminant validity of Industry 4.0 enablers 163
Table 5.12	Fornell-Larcker Criterion analysis for examining discriminant validity of Industry 4.0 barriers..... 165
Table 5.13	Results of hypothesis testing for Industry 4.0 enablers: model path coefficients (β), t-statistics, p-values 166
Table 5.14	Results of hypothesis testing for Industry 4.0 barriers: model path coefficients (β), t-statistics, p-values 166
Table 6.1	VPM representation of all sub-criteria barriers of Industry 4.0..... 200
Table 6.2	Permanent function value for sub-criteria barriers of Industry 4.0..... 201
Table 6.3	Permanent function values for best-case and worst-case scenarios..... 207
Table 6.4	Categorization of organizations based on normalized I4.0BII value..... 210
Table 6.5	Normalized scale for I4.0BII values at different scenarios 210
Table 6.6	Normalized I4.0BII values for sub-criteria barriers at different scenarios..... 211
Table 7.1	Application of SWARA-WASPAS methods..... 220
Table 7.2	Determining the weights for major criteria barriers 233
Table 7.3	Obtaining the weights for (SB), OB, TIB, LB and SCB 233
Table 7.4	The final ranking of Industry 4.0 barriers..... 235
Table 7.5	Obtaining the decision matrix (Step1)..... 236
Table 7.6	Obtaining the normalized decision matrix (Step 2)..... 237
Table 7.7	Obtaining the total relative importance values for summarizing part (i.e. WSM) $Q_i(1)$ (Step3a)..... 238
Table 7.8	Obtaining total relative importance values for multiplication part (i.e. WPM) $Q_i(2)$ (Step3b)..... 239

Table 7.9	Obtaining (Q_i) total relative significance values for the alternatives (Step 4)	240
Table 7.10	Priority list of strategies for Industry 4.0	241
Table 7.11	Sensitivity analysis with respect to marginal changes in criteria weight ..	250
Table 8.1	Linguistic variable scale based on the triangular Neutrosophic number form	266
Table 8.2	Random Index value (Saaty1980).....	268
Table 8.3	Determining the weights for major criteria enablers	283
Table 8.4	Obtaining the weights for (SE), OE, TIE, FE and SCE.....	283
Table 8.5	Final ranking of enablers for implementing Industry 4.0	284
Table 8.6	Developing the initial decision matrix after converting the Neutrosophic Triangular numbers into Crisp numbers	288
Table 8.7	Developing the normalized decision matrix	289
Table 8.8	Determining total of the weighted comparability sequence matrix for the Pos (S_i)	290
Table 8.9	Obtaining the whole of the power weight of comparability sequences matrix for the POs (P_i).....	291
Table 8.10	Final ranking of POs based on assessment value K_i	292
Table 8.11	Sensitivity analysis results	300
Table 9.1	Recent applications of the SAP-LAP method.....	314
Table 9.2	Development of questions/queries to define SAP-LAP sub-elements for Industry 4.0 implementation	331
Table 9.3	Development of Cross-interaction matrix (CIM) for actors w.r.t processes	347
Table 9.4	Development of Interpretive matrix for actors w.r.t processes.....	350
Table 9.5	Dominance relation analysis of actors w.r.t processes	352
Table 9.6	Prioritization of actors based on Dominance index (DI) value	353

Table 9.7	Development of Cross-interaction matrix (CIM) of actions w.r.t performances.....	354
Table 9.8	Development of Interpretive matrix for actions w.r.t performance	355
Table 9.9	Dominance relation analysis of actions w.r.t performance.....	358
Table 9.10	Prioritization of actions based on Dominance index (DI) value.....	358
Table 10.1	Mapping of research questions and objectives to research methods	364

LIST OF ABBREVIATIONS

PLS-SEM	Partial Least Square-Structural Equation Modeling
ISM	Interpretive Structural Modeling
N-AHP	Neutrosophic-Analytical Hierarchy Process
N-CoCoSo	Neutrosophic-Combined Compromised Solution
SWARA	Stepwise Weight Assessment Ratio Analysis
WASPAS	Weighted Aggregated Sum Product Assessment
I4.0BII	Industry 4.0 Barrier Intensity Index
I4.0E	Industry 4.0 enablers
I4.0B	Industry 4.0 barriers
SSM	Soft System Methodology
CATWOE	C-Customer, A-Actor, T-Transformation Process, W-Worldview, O-Owner And E-External Environment
IoT	Internet of Thing
CPS	Cyber-Physical System
BDA	Big Data Analytics
GTA	Graph Theoretic Approach
SAP-LAP	S-Situation, A-Actor, P-Process And L-Learning, A-Actions and P- Performance
E-IRP	Efficient-Interpretive Ranking Process
PO	Performance Outcome
ICT	Information And Communications Technology
FIR	Fourth Industrial Revolution
IoS	Internet of Service
IT	Information Technology
AR	Augmented Reality
CB-SEM	Covariance-Based Structural Equation Modeling
SLR	Systematic Literature Review

CSFs	Critical Success Factors
RBWM	Robust Best Worst Method
AHP	Analytical Hierarchy Process
SMEs	Small And Medium Size Enterprises
ANP	Analytical Network Process
SE	Strategic Enablers
OE	Organizational Enablers
TIE	Technical Infrastructural Enablers
SCE	Social-Cultural Enablers
FE	Financial Enablers
SB	Strategic Barriers
OB	Organizational Barriers
TIB	Technological And Infrastructural Enablers
SCB	Social-Cultural Barriers
LB	Legal Barriers
I4.0Es	Industry 4.0 Enablers
UNIDO	United Nations Industrial Development Organization
CE	Circular Economy
SMMEs	Small, Medium And Micro Enterprises
PMs	Performance Measures
KPIs	Key Performance Indicators
SC	Supply Chain
QSC	Quality Scorecard
TBL	Triple Bottom Line
AR	Action Research
R&D	Research And Development
PPC	Production Planning And Control
HR	Human Resource
IPR	Intellectual Property Rights
NGOs	Non-Governmental Organizations
EPR	Extended Producer Responsibility

FMCG	Fast Moving Consumer Goods
SSIM	Self-Structured Interaction Matrix
IRM	Initial Reachability Matrix
FRM	Final Reachability Matrix
EFA	Exploratory Factor Analysis
CR	Composite Reliability
AVE	Average Variance Extracted
AMP	Automotive Mission Plan
PFV	Permanent Function Value
VPM	Variable Permanent Matrix
MCDM	Multi-Criteria Decision Making
WSM	Weighted Sum Method
WPM	Weighted Product Method
FEM	Fuzzy Evaluation Method
SMART	Simple Multi-Attribute Rating Technique
DEMATEL	Decision-Making Trial And Evaluation Laboratory
EM	Entropy Method
IVFSs	Intervals-Valued Fuzzy Sets
PFSs	Pythagorean Fuzzy Sets
HFSs	Hesitant Fuzzy Sets
TNN	Triangular Neutrosophic Numbers
CI	Consistency Index
RI	Random Index
SAW	Simple Additive Weighting
EWP	Exponentially Weighted Product
WEEE	Waste Electrical And Electronics Equipment
CIM	Computer Integrated Manufacturing
CoE	Centre of Excellence
CEF	Common Engineering Facilities
ID	Implicit Dominance
IND	Implicit Non-Dominance

InD	Interpretive Dominance
TD	Transitive Dominance
AND	Adjusted Net Dominance
DI	Dominance Index
ACMA	Automotive Component Manufacturers Association
SIAM	Society of Indian Automobile Manufacturers
CII	Confederation of Indian Industry
SWOT	Strength, Weakness, Opportunity And Threat
QCI	Quality Council of India
SCI	Skill Council of India
NASSCOM	National Association of Software And Service Companies