ROLE OF EMERGING TECHNOLOGIES IN DEALING WITH SUPPLY CHAIN DISRUPTIONS

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ROLE OF EMERGING TECHNOLOGIES IN DEALING WITH SUPPLY CHAIN DISRUPTIONS

by

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Submitted

in fulfilment of the requirements of the degree of

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JUNE 2026

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ABSTRACT

Disruptions have always had a prevalent effect on the supply chain. Natural (Earthquake, Floods and Cyclone etc.) and man-made (Terrorist attack, Cyber-attacks, Transportation attacks and supplier's withdrawal) disruptive events trigger disturbances in supply chain processes, as these events jeopardize the regular flow of material and information. The pandemic has changed the configuration and the way of doing and managing supply chain operations. Practitioners and senior supply chain executives emphasize focusing upon agile and resilient supply chains. This pandemic highlights the vulnerability and loopholes of the supply chain. Technology adoption can be one tool to address all the shortcomings of the supply chain that came into the picture during COVID. This thesis is an attempt to highlight the role of emerging technologies to restructure or construct the supply chain for resilience.

Research starts with analyzing the inter-relationship between the constructs; how technology adoption affects the upstream and downstream supply chains both. Empirical study is used to validate the hypotheses developed between the constructs. Data has been collected from more than two hundred industry professionals who have exhaustive knowledge of inner working environment of that industry. The respondents of this research have seven or more years of work experience. Validity and reliability of the hypotheses is tested using software SPSS and AMOS. After validity and reliability check, SEM is applied to test the proposed hypotheses and evaluate the effect of technology adoption on supply chain flexibility in presence of moderator.

After assessing this, the study focuses upon sustainability aspect of the supply chain. As resilience is sometimes a precondition for sustainability, looking for a sustainability approach is helpful in improving the performance of the supply chain. This study uses bibliometric analysis followed by multi-criteria decision analysis. Bibliometric analysis supports the literature gap of presenting the metaverse as a possible sustainable solution apart from its social

side advantages. This is a case-based study that employs the Best-Worst method and sensitivity analysis to find the best enabler for the adoption of metaverse that promotes sustainability. In this study, sustainability is categorized into 4 main enablers: technological, social, economic and environmental. The outcome of this study shows the metaverse as a transformative solution for advancing sustainability in the apparel supply chain (case study) by addressing key challenges. In this way, the metaverse has the potential to address critical challenges like excess waste generation and counterfeiting.

The thesis further proposes a collaborative framework that can be achieved through industry 5.0. This research highlights the importance of adoption I5.0, as it enables the human-machine collaborative environment. Barriers are identified from the previous literature and uses fuzzy ISM-MICMAC approach to establish the hierarchical relationship between barriers. A diagraph is developed based on the inputs from the industry experts and academicians. Through this research, we are trying to discuss about new industrial revolution and how it transforms the manufacturing industry towards greater production efficiency, more enhanced digitalization and intelligence, more integrated human-machine collaboration, higher product complexity and greater customization flexibility.

After studying the effect of technology adoption on various constructs and qualitatively studying the relationship between barriers and enablers, a simulation approach is explored. Seeing the pandemic, we came to the conclusion that there is a requirement to give attention to the perishable product supply chain. A secure supply chain is the need of today's environment to manage any disruption that affects the supply chain's stability. The purpose of this study is to model the multiple risks and vulnerabilities of the supply chain. By modelling the risk, the behaviour of the supply chain can be assessed and the impact of disruption evaluated. Disruption duration and disruption activity are taken and modelled along the whole supply chain. Both these factors can be varied to understands the system’s behaviour. This study is an

overall glimpse of system risk assessment for improving the supply chain performance and its resilience. The system dynamics model can be used at the SC design and planning stage to estimate the impact of possible disruptions on inventory, cost, transportation, and production processes.

This thesis contributed to the existing body of knowledge through different phases of research work. In the last, the thesis summarized all chapters and provides a significant contribution to academicians, researchers and practitioners.

Keywords: Supply Chain Risk, Supply Chain Resilience, Sustainability, Human-machine collaboration, Simulation, System Dynamics Modelling, COVID-19 pandemic, EFA, CFA, SEM, IPMA, BWM, Fuzzy ISM-MICMAC.

सार

आपूर्ति श्रृंखला पर व्यवधानों (disruptions) का प्रभाव सदैव से ही प्रबल रहा है। प्राकृतिक (जैसे भूकंप, बाढ़ और चक्रवात) और मानव-जनित (जैसे आतंकवादी हमले, साइबर-हमले, परिवहन पर हमले और आपूर्तिकर्ता की वापसी) विघटनकारी घटनाएँ आपूर्ति श्रृंखला प्रक्रियाओं में अस्थिरता उत्पन्न करती हैं, क्योंकि ये घटनाएँ सामग्री और सूचना के नियमित प्रवाह को खतरे में डालती हैं। महामारी ने आपूर्ति श्रृंखला के संचालन की संरचना और उनके प्रबंधन के तरीके को बदल दिया है। व्यवहारकर्ता और वरिष्ठ आपूर्ति श्रृंखला कार्यकारी **चंचल (Agile)** और **सुदृढ़ (Resilient)** आपूर्ति श्रृंखलाओं पर ध्यान केंद्रित करने पर बल देते हैं। इस महामारी ने आपूर्ति श्रृंखला की सुभेद्यता और कमियों को उजागर किया है। प्रौद्योगिकी को अपनाना, COVID-19 के दौरान सामने आई आपूर्ति श्रृंखला की सभी कमियों को दूर करने का एक साधन हो सकता है। यह शोध-प्रबंध सुदृढ़ता के लिए आपूर्ति श्रृंखला के पुनर्गठन या निर्माण में **उभरती प्रौद्योगिकियों** की भूमिका को रेखांकित करने का एक प्रयास है।

शोध का प्रारंभ रचनाओं (constructs) के बीच अंतर्संबंधों का विश्लेषण करने से होता है; यह अध्ययन करता है कि प्रौद्योगिकी को अपनाना, अपस्ट्रीम और डाउनस्ट्रीम दोनों आपूर्ति श्रृंखलाओं को कैसे प्रभावित करता है। रचनाओं के बीच विकसित की गई परिकल्पनाओं (hypotheses) के सत्यापन के लिए **आनुभाविक अध्ययन (Empirical study)** का उपयोग किया जाता है। उद्योग के आंतरिक कार्य वातावरण का विस्तृत ज्ञान रखने वाले दो सौ से अधिक उद्योग पेशेवरों से डेटा एकत्र किया गया है। इस शोध के उत्तरदाताओं के पास सात या उससे अधिक वर्षों का कार्य अनुभव है। परिकल्पनाओं की **वैधता (Validity)** और **विश्वसनीयता (reliability)** का परीक्षण SPSS और AMOS सॉफ्टवेयर का उपयोग करके किया जाता है। वैधता और विश्वसनीयता की जाँच के बाद, प्रस्तावित परिकल्पनाओं का परीक्षण करने और **मध्यस्थ (moderator)** की उपस्थिति में आपूर्ति श्रृंखला लचीलेपन पर प्रौद्योगिकी अपनाने के

प्रभाव का मूल्यांकन करने के लिए **संरचनात्मक समीकरण मॉडलिंग (Structural Equation Modeling - SEM)** लागू किया जाता है।

इसका आकलन करने के बाद, अध्ययन आपूर्ति श्रृंखला के **संपोषणीयता (sustainability)** पहलू पर केंद्रित होता है। चूँकि सुदृढ़ता कभी-कभी संपोषणीयता के लिए एक पूर्व शर्त होती है, इसलिए संपोषणीयता दृष्टिकोण की तलाश आपूर्ति श्रृंखला के प्रदर्शन में सुधार करने में सहायक होती है। यह अध्ययन **ग्रंथसूची विश्लेषण (bibliometric analysis)** के बाद **बहु-मानदंड निर्णय विश्लेषण (multi-criteria decision analysis)** का उपयोग करता है। ग्रंथसूची विश्लेषण, मेटावर्स को उसके सामाजिक पक्ष के लाभों के अतिरिक्त एक संभावित संपोषणीय समाधान के रूप में प्रस्तुत करने के **साहित्य अंतराल (literature gap)** का समर्थन करता है। यह एक **केस-आधारित अध्ययन** है जो संपोषणीयता को बढ़ावा देने वाले मेटावर्स को अपनाने के लिए सर्वश्रेष्ठ **सक्षमता-कारक** को खोजने हेतु **सर्वश्रेष्ठ-सबसे खराब विधि (Best-Worst method - BWM)** और **संवेदनशीलता विश्लेषण (sensitivity analysis)** का उपयोग करता है। इस अध्ययन में, संपोषणीयता को 4 मुख्य सक्षमता-कारकों में वर्गीकृत किया गया है: **तकनीकी, सामाजिक, आर्थिक,** और **पर्यावरण**।

इस अध्ययन का परिणाम मेटावर्स को प्रमुख चुनौतियों का समाधान करके **परिधान आपूर्ति श्रृंखला (apparel supply chain) (केस स्टडी)** में संपोषणीयता को आगे बढ़ाने के लिए एक **रूपांतरकारी समाधान (transformative solution)** के रूप में दर्शाता है। इस प्रकार, मेटावर्स में अत्यधिक अपशिष्ट उत्पादन (excess waste generation) और जालसाजी (counterfeiting) जैसी गंभीर चुनौतियों का समाधान करने की क्षमता है।

यह शोध-प्रबंध आगे एक **सहयोगात्मक ढाँचे (collaborative framework)** का प्रस्ताव करता है जिसे **उद्योग 5.0 (Industry 5.0)** के माध्यम से प्राप्त किया जा सकता है। यह शोध I5.0 को अपनाने के महत्व को रेखांकित करता है, क्योंकि यह **मानव-मशीन सहयोगात्मक वातावरण (human-machine collaborative environment)** को सक्षम बनाता है। पिछली साहित्य से **बाधाओं** की पहचान की जाती

है और बाधाओं के बीच पदानुक्रमित संबंध स्थापित करने के लिए **फ़ज़ी आईएसएम-एमआईसीएमएसी दृष्टिकोण (fuzzy ISM-MICMAC approach)** का उपयोग किया जाता है। उद्योग विशेषज्ञों और शिक्षाविदों से प्राप्त जानकारी के आधार पर एक **दिग्राफ (diagraph)** विकसित किया जाता है। इस शोध के माध्यम से, हम एक नई औद्योगिक क्रांति और यह विनिर्माण उद्योग को अधिक उत्पादन दक्षता, अधिक उन्नत डिजिटलीकरण और बुद्धिमत्ता, अधिक एकीकृत मानव-मशीन सहयोग, उच्च उत्पाद जटिलता और अधिक अनुकूलन लचीलेपन की ओर कैसे रूपांतरित करता है, इस पर चर्चा करने का प्रयास कर रहे हैं।

विभिन्न रचनाओं पर प्रौद्योगिकी अपनाने के प्रभाव का अध्ययन करने और बाधाओं और सक्षमता-कारकों के बीच संबंधों का गुणात्मक अध्ययन करने के बाद, **सिमुलेशन** दृष्टिकोण की खोज की जाती है। महामारी को देखते हुए, हम इस निष्कर्ष पर पहुँचे कि **नष्ट होने वाले उत्पाद (perishable product)** आपूर्ति श्रृंखला पर ध्यान देने की आवश्यकता है। आपूर्ति श्रृंखला की स्थिरता को प्रभावित करने वाले किसी भी व्यवधान का प्रबंधन करने के लिए **सुरक्षित आपूर्ति श्रृंखला (secure supply chain)** आज के वातावरण की आवश्यकता है। इस अध्ययन का उद्देश्य आपूर्ति श्रृंखला के कई **जोखिमों** और **सुभेद्यताओं** का मॉडल बनाना है। जोखिमों का मॉडल बनाकर, आपूर्ति श्रृंखला के व्यवहार का आकलन किया जा सकता है और व्यवधान के प्रभाव का मूल्यांकन किया जा सकता है। **व्यवधान की अवधि (Disruption duration)** और **व्यवधान गतिविधि (disruption activity)** को लिया जाता है और पूरी आपूर्ति श्रृंखला के साथ मॉडल किया जाता है। इन दोनों कारकों को प्रणाली के व्यवहार को समझने के लिए बदला जा सकता है। यह अध्ययन आपूर्ति श्रृंखला के प्रदर्शन और इसकी सुदृढ़ता में सुधार के लिए **प्रणाली जोखिम आकलन (system risk assessment)** की एक समग्र झलक है। **प्रणाली गतिशीलता मॉडल (System Dynamics model)** का उपयोग आपूर्ति श्रृंखला के डिजाइन और नियोजन चरण में **इन्वेंट्री, लागत, परिवहन** और **उत्पादन प्रक्रियाओं** पर संभावित व्यवधानों के प्रभाव का अनुमान लगाने के लिए किया जा सकता है।

यह शोध-प्रबंध अनुसंधान कार्य के विभिन्न चरणों के माध्यम से ज्ञान के मौजूदा भंडार में योगदान देता है। अंत में, शोध-प्रबंध सभी अध्यायों का सारांश प्रस्तुत करता है और शिक्षाविदों, शोधकर्ताओं और व्यवहारकर्ताओं को महत्वपूर्ण योगदान प्रदान करता है।

मुख्य शब्दः आपूर्ति श्रृंखला जोखिम (Supply Chain Risk), आपूर्ति श्रृंखला सुदृढ़ता (Supply Chain Resilience), संपोषणीयता, मानव-मशीन सहयोग, सिमुलेशन, प्रणाली गतिशीलता मॉडलिंग, COVID-19 महामारी,

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LIST OF INDICES, VARIABLES AND PARAMETERS

Indices

i= denotes the supply chain echelon	1 (Supplier) 2 (Plant) 3 (Distributor) 4 (Retailer)

Parameters

Bakadjt	Backlog Adjustment Time (Day)
BakC	Backlogged Cost (Rs/Day)
BaklOr	Backlogged Orders (unit)
BaklPr	Backlogged Penalty Rate (Dmnl)
BakOradjt	Backlog Order Adjustment Time (Day)
BakOrC	Backlog Order Cost (Rs/Day)
BUC	Base Unit Cost (Rs/unit)
CExr	Currency Exchange Rate (Dmnl)
Foradjf	Firm Orders Adj factor (unit/Day)
FPSS	Finished Products Safety Stock (Day)
Fradjf	Forecasting adjustment factor (Day)
Holdr	Holding Rate (Dmnl)
InInven	Initial Inventory (unit)
InpPradjt	In process Products adjustment Time (unit)

InvReadjt	Inventory Revision Adjustment Time (Day)
Lt	Lead Time (Day)
MinTrt	Minimum Transportation Time (Day)
Nprodt	Normal Production Time (Day)
Oradjt	Orders adj time (Day)
OrFP	Orders Finished Products (unit/Day)
Ort	Order Time (Day)
PDt	Product Delivery Time (Day)
PInrC	Purchase Increment Rate Cost (Dmnl)
PrInr	Price Increment Rate (Dmnl)
ProdInrC	Production Increment Rate Cost (Dmnl)
Psadjt	Products shipping adjustment time (Day)
PTt	Plant Transportation Time (Day)
RMCr	Raw Material Consumption Rate (unit/Day)
RMHr	Raw Material Holding Rate (Dmnl)
RMI	Raw Material Inventory (unit)
RMIC	Raw Material Inventory Cost (Rs/Day)
RMImax	Raw Material Max Inventory (unit)
RMIRadjt	Raw Material Inventory Revision Adj time (Day)
RMO	Raw Material Order (unit/Day)
RMOradjt	Raw Material Order Adjustment Time (Day)
RMOt	Raw Material Order Time (Day)
RMRR	Raw Material Received Rate (unit/Day)
RMSS	Raw Material Safety Stock (Day)
RMUC	Raw Material Unit Cost (Rs/unit)

ROP	Reorder Point (unit)
So	Stockout (unit/Day)
SS	Safety Stock (Day)
SSFPD	Safety Stock Days Finished product (Day)
Tcap	Total Production Capacity (unit/Day)
TO	Time To Order (Day)
Trq	Number of Trucks (truck/Day)
We	Workforce efficiency (Dmnl)

Variables

BakInf	Backlogged Orders Inflow (unit/Day)
BakInfr	Backlog Inflow Rate
BakOrdel	Backlog Orders Delivered (unit/Day)
BakOrdelr	Backlog Order Delivery Rate (unit/Day)
BakOut	Backlogged Orders Outflow (unit/Day)
BUPC	Base Unit Product Cost (Rs/unit)
Cap	Capacity (unit/Day)
CInvenp	Current Inventory Position (unit)
CumP	Cumulative Profit (Rs)
CumTC	Cumulative Total cost (Rs)
De	Demand (unit/Day)
Delprod	Delivered Products (unit/Day)
DemR	Demand for Retailer (unit/Day)
For	Firms Order (unit/Day)
FP	Finished Product (unit/Day)

FPInven	Finished Product Inventory (unit)
FPOr	Finished Product Orders (unit/Day)
Fprdelr	Finished Products Delivery Rate (unit/Day)
Frerr	forecast error calculation (unit/Day)
Inv	Inventory (unit)
InvC	Inventory Cost (Rs/Day)
InvP	Inventory Position (unit)
Matadjf	Material Adjustment Factor (Dmnl)
MaxInv	Maximum Inventory (unit)
Or	Orders (unit/Day)
PerCD	Perceived Consumer Demand (unit/Day)
PerCr	Percieved consumption rate (unit/Day)
PerRMO	Percieved Raw Material Order (unit/Day)
Pr	Profit (Rs/Day)
PRese	Products ready to sell (unit/Day)
PResh	Products Ready to ship (unit/Day)
ProdCap	Production Capacity (unit/Day)
ProdD	Production Demand (unit/Day)
Prodelr	Product Delivery Rate (unit/Day)
Prodelt	Product Delivery Time (Day)
ProdF	Product Flow (unit/Day)
ProdPr	Product Price (Rs/unit)
Prodprr	Produced Products Rate (unit/Day)
Prodr	Production Rate (unit/Day)
Prodr	Feasible Production Rate (unit/Day)

Prodt	Production Time (Day)
RP	Received Product (unit)
Rev	Revenue (Rs/Day)
Sl	Service Level (Dmnl)
TBUC	Total Base Unit Cost (Rs/unit)
TC	Transportation Cost (Rs/Day)
TC	Total Cost (Rs/Day)
TrC	Cost per Truck (Rs/truck)
TrCap	Truck Capacity (unit/truck)
TUC	Total Unit Cost (Rs/unit)
UIC	Unit Inventory Cost (Rs/unit)
UPC	Unit Product Cost (Rs/unit)
WIP Inventory	Work in Progress Inventory (unit)

LIST OF ABBREVIATIONS

3C	Cooperation, Collaboration and Coordination
AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
AMOS	Analysis of Moment Structures
ANN	Artificial Neural Network
ANP	Analytical Network Process
AR	Augmented Reality
BCES	Blockchain Enabled Circular Economy System
BD	Big Data
BWM	Best-Worst method
CB-SEM	Covariance-Based Structural Equation Modelling
CFA	Confirmatory Factor Analysis
COVID	Coronavirus Disease
CPS	Cyber -physical system
CVs	Connected vehicles
DC	Distribution Centres
DEMATEL	Decision Making Trial and Evaluation Laboratory
Dmnl	Dimensionless
DST	Department of Science & Technology
DT	Digital Twins
DT	Digital Technologies
EFA	Exploratory Factor Analysis
EST	Event System Theory

FCM	Fuzzy Cognitive Map
Fuzzy-ISM	Fuzzy-Interpretive Structural Modelling
G-OPA	Grey-Ordinal Priority Approach
HSR	High-Speed Rail
I5.0	Industry 5.0
ICT	Information and Communication Technology
IoT	Internet of Things
IPMA	Importance and Performance Analysis
IRT	Innovative Resistance Theory
m-TISM	Modified Total Interpretive Structural Modelling
MCDM	Multi-Criteria Decision-Making techniques
MICMAC	Cross-Impact Matrix Multiplication Applied to Classification
ML	Machine Learning
NAT	National Accident Theory
NFT	Non-fungible Token
OIPT	Organizational Information Processing Theory
PPE	Personal Protective Equipment
RBV	Resource-Based View
RMG	Readymade Garments
RMSN	Raw Material Supplier Nodes
SAS	Sustainable autonomous systems
SC	Supply Chain
SCD	Supply Chain Disruptions
SCPs	Smart Connected Products
SCRe	Supply Chain Resilience

SDM	System Dynamics Modelling
SDN	Software-Defined Networking
SEM	Structural Equation Modelling
SIT	Structural Inertia Theory
SLNA	Systematic Literature Network Analysis
SLR	Systematic Literature Review
SPSS	Statistical Package for the Social Sciences
TAM	Technology Acceptance Model
TRA	Theory of Reasoned Action
TRP	Threat-Rigidity Perspective
UAVs	Unmanned Ariel Vehicles
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
UTAUT	Unified Theory of Technological Acceptance and Use of Technology
VIKOR	Vlse Kriterijumska Optimizacija Kompromisno Resenje
VR	Virtual Reality
WHO	World Health Organization