Analysis of Supply Chain Challenges in Implementation of Industry 4.0 for Textile Sector

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CANDIDATE'S DECLARATION

I Hamish Ali (2K22/IEM/05) hereby certify that the work which is being presented in the thesis entitled "Analysis of Supply Chain Challenges in Implementation of Industry 4.0 for Textile Sector" in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Mechanical Engineering , Delhi Technological University is an authentic record of my own work carried out during the period from January, 2024 to May 2024 under the supervision of Dr Girish Kumar and Dr Naushad Ansari.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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CERTIFICATE BY THE SUPERVISOR(S)

Certified that Hamish Ali (2K22/IEM/05) has carried out his search work presented in this thesis entitled "Analysis of Supply Chain Barriers in Implementation of Industry 4.0 for Textile Industry" for the award of Master of Technology from Department of Mechanical Engineering, Delhi Technological University, Delhi, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT

The integration of I4.0 technology into the textile sector brings revolutionary opportunities that promise to increase efficiency, flexibility and competitiveness. However, the implementation of I4.0 in the textile supply chain faces many challenges. This thesis aims to identify the key SC challenges faced when implementing I4.0 in the textile sector, focusing on the interaction between processes, technologies and stakeholders. Through literature review and discussions with experts the challenges were found to be of operational, organizational and human factors. Operational challenges include interoperability issues between different systems, cybersecurity issues, and the high cost of technology and upgrades. Organizational challenges include resistance to change, lack of digital planning and the need for significant investment in infrastructure. Human factors include skills gaps, employee performance, and the need for cultural change to embrace digitalization. The challenges have been analysed using a hybrid model of Best Worst Method and DEMATEL (Decision making trial and evaluation laboratory) to give ranking to the challenges by weightage assigning and classifying them into cause-and-effect groups respectively. Resolving the challenges of industry 4.0 can facilitate informed decision-making and strategic planning and by addressing these issues, stakeholders can successfully transition to I4.0 and achieve sustainable growth and competitiveness.

Key words: Industry 4.0, Supply Chain, BWM, DEMATEL.

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Abbreviations	
AI	Artificial Intelligence
BWM	Best-Worst Method
DEMATEL	Decision making trial and evaluation laboratory
I4.0	Industry 4.0
ML	Machine Learning
SC	Supply Chain
SCM	Supply Chain Management

CHAPTER 1

INTRODUCTION

1.1 Background

The research in applying Industry 4.0 in the textile sector has been growing. In fact, several studies and projects taking place at the moment with an aim of investigating potential and challenges with these technologies. Adoption and Integration of Technology: A cornucopia of research works focuses on the adoption and integration into textile manufacturing of IoT, AI, and robotics. Consider, in particular, the work of Chiarini et al. (2020), which deals with the application of IoT–powered devices in the monitoring of production processes and how this can increase the efficiency of the operation in factories producing textiles. Such an increase in efficiency comes from benefits related to data collecting and maintenance, which helps to lower the machine time-outs.

Big data analytics and AI have been extensively explored for the purpose of supply chain optimization. For instance, Ivanov et al. (2019) report an application of AI to predictive analytics that enhance demand forecasting and inventory management within the textile supply chain. The study finds evidence of achieving significant improvements in both the flexibility and responsiveness of a SC through use of AI-driven models.

According to García-Muiña et al. (2018) in research available through I4.0 inventions for the textile sector, sustainability initiatives were based on the potential for smart management of waters and energy-efficient production techniques that reduce environmental footprint and, at last, increase material flow rate. Thus, a direct relationship with the use of technology is sustainable outcomes. Another major area where research has been conducted into the impact that Industry 4.0 may play with regard to the workforce is Human Resource Development.

Hirsch-Kreinsen, (2016), pointed out the skills gap and thus the upskilling in the workforce for handling advanced technologies. Her study also emphasizes the need for total training programs and designing new curricula to make the workforce ready for I4.0.

According to (Hoffman et al 2017), there are operational challenges placed on manufacturers with the advent of Industry 4.0 implementation. In more detail, the issues of high technology adoption costs, integration problems with continued systems, and the necessity for significant reengineering of the processes are the three major critical entry barriers identified therein. It is also identified how these issues can be overcome with strategic planning and phased implementation.

Case Studies and Best Practices: A lot of research have reported the victorious use of I4.0 practices. For instance, a study carried out by Schneider Electric in 2019 on how a textile manufacturer achieved significant improvement in manufacturing productivity by operationalizing IoT and AI technologies is available. These insights could be best practices to other manufacturers who are undergoing similar transformations.

1.2 Industry 4.0

The 21st century is witnessing a digital revolution in manufacturing, often called Industry 4.0. This isn't just hype; it's a real trend that's gained momentum since the early 2010s. Industry 4.0 is pushing businesses to go digital, and both companies and governments are taking notice. This need for digital change comes from a long-standing challenge: how to make more stuff with fewer resources, as our consumption keeps growing. We also need to avoid hurting the environment and society in the course. I4.0 offers a good solution. The initial industrial revolution commenced towards the eighteenth century, marked through emergence of mechanical production facilities powered by water and steam. Following this, the second industrial revolution unfolded at the onset of the twentieth century, epitomized by mass production techniques reliant on electrical energy. Subsequently, the III manufacturing revolution commenced to take shape in the 1970s, characterized by automated production methods leveraging electronics and internet technologies. Presently, the IV industrial revolution, denoted as I4.0, is underway, facilitated by the fusion of diverse data and knowledge sources. (Dusko Lucak 2015)

Industry 4.0 is revolutionizing the cloth industry, transforming it into a more data-driven and intelligent sector. This industrial evolution integrates physical and digital technologies like the Internet of Things (IoT), artificial intelligence (AI), and big data analytics across the textile value chain. Research suggests that Industry 4.0 can increase productivity by up to 20%, reduce costs by 10-40%, and accelerate time-to-market by 20-50% (Trivedi, Y. 2021). By implementing these technologies, textile manufacturers can create smart factories where machines communicate with each other, analyze data, and optimize processes in real-time, leading to increased efficiency, reduced waste, and improved product quality (Naseem et al 2021). However, research also highlights that the textile industry is still in the initial phases of I4.0.

I4.0 signifies an upheaval in industrial, that is the incorporation of knowledges such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics and mechanization. In this industry, I4.0 leaders are revolutionizing engineering processes, SCM and production. By using advanced technology, textile companies can achieve better performance, flexibility and sustainability throughout the entire life cycle (Stock et al 2018). For example, smart sensors built into machines can instantly monitor the production process, simplifying maintenance and reducing downtime. Additionally, AI-supported algorithms can reduce waste and improve resource utilization by improving productivity and inventory management. Additionally, digital platforms improve collaboration and visibility across devices, allowing business needs and customer preferences to change. However, there are also difficulties in application of I4.0 in the textile sector, such as outdated systems, cyber security risks and the need for employee support. However, by solving these problems, textile companies can open new opportunities for innovation and competition in the worldwide market (Naseem et al 2021).

In recent literature and industrial papers, the concept of Industry 4.0 has been primarily focused on production. While it is normally accepted that I4.0 and its related inventions can disturb different parts of establishments, such as supply chain and logistics management. As business systems become more automated, organizations are experiencing enhanced efficiency, productivity, and quality. This has prompted them to adopt the industry 4.0 approach in other areas, like SCM.

This study seeks to identify obstacles that organizations face when integrating I4.0 into their SC, given growing importance of technology in these operations.

In this thesis, we employed two robust methodologies, the Best Worst Method (BWM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL), to comprehensively analyze the supply chain challenges in applying I4.0 within the textile area. The BWM was utilized to determine the relative importance of various challenges by systematically comparing the best and worst criteria against all others. This method provides a structured and precise prioritization of challenges. Following this, the DEMATEL method was applied to elucidate the complex causal relations amid these challenges, offering an in-depth understanding of their interdependencies. By integrating BWM and DEMATEL, we achieved a nuanced analysis that highlights both the criticality and the intricate interactions of supply chain challenges, thereby facilitating informed decision-making for the operative adoption of I4.0 in the textile industry.

In the subsequent chapters of this thesis, we delve into the various aspects of our study on the application of I4.0 in the textile area.

Chapter 2 provides a full literature review, discussing the influence of I4.0 on the textile industry, exploring essential technologies such as big data analytics, artificial intelligence and machine learning, and advanced robotics, and examining their inferences for the textile SC. This chapter also addresses SC sustainability, tracing, and digitalization, identifying key challenges and highlighting research gaps that inform our research objectives.

Chapter 3 outlines the procedure of our study, detailing the application of the Best Worst Method (BWM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach to evaluate and prioritize the identified challenges.

In Chapter 4, we present the results and discussions, including the development of a hybrid model, the implementation of the DEMATEL method, and the key findings from both the BWM and DEMATEL analyses. Practical recommendations based on our findings are also provided.

Finally, Chapter 5 completes the thesis with a brief of the key insights, boundaries of the study, and proposals for upcoming research directions.

CHAPTER 2

LITERATURE REVIEW

2.1 The Impact of Industry 4.0 on the Textile Industry

I4.0 means the development of a game-changing time for manufacturing and production, where the total combination of cyber-physical systems, the IoT, big data analytics, artificial intelligence, and advanced robotics is made into being. This fourth revolution is set to optimize operational efficiencies, enhance product quality, and stimulate innovation in all sectors. Textile industry stands at significant advantage from this revolution with optimized SCM processes.

I4.0 is the evolution from erstwhile old-style industrial shop floors to smart factories where all machines intercommunicate, self-monitor, and take decentralized decisions. This heralds a major transformation for the textile industry, which is conventionally labor-intensive and, therefore, bears the maximum potential for innovation and efficiency.

2.2 Technologies for 4th Industrial Revolution in Textiles

It can, therefore, be used to embed into machinery and products for data collection and real-time transmission. For instance, in the textile manufacturing industry, IoT sensors would be in place to monitor performance as well as give the records on usage of the raw material, giving further insights into production efficiencies. It helps in achieving the reduction of downtime and an increase in the lifespan of machinery in predictive maintenance.

2.2.1 Big data analytics

The huge volume of data generated with the usage of various IoT devices is analyzed to reconcile patterns and insights. For a textile manufacturer, this results in better demand forecasting, inventory optimization, and more effective supply chain planning. That further escalates market change responses toward swifter, accurate data-driven decisions.

2.2.2 AL and ML

AI algorithms used in reading data could make it possible to optimize production schedules, predict equipment failures to ensure minimal downtime for maintenance, and enhance quality control. Machine learning models are able to learn from past data about an improved design in fabrics, color matching, and defect detection to increase the quality of products.

2.2.3 Advanced Robotics

They can be found in automation for fabric cutting, sewing, and even handling heavy fabrics. This enhances productivity not just due to speed but also because there will be less human error and more precision. Cobots can collaborate with human operators. In textile manufacturing, CPS can be configured to control and optimize several stages in the manufacturing process, from spinning and weaving to dyeing and finishing, in a manner that helps to secure consistency and quality.

2.3 Industry 4.0 technologies impact for textile supply chain

The incorporation of I4.0 skills into the textile SC should be expected to connect better with related stakeholders by progressing the visibility of SC. Better visibility across their respective supply chains means that suppliers, producers, and retailers will be in a good position to coordinate in such a manner as to track raw materials and finished goods efficiently—in a bid to cut down on lead times, stockouts, or overstock situations.

Another added benefit of digitalization of the supply chain is the improved risk management. By means of analytical prognostics, it's possible to predict some caused upsets of the supply chain: for example, delays in supplying raw materials, some measures to perform for risk mitigation, or equipment failure.

In the case of textile manufactures, Industry 4.0 adoption is not for improvement regarding operational efficiencies but for salient competition in the world market. As other industries adopt the digital revolution, the capability to yield goods with high quality at little costs will be a game-changer. Industry 4.0 technologies would empower a manufacturer catering to the ever-increasing demands in the textiles sector viz-a-viz customization and personalization.

Another important dimension in which Industry 4.0 can leave a significant mark is sustainability. The use of more advanced technologies allows for resource use that is much more efficient, with less waste and energy expenses. For instance, smart water management systems stand to reduce water use in dyeing processes by large percentages, while AI-based quality control can minimize defective products and avoid wastage.

2.4 SC Sustainability

The sustainability of SCM is an approach to strategically and transparently consider a company's economic, and social purposes in managing material information and capital flows, working together with other firms in the supply chain. They are based on customer necessities from stakeholders and are brought about by a triple bottom line based on traceability, risk management, transparency, strategy, and culture.

This calls for responsible management not only of the activities of the leading company but of the entire supply chain, extending from raw supplies to finished products. Companies must ensure that every facet of the production process respects the aspects of sustainability. Companies that can indeed be said to be sustainable are those that can do business without impacting negatively on the environment and society while remaining profitable. However, a few companies are operating at this level. Most of the domain's most sustainable companies have significantly higher relative sustainability than others within the same industry (Pagell & Wu, 2009) since sustainability, by itself, is full of trade-offs. Few business decisions satisfy simultaneously all ethical, environmental, and financial criteria (Closs et al., 2011).

Sustainability transcends right through the product design, durability, and features—not to mention the channels used for marketing and the strategies for communicating. It is the deliberate choice of resources and components, manufacture processes, packaging, distribution, and recycling coherent with sustainability goals (Closs et al., 2011). It is an approach towards sustainability concerning better product sustainability, client gratification, and keeping a competitive edge in the sector. Companies can achieve this by introducing a completely new and sustainable supply chain or, ideally, by actively strengthening the existing one with more sustainable practices, which can include eco-friendly packaging for instance (Bowen et al.2001; Seuring & Müller, 2008). For example, these can be strategies that coexist: the one developed over time and the endangered.

Companies are being pushed or pulled towards sustainability by other forces and variables, as found in previous research: external pressures and stimuli. However, of all these pressures, the customers and the governments place the most significant pressure. A customer will dictate the demand for an organization's product, while government regulations will put a legal demand on the activities of a firm. Indications of other external pressures may include legal demands, stakeholder responses, social pressure groups, and reputation concerns. There is also pressure from the sustainability efforts of industry competitors (Gold, Seuring, & Beske, 2010). Companies cascade these pressures down the supply chain to the suppliers, who in turn cascade them down to their suppliers (Seuring & Müller, 2008).

But, the improvement of sustainability cannot be realized without external pressures. These pressures need to integrate with the internal capabilities of the firm and the SC. The aspect here regards resources, competencies, and abilities that will thus be capable of availing for the management of the SC sustainably. Firms have to develop strategic and comprehensive procedures and policies for purchasing. Forging collaborative and effective relations with suppliers and customers and communication is essential. Cross-functional teams within the company and with suppliers are vital in buying the product and being part of the product design at an early stage (Bowen et al., 2001). Staff training gives assurance of proactive measures, and purchasing personnel are expected not only to conduct procedures but to be knowledgeable in the areas of sustainability and the technical requirements thereof (Seuring & Müller, 2008). The use of organization system ideals, such as ISO 14001, and intensive care, assessing, and writing supplier performance are also very important.

The push business-wise for sustainability would then depend on the company's commitment, and, ultimately, on a strategic choice to pursue the same. Sustainability objectives will have to be embedded as a part of the company strategy. This thing will ensure that there is commitment at all levels-from, top management level, to the operational staff embracing sustainability. These external pressures would have to be supported by internal capabilities and resources. However, some barriers resist actions of this nature. Supply chain management for sustainability involves a chain with higher costs and efforts of coordination that are put into practice. It may complicate the supply chain with such goals, and poor communication may hamper strategy implementations. It needs to overcome all these barriers with a long-standing visualization toward improved performance for the supply chain as a whole (Seuring 2008). Strict emphasis on the triple bottom line is believed to leave room for better efficiency and profitability in the lasting .

In addition, partnership is a strategic issue that roots the sustainability of the respective actors within the SC (Garcia-Torres, 2019; Pagell & Wu, 2009). Cooperative relationships incorporate proactive interaction and frequent communication channels with the partners, besides high communication between them. Trust is a critical component in cooperation and good relationships that will potentially exist among organizations. This will mean that the partners will have to trust each other, and they must have strong relationships between themselves. They should, therefore, be at liberty and willing to share information for sustainability in the development of the

SC. That sustainability only renders operations more complicated, time-consuming, and expensive. For this reason, supply chain collaboration should be pursued only by the results that it can bear on a supplier-by-supplier basis. Actually, based on market dominance and power distribution between the supplier and buyer, it may not be possible for collaborative relationships.

2.5 Supply Chain Tracing

Besides, some of the significant challenges to the manufacturing sector include the complexity and uncertainty in the SC, which is the primary cause of poor traceability and hence majorly results in a dearth of trust amongst the clients and investors in the reliability of the resources used. As discussed earlier, the onus of the entire supply chain performance is on the company. Other reasons that necessitate traceability in a sustainable supply chain include shared information with partners, the pressure from customers regarding sustainability, and, most importantly, the fear of the unknown that might be found within the SC. Loss of visibility within the SC costs the company a competitive advantage and reputation. For example, the very nature of complex supply chains mandates that issues such as underperformance, fraud, inefficiency, and theft be traced.

It becomes the track-and-trace capability of the SC. Traceability, for its part, is the ability to access information at a very detailed level concerning some production lots or processes, in contrast to transparency, which means visibility across the whole supply chain. It demands knowledge of previously used practices and current activities. This is best done by tracing every step from the end product back to the original raw material so that the authenticity of every step is established (Cheng & Simmons, 1994). According to ISO 9000, it is the capability of tracing the history of a product back to the source with regard to raw material, processes that were involved in its making, and its location. Another definition traces the current status of goals and goal traceability, which compares actual performance with the plans of performance against objectives, respectively—we trace them by performance traceability (Cheng & Simmons, 1994).

In addition, Agrawal et al. (2021) argue that such a complex multi-tier supply chain should be upgraded into a much more traceable and clear type for better sustainability and accountability.

The establishment of traceability is one of the critical enablers for a sustainable journey over a long period. Proper implementation of these methods requires the ability to map each step, from the manufacturing of resources to the product, with all information collected, stored, and publicly available. This allows them to make value-based purchasing decisions. As a result, some of the critical features of traceability include governance, collaboration, and tracking or tracing. Perfect traceability provides for the existence of partnerships between the providers and the retailers to realize complete traceability, which can extend to the guarantee of origin of products, recalling, and managing with effectiveness, among others.

Detection and measurement are cornerstone activities to traceability since effective supply chain management mandates measurements towards process control and management (Cheng & Simmons, 1994). On the other hand, the company is responsible for the chain, but in most cases, there is reduced visibility regarding the SC (Garcia-Torres et al., 2019). Across the entire SC, effective sharing of information, visibility, and managing of competencies and knowledge are essential in the realization of goals of sustainability. Today, the environment has come to embrace the dimensions of environment and society besides economic factors, signifying that the consumer of today is willing to pay an extra sum for products produced sustainably. Decisions to purchase such products must be based on precise information accessible to the consumers themselves 4. Customers won't go with the 'greener' option if the product prices are high, yet pieces of information are inconsistent or hard to find. The supply chain should be transparent to the customers. They should be able to deduce raw material origins, environmental respective practices, and worker conditions. Information should be easily accessible, understandable, and comparable. Good traceability: It works well for risk management and certification.

Thus, traceability makes the process more efficient and reduces risks, enabling appropriate knowledge. Problems may quickly arise in an open and well-known supply chain, but they will also be solved much more accessible. It has to be implemented as clarity between the SC partners, facilitated by RM systems and collaborative relationships. "The same importance of traceability to certification" applies, for example, to organic cotton, for which each phase of the chain from the field to the last good must be traceable, the traceability of the cotton itself (Da Cruz et al., 2020). "In such context, traceability systems represent applicable tools in management regarding supply chain sustainability" (Da Cruz et al,. 2020).

While it is a benefit in getting involved, implementing traceability comes with costs. Indeed, Cheng & Simmons (1994) reported that traceability barely adds value, but all this has since changed, and the impact of the research remains little. A proper and robust traceability system will allow and balance the cost of being accurate regarding information called for. Too much of the information that is not analytically critical can have more negative effects than positive ones. The traceability talks of the barriers to standards, responsibilities and double records. Not all supply chains can bear the increased costs of traceability, and some of the products would not even be bought because they come with premium costs (Sunny et al., 2020). No entirely conclusive traceability model is possible since it cannot incorporate all the info and all the events (Cheng & Simmons, 1994). Centralization helps to reduce the dependency on It persists across all industries (Da Cruz et al., 2020). Currently, all the supply chains rely on a centralized information management system, such as the ERP and third-party companies, to house most of the invaluable and, at the same time, very sensitive data to keep the operations in the SC going smoothly (Saberi et al., 2019).

2.6 Digitalization

It explains the curation of I4.0 technologies—the IoT, blockchain, and RFID—into the information systems of a firm that enables the SC of the firm to be sustainable and traceable. These advanced technologies will enhance the possibility of collaboration for shared data across the supply chain partners, which include even the suppliers and customers, among others. The authenticity and integrity of the data will be taken care of. This is so because the current traditional systems come short of placing the modern traceability requirements. Real-time data cannot be effectively collected in conventional systems, and the data provided is mainly challenging to analyze for further applications.

Faridi. (2021) have proposed, in their research, the infusion of IoT and Blockchain technologies into the textile manufacturers' information systems to achieve data collection in real-time, credible data, and improved satisfaction levels for customers. On the other hand, such a system integrating IoT and blockchain will go beyond the limitation of the existing system and provide a traceable, reliable supply chain. This can be done by automating the data collection process using IoT and blockchain technology, which aims to achieve a decentralized, immutable, auditable, and trustable data system.

This kind of technology will enable linkages between business processes, improvements in the quality, fault traceability in products, and increased transparency and trust from customers in the supply chain. Technologies of this nature are likely to digitize the processes and ensure that access to information regarding products is gained in real-time. In addition, they have recommended the integration of RFID, IoT, and Blockchain within the same SC. The approach suggests an incorporation where the connection of the RFID to the internet for collecting the data without human interference in real-time increases the traceability and transparency in the system and checks the reliability of the data obtained using a Blockchain.

2.6.1 RFID

This aspect makes Radio Frequency Identification (RFID) systems mainly consist of magnetic chips, which store vast data besides the ability to give every product an identity using an Electronic Product Code (EPC). Only when the tags are put on the products can the supply chain be seen in real-time. The information collected by the RFID is to be fed into the systems through readers that have been built for this purpose. This system would significantly enhance the dimension of supply chain traceability because data will be built into the chip. This information will help to reduce costs and optimize processes and logistics, and hence enhance the safety and quality of the product. This technology is not new in the application process, although many benefits accrue to the supply chain management. More so, data mainly shared is transferred through Bluetooth or Near Field Communication (NFC), and its approach is diluted by the kind of protection with data that is required, including supporting technologies for authentication and certification of data, among others. These include IoT and Blockchain.

2.6.2 IoT

The IoT refers to the system application that connects everything that is associated with the user through the Internet for an interaction or to collect enormous data about the item, facility, or activity nowadays. Internet of Things devices can range from wearables to hardware in this day and age. Other technologies Among those affixed to different sensors and devices with the use of wireless sensors and Quick Response (QR) codes, EPC, and RFID to material or product, the ability to join the products to networks that will automate the entry of information and do away with human involvement in the collection of data is accurate (Montecchi et al., 2019). The main objective is that data can be obtained without human input as physical things connect themselves to the Internet.

The IoT will make possible the interconnection of the products and processes making up the textile manufacturing industry. For example, RFID tags can be connected to the process control loop; the tags can carry the electronic product code of each product to indicate, in real time, the process step of the product. It enables real-time data through physical objects, the uses of which may be applied systematically in the operations decision-making process. This is already being applied in the garment industry for inventory and transportation tracking and in material-based tracking linked to SCM recently. It has also been referred to as an apt technology for traceability management systems by (Faridi et al., 2021)

Though, there are a couple of problems with IoT that make it laborious: limited memory, computational capacity, and unreliability. There is a concern in making the information right; otherwise, it can be entered wrong to benefit oneself. The technology is centralized and requires authorization. Even with the development being strong and the use of it increasing, IoT has a lot more potential and a gap in security and privacy. All parties have to be in a position to access the information and verify it before trusting the information. This is a security issue that blockchain technology is in to address. This leads to better security and reliability because of decentralized management.

2.6.3 Blockchain

Blockchain technology ensures security and provides a solution for protecting sensitive data concerning economic transactions. In security across various parts of the IoT, the validation of each transaction under the agreement of utmost of the chain assures the reliability and transparency of data.

(Nakamoto, 2008) came forward with a proposal for blockchain as a platform to manage Bitcoin as a technological solution. Blockchain is a distributed technology that records, stores, time-stamps, and synchronizes data regarding all members of digital ledgers related to any transactions; each of these transactions forms a so-called chained, time-ordered block that is visible and verifiable to all the members. Each block is cryptographically linked to avoid its use for any data manipulation. It will not allow the data written to the blockchain to be tampered with unless the authorized parties have given ironclad permission; in other words, it will not tolerate corruption. Once any participant starts a new transaction, the transaction becomes a part of the blockchain the moment the transaction is validated and audited majority under pre-specified rules by the network. It will be a new block in the chain after being validated. By definition, blockchain technology is a method of organizing data into special blocks linked continuously. Security, checkability, and confidence are provided through access to the blockchain without the intervention of intermediaries. This is the very kind of neology in the field of informational technologies: such applications are well-suited for a blockchain, even for specific applications where they have evident advantages over traditional centralized, poorly transparent, and low-trusted systems.

2.6.4 Blockchain in SCM

Implementation of block-chain technology in SCM began to have applications in the recent years and more especially since it promises increased transparency and traceability, and more security (Agrawal et al., 2021; Saberi et al., 2019). As it matures, however, blockchain technology will likely be one of the major disruptive forces in supply chain management (Agrawal et al., 2021; Saberi et al., 2019).

It enables getting present info about the product, location, quantity, and ownership and reduces the impact of information infrastructure outages or latency, and breakdowns or problems in compatibility between the partners in the SC, reducing information friction. Blockchain helps parties without trust reach a consensus, and it doesn't need a central authority. At the same time, it is both safe and transparent, so this will make the certification process of a product much simpler. Blockchains can be public or private, depending on the application, but for the application at hand, it would usually have to be private and permissioned. Nevertheless, inefficiencies of the blockchain, particularly the resource-intensive mechanisms of consensus employed in (Proof of Work) PoW, persist in challenging the sustainability of blockchain technology from an environmental perspective.

While the blockchain proves effective for products relating to high involvement, such as luxury goods and pharmaceuticals, which are, in turn, prone to counterfeiting, scalability and capacity issues continue to be plenty. Sunny et al. (2020) further add: 'The sector is rich in potential, yet its full potential is not realized as yet. Investments in blockchain at the strategic level could eliminate the integrators and simplify supply chains for traceability in manufacturing (Montecchi et al., 2019). Yet, educating users on how to access blockchain data often would need some packaging, marketing, and application adjustments.

2.7 Supply Chain Challenges

The issues faced by supply chain (SCs) in the textile industry, are conversed in this section. Surveys of the literature and interviews with textile industry supply chain experts are used to identify the problems. We go into great detail about each challenge in the ensuing subsections.

2.7.1 Legacy Infrastructure

Old Equipment and Facilities: Many textile makers use machines and buildings that are too old for Industry 4.0. Upgrading or changing these old systems involves high expenses and interruptions to how things are made. According to the paper by (Akram et al., 2022), titled " Application of digitized technologies for Fashion Industry 4.0: Opportunities and challenges," improving infrastructure is essential but difficult because of the high prices and the difficulty of combining novel technologies with old systems.

2.7.2 Lack of Awareness and Knowledge

Limited Understanding: A significant number of smaller textile firms, especially those in the industry, may not fully comprehend the concept of I4.0. They may not fully comprehend the particular technologies like IIoT sensors, automation etc (Elibal & Özceylan, 2021).

2.7.3 Skills Gap and Workforce Training

To implement advanced technologies in the textile industry, it is crucial to have a manpower with the required skills to handle, maintain, and resolve intricate systems. Nevertheless, there is usually a large difference between the abilities required by Industry 4.0 and those that the current workers have. To ensure successful implementation, it is essential to offer sufficient skill-up sessions to improve the skills of existing employees and attract fresh talent.(Kagermann, et al. (2013))

2.7.4 Supply Chain Complexity:

Global networks of stakeholders, including raw material suppliers, yarn manufacturers, fabric makers, clothing dealers, retailers, and consumers, are frequently involved in textile supply chains. There are difficulties in smoothly integrating I4.0 throughout the network due to this disjointed topology. (Elibal & Özceylan, 2021)

2.7.5 Technological Infrastructure Limitations:

I4.0 is the achievement of solid construction, including reliability and compatibility between devices. This ensures the seamless transfer of information at all stages, from the purchase of input to output (Majumdar et al., 2021). However, reliable electronic equipment and robust communications for real-time data exchange may not be available in all production areas, especially outside developing countries (Elibal & Özceylan, 2021).

2.7.6 Data overload and management

Industry 4.0 generates vast amounts of data, and the textile sector needs effective strategies to manage and analyze this data to optimize resource utilization and minimize waste throughout the SC (Manglani et al 2019).

2.7.7 Collaboration and Trust

Effective application of I4.0 requires partnership and info distribution between different investors in the SC. However, some companies may be hesitant to share sensitive data due to competitive concerns (Rahanu et al., 2021).

2.7.8 Budgetary Constraints

Technology costs: Acquiring new technologies like sensors, industrial internet of things (IIoT) devices, and advanced analytics software can be expensive (Majumdar et al., 2021). Infrastructure upgrades: Integrating Industry 4.0 requires robust IT infrastructure, including data storage, network upgrades, and cybersecurity solutions, which can require significant capital expenditure (Rahanu et al., 2020).Workforce training: Upskilling the workforce to operate and maintain new technologies necessitates training programs, which add to the overall cost (Majumdar et al., 2021).

2.7.9 Ethical Challenges

The application of I4.0 in the textile sector presents several ethical challenges. Automation through I4.0 technologies might result in job losses, particularly for tasks that can be easily replaced by machines. This raises concerns about worker retraining and potential unemployment (Majumdar et al., 2021). Furthermore, the huge quantity of data generated in I

4.0 systems, including data related to workers and production processes, needs to be managed ethically. Concerns around data security, ownership, and potential misuse require robust data protection measures. Additionally, algorithms used in Industry 4.0 for decision-making (e.g., resource allocation, quality control) can be biased based on the training data they are built upon. This can lead to unfair outcomes for certain workers or suppliers (Rahanu et al., 2020). Lastly, while I4.0 promises greater transparency in supply chains, ensuring moral obtaining performs and fair labor conditions throughout the complex textile supply chain can be challenging (Sarmad et al., 2020).

2.8 Research Gap

Despite extensive literature on I4.0 and its probable transformative influence on various industries, there is a noticeable gap in understanding its specific challenges and implications within the textile sector's supply chain. Most existing research focuses on the technological progressions and theoretical benefits of I4.0 without sufficiently addressing the practical obstacles faced during implementation. Furthermore, while some studies have examined supply chain management in the context of other industries, the exclusive features and complexities of the textile sector are often overlooked.

Additionally, there is a shortage of experiential data and case studies that explore the real-world application and integration of Industry 4.0 technologies in textile supply chains. This lack of detailed, sector-specific research leaves practitioners without clear guidelines or best practices to follow. Moreover, there is limited analysis on the interplay between technological adoption and other critical factors such as workforce skills, organizational readiness, and regulatory frameworks in the textile sector.

The justification for addressing this research gap lies in the critical need for a complete understanding of the specific challenges and inferences of applying Industry 4.0 within the textile sector's supply chain. The textile industry, with its unique characteristics and complexities, demands tailored approaches to effectively leverage I4.0 technologies. Without empirical data and detailed case studies, practitioners lack the necessary insights to navigate the practical obstacles of integration, leading to potential inefficiencies and setbacks. Additionally, the interplay between technological adoption and factors such as workforce skills, organizational readiness, and regulatory frameworks is crucial for successful implementation. By concentrating on these undived areas, this research aims to bond the gap between theoretic advancements and practical applications, providing actionable guidelines and best practices for industry stakeholders. This will not only enhance the understanding of I4.0's impact on the textile supply chain but also facilitate its smooth and effective adoption, ultimately driving the industry's innovation and competitiveness.

2.9 Research Objective

To classify the key challenges specific to the application of I4.0 technologies in the textile industry's SC.

To apply the Best Worst Method (BWM) for determining the relative importance of identified challenges and utilize the DEMATEL approach to analyze the cause-effect relationships among these challenges.

To provide actionable recommendations for facilitating the effective implementation of I4.0 technologies in textile sector.

CHAPTER 3

METHODOLOGY

The preceding chapter has pinpointed the supply chain challenges encountered in applying I4.0 within the textile sector. This chapter delineates the methodologies utilized in the study to prioritize and categorize these challenges. Subsequent subsections provide an outline of the methodologies employed.

3.1 Best Worst Method (BWM)

The Best Worst Method (BWM) is a multi-criteria decision-making (MCDM) approach developed to find the weights of numerous standards by comparing them in pairs. Introduced by Dr. Jafar Rezaei in 2015, the BWM involves identifying the best (most important) and worst (least important) criteria and then comparing these against all other criteria to generate pairwise comparison vectors. The method involves a structured process where decision-makers first select the best and worst criteria from a set. They then rate the importance of the best criterion over all others and similarly rate all criteria against the worst criterion. These ratings are used to form two comparison matrices, which are subsequently utilized to calculate the optimal weights for each criterion by solving a simple linear programming model. This method stands out for its consistency and reduced comparison requirements, making it both practical and reliable for complex decision-making scenarios. The BWM has been effectively used in numerous sectors, including SCM and I4.0 implementations, demonstrating its effectiveness in prioritizing criteria and addressing decision-making challenges (Rezaei, 2015; Rezaei et al., 2016).

Step by step procedure is detailed in the following:

Step 1: A crew of specialists in verdict making, recognize all the aspects that are to be considered and lists them out.

Step 2: For the present study these factors are identified on grounds of literature review and expert discussions. These challenges are listed in Table 3.1.

Choose the best (most important) and the worst (least important) factor affecting the decision-making by a team of specialists in decision-making.

Step 3: Choose the preference of the top criterion over all the other factors using the scale which is depicted in Table 3.2.

Table 3.1 Supply Chain Challenges in Implementation of Industry 4.0

Challenge no.	**Abbreviation**	**Description**
1	B1	Legacy Infrastructure
2	B2	Lack of Awareness and Knowledge
3	B3	Skills Gap and Workforce Training
4	B4	Supply Chain Complexity
5	B5	Tech. Infrastructure Limitations
6	B6	Data overload and management
7	B7	Collaboration and Trust
8	B8	Budgetary Constraints
9	B9	Ethical challenges

Table 3.2 Importance scale (Reazaei, 2015).

Rating (1–9)	Description
1	Same importance
2	Somewhere in Equal and Moderate
3	Moderately more important than
4	Somewhat between Moderate and Strong
5	Strongly more important than
6	Somewhat between Strong and Very strong
7	Very strongly important than
8	Somewhat between Very strong and Absolute
9	Absolutely more important than

As explained by (Rezaei, 2015) the resulting Best-to-Others (BO) vector would be, X1:

$$X1 = (x_{y1}, x_{y2}, x_{y3}, \ldots\ldots\ldots x_{yn}) \quad (3.1)$$

where $x_y k$ indicates the choice of the best criterion ‘y’ over criterion ‘k’.

Step 4: Rated on a scale of 1–9, the worst criterion is based on their relative importance over what all other factors (Refer to Table 3.1). After which, these measures are put into a vector. The resulting vector OW (other to worst) will be the vector X2

$$X2 = (x_{1z}, x_{2z}, x_{3z}, \ldots\ldots\ldots x_{nz})^r \quad (3.2)$$

Where $'x_{kz}'$ shows importance of the criterion ‘k’ over the worst criterion ‘z’.

Step 5: The calculation of the optimal weights is done using the Linear Programming Problem as expressed by (3.3).

$\text{Min } \xi^L$

s.t.

$|w_y - x_{yk} w_k| \leq \xi^L$, for all k

$|w_k - x_{kz}w_z| \leq \xi^L$, for all k

$\sum w_k = 1$

$w_k \geq 0$, for all k (3.3)

The solution to the expression (3.3) will provide the optimal weights.

Step 6: The best-to-worst rate is derived based on the optimal weights. BWM is constructed based on the principle of pairwise Compare to obtain the weights (w_j) of the factor. Pairwise comparison 'a_{ij}' gives how how much more the decision-maker prefers to satisfy criterion `i' than satisfying criterion `j.

3.2 DEMATEL approach

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) is a multi-criteria decision-making (MCDM) technique developed to analyze and visualize the complex causal relationships among criteria. Originating from the Battelle Memorial Institute in the 1970s, DEMATEL converts qualitative assessments into quantitative data, enabling the identification of cause-and-effect chains among factors. The process begins with the construction of a direct-relation matrix based on expert evaluations of the pairwise influence among criteria. This matrix is then normalized and used to derive a total-relation matrix, which reveals both direct and indirect influences. By mapping these relationships, DEMATEL helps decision-makers to identify critical criteria and understand their interdependencies, facilitating more informed decision-making. This method is particularly useful in complex environments where factors are interrelated, such as SCM and I4.0 implementations. DEMATEL has been broadly accepted in numerous fields to tackle intricate decision-making challenges and improve strategic planning (Tzeng et al., 2007).

The stepwise process is as follows:

Step 1: Create a direct relation matrix (M).

In the following section, the expert estimates any two factors on an interval scale of 0–5, as shown in Table 3.3. Therefore, if there are m factors for a complex decision-making problem and N number of decision-makers, then each decision-maker develops an "*m X m*" matrix representing the interrelationships between the various factors. The next index depicts the meaning of each element is X_{ab}^{n}, that the meaning of the a^{th} row and b^{th} column where n is equal one to five. The next procedure is constructing a transformed average direct relationship matrix (A) from the values.

'N' matrices to account for the views of all the 'N' verdict makers via the Eq. (3.4)

$$A_{ab} = \frac{1}{N} \sum_{n=0}^{N} X_{ab}^{n} \tag{3.4}$$

Step 2: Calculation of direct relation matrix (B)

The straightforward matrix operation described in Eq. (3.5) can be used to transform the average matrix (A) into a normalized direct relation matrix (B).

$$B = A \; X \; Q \tag{3.5}$$

Where

$$Q = \min\left[\frac{1}{\max(\sum_{a=1}^{N}|A_{ab}|}\right], \left[\frac{1}{\max(\sum_{a=1}^{N}|A_{ab}|}\right]$$

Step 3: Develop the total relation matrix (P) (3.6)

$$P = B(I - B)^{T} \tag{3.7}$$

I = Identity matrix

Step 4: Finding the Threshold Value

The threshold value has been set up at the mean equivalent of all the elements in the relation matrix (P). In that context, the threshold does appear to be of much assistance in the activity of developing the cause-and-effect diagram because, in the cause-and-effect diagram, the values will only be shown that are above the threshold. In such a situation, the threshold value lies at the most optimal strategic position. The causal diagram that arises pinpoints the interactive association between the characteristics, and it will be easier and more intuitive to understand the interdependency and the behavior of attributes depending on one another.

Table 3.3 Scale for pairwise comparison

Definition	Numerical rating
No Impact	0
Very Minimal Impact	1
Minimal Impact	2
Medium Impact	3
Strong Impact	4
Very Strong Impact	5

Using the 1–9 scale proposed by Rezaei (2015) and displayed in Table 3.2, the professionals were asked to rank their choices and results are displayed in table 3.4 after taking average.

Table 3.4 Best to Other

Best to others	B1	B2	B3	B4	B5	B6	B7	B8	B9
B2	2	1	4	5	3	9	7	6	8

The respondents were additionally asked to rate their preferences for all other challenges relative to the least valuable challenge, using the same 1-9 scale. The responses from all the specialists were collected and averaged, resulting in the data presented in Table 3.5.

Table. 3.5 Rest of challenges to worst challenge

Others to the worst	B6
B1	8
B2	9
B3	6
B4	5
B5	7
B6	1
B7	2
B8	4
B9	2

Applying BWM procedure yields optimal weights of each challenge depicted in Table 3.6

Table 3.6 Optimal weights.

B1	B2	B3	B4	B5	B6	B7	B8	B9
0.1913	0.3145	0.0956	0.0764	0.1276	0.0275	0.0548	0.0637	0.0478

CHAPTER 4

RESULTS AND DISCUSSIONS

The fourth section of this thesis presents the findings from the hybrid methodology employed to analyze the supply chain challenges in the application of I4.0 within the textile sector. This chapter integrates the results obtained from the Best Worst Method (BWM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach. The hybrid methodology leverages the strengths of both methods: BWM's ability to find the relative importance of various challenges, and DEMATEL's capacity to unravel the complex interrelationships among these challenges. By combining these approaches, we aim to provide a complete understanding of the prioritization and causal structure of the identified challenges.

The chapter begins with the application of the BWM to derive the weights of the supply chain challenges, reflecting their relative importance. Following this, the DEMATEL method is implemented to explore the direct and indirect relationships between the challenges, highlighting the causal chains and critical factors that influence the application of I4.0 technologies in the textile supply chain.

The results section elaborates on the hybrid model's findings, detailing the DEMATEL implementation process, including the construction and normalization of the direct relation matrix, and the subsequent calculation of the total relation matrix. The discussion then interprets these findings, identifying key challenges, their interdependencies, and offering practical recommendations based on the integrated analysis. The insights gained from this hybrid approach provide valuable guidance for industry practitioners and policymakers, aiding in the tactical preparation and successful application of I4.0 initiatives in the textile sector.

4.1 Hybrid Model

A thorough analysis of the literature and input from industry professionals helped identify the difficulties in applying I4.0. Following the identification of the difficulties, a questionnaire was sent to professionals with in academia and industry to further evaluate the weights and classifications of the challenges. There were 5 experts chosen for this investigation. The implementation of BWM and DEMATEL techniques was based on their response and opinion**.**

The hybrid methodology's application follows a step-by-step process. Initially, the BWM methodology is used to allocate weightages and rank various challenges, with the results presented in Table 4.5. Subsequently, the DEMATEL methodology is employed to classify the challenges into cause-and-effect groups. The steps outlined in Section 3.2.1 for implementing DEMATEL have been adhered to, with the outcomes detailed in Table 4.8.

4.2 DEMATEL Implementation

The DEMATEL method is applied to the problems, which helps to divide the issues into cause-and-effect groups. The expert responses were collected into a comparison matrix for assessment of the effects of each issue. Averages Direct-Relation Matrix is developed on the numbers rated by the experts. Normalizing Equation (3.2) is used to normalize the direct matrix to the start in Table 4.2. The total relational matrix via Equation (3.3) is formed. On the other hand, Rm and Cm are assessed after completing the relational matrix. where R_m is the sum of all elements in m^{th} row and C_m is the sum of all elements in m^{th} column. These results are shown in Table 4.4.

The Direct Relation Matrix (Table 4.1) is an average of the opinions given by the experts established on numerical rating.

Table 4.1 Direct Relation Matrix

	B1	B2	B3	B4	B5	B6	B7	B8	B9
B1	1	5	5	4	3	2	4	2	3
B2	5	1	5	4	3	2	3	1	4
B3	5	4	1	3	4	4	3	3	3
B4	1	1	3	1	5	2	3	4	4
B5	1	1	4	4	2	2	4	3	5
B6	3	4	5	1	1	1	5	2	3
B7	4	3	4	3	1	3	1	4	2
B8	4	3	4	4	2	1	4	1	2
B9	1	2	4	4	5	1	3	3	1

The Normalized Relation Matrix (Table 4.2) is obtained by dividing each element by the maximum row sum, to ensure that all the value are between 0 and 1.

Table 4.2 Normalized Relation Matrix

	B1	B2	B3	B4	B5	B6	B7	B8	B9
B1	0.033	0.167	0.167	0.133	0.100	0.067	0.133	0.067	0.100
B2	0.167	0.033	0.167	0.133	0.100	0.067	0.100	0.033	0.133
B3	0.167	0.133	0.033	0.100	0.133	0.133	0.100	0.100	0.100
B4	0.033	0.033	0.100	0.033	0.167	0.067	0.100	0.133	0.133
B5	0.033	0.033	0.133	0.133	0.067	0.067	0.133	0.100	0.167
B6	0.100	0.133	0.167	0.033	0.033	0.033	0.167	0.067	0.100
B7	0.133	0.100	0.133	0.100	0.033	0.100	0.033	0.133	0.067
B8	0.133	0.100	0.133	0.133	0.067	0.033	0.133	0.033	0.067
B9	0.033	0.067	0.133	0.133	0.167	0.033	0.100	0.100	0.033

Table 4.3 Total Relational Matrix

	B1	B2	B3	B4	B5	B6	B7	B8	B9	Rm
B1	0.780	0.857	1.148	0.957	0.889	0.626	0.980	0.766	0.892	7.895
B2	0.871	0.716	1.117	0.932	0.869	0.608	0.926	0.716	0.897	7.652
B3	0.918	0.852	1.061	0.950	0.935	0.697	0.982	0.812	0.914	8.121
B4	0.632	0.599	0.902	0.711	0.801	0.516	0.796	0.702	0.772	6.430
B5	0.679	0.644	0.993	0.855	0.762	0.554	0.877	0.719	0.851	6.934
B6	0.762	0.753	1.030	0.763	0.721	0.528	0.906	0.677	0.786	6.926
B7	0.781	0.717	0.993	0.818	0.720	0.582	0.782	0.732	0.753	6.878
B8	0.774	0.709	0.988	0.849	0.754	0.522	0.869	0.644	0.754	6.863
B9	0.640	0.633	0.937	0.810	0.811	0.493	0.800	0.678	0.689	6.490
Cm	6.198	5.849	8.231	6.835	6.451	4.632	7.118	5.766	6.619	

The Total Relational Matrix (Table 4.3) has been formed using the formula in equation 3.7, through MATLAB.

The Total of $R_m + C_m$ and difference $R_m - C_m$ are assessed for each challenge to determine their level of prominence and their relation to other challenges, respectively. Ultimately, the challenges are categorized into cause-effect groups based on the $R_m - C_m$ values. The analysis is presented in Table 4.8.

Table 4.4 Classification of challenges into –cause-effect groups

Sr.No.	Challenges	Notation	R_m	C_m	$R_m + C_m$	$R_m - C_m$	Group
1	Inadequate technical skills of workers	B1	7.894	6.198	14.091	1.697	cause
2	Lack of awareness of workers	B2	7 .653	5.847	13.502	1.806	cause
3	Skills Gap and Workforce Training	B3	8.121	8.231	16.352	− 0.111	effect
4	Supply Chain Complexity	B4	6.430	6.835	13.265	− 0.405	effect
5	Tech. Infrastructure Limitations	B5	6.93	6.451	13.385	0.484	cause
6	Data overload and management	B6	6.925	4.634	11.558	2.291	cause
7	Collaboration and Trust	B7	6.877	7.119	13.996	− 0.242	effect
8	Budgetary Constraints	B8	6.863	5.766	12.629	1.097	cause
9	Ethical Challenges	B9	6.490	6.619	13.109	− 0.128	effect

According to Table 4.4, challenges such as Skills Gap and Workforce Training (B3), Supply Chain Complexity (B4), Collaboration and Trust (B7), and Ethical challenges (B9) fall into the effect category, indicated by their negative 'Rm - Cm' values, meaning they are influenced by other challenges. Conversely, challenges like Legacy Infrastructure (B1), Lack of Awareness and Knowledge (B2), Tech. Infrastructure Limitations (B5), Data overload and management (B6), and Budgetary Constraints (B8) have positive 'Rm - Cm' values, indicating they influence other challenges and are therefore in the cause category.

Table 4.5 Ranking of Challenges

Rank No.	Challenges
1	Lack of Awareness and Knowledge
2	Legacy Infrastructure
3	Tech. Infrastructure Limitations
4	Skills Gap and Workforce Training
5	Supply Chain Complexity
6	Budgetary Constraints
7	Collaboration and Trust
8	Ethical challenges
9	Data overload and management

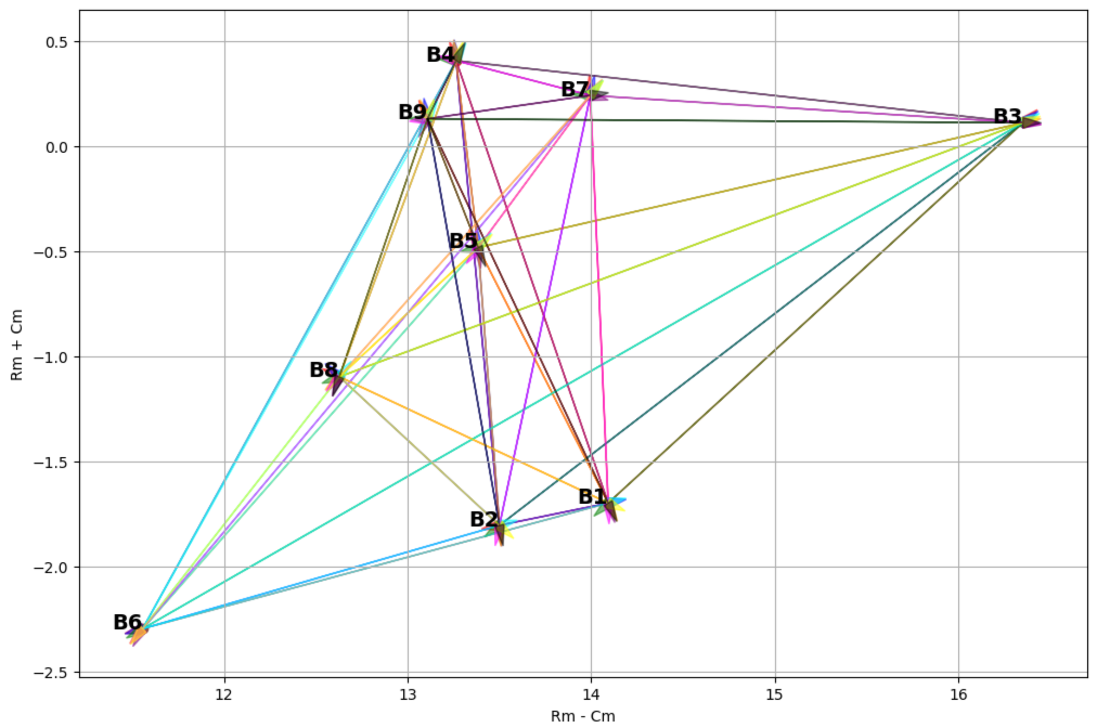

Figure 4.1 Influential Relationship Map (IRM)

The final step involves developing an Influential Relation Map (IRM) shown in figure 4.1, which is plotted with Relation values (Rm - Cm) on the Y-axis and Prominence values (Rm + Cm) on the X-axis. The IRM graph indicates that challenges such as Data Overload and Management (B6) and Lack of Awareness and Knowledge (B2) have the highest repercussions on the entire system, evidenced by their higher 'Relation' values. However, these challenges exhibit low 'Prominence' values, suggesting that while they exert significant influence on other factors, they themselves are less influenced by other challenges in return. On the other hand, Skills Gap and Workforce Training (B3) displays both high 'Relation' and high 'Prominence' values, indicating its critical influence on other challenges such as Technological Infrastructure Limitations (B5), Supply Chain Complexity (B4), Collaboration and Trust (B7), and Ethical Challenges (B9). Conversely, challenges like Ethical Challenges (B9) and Budgetary Constraints (B8) are characterized by low 'Relation' and 'Prominence' values, indicating that they have minimal influence on and from other factors in the system. This mapping helps in identifying key leverage points where interventions can be most effective in addressing the interconnected challenges.

4.3 Key Findings of the Best-Worst Method

The application of the Best Worst Method (BWM) in this study has provided a clear prioritization of the supply chain challenges associated with the implementation of Industry 4.0 in the textile sector. The results, summarized in Table 4.5, reveal the relative importance of each challenge.

The most critical challenge identified is the "Lack of Awareness and Knowledge," which highlights the significant need for better understanding and education regarding I4.0 technologies in the textile sector. This is followed by "Legacy Infrastructure," indicating that outdated systems and equipment pose substantial obstacles to the acceptance of new technologies. "Technological Infrastructure Limitations" ranks third, emphasizing the importance of having robust and advanced technological foundations to support Industry 4.0 initiatives.

The fourth-ranked challenge, "Skills Gap and Workforce Training," points to the necessity for workforce expansion and skillup sessions to prepare workers with the services needed for modern technological environments. "Supply Chain Complexity" comes in fifth, underscoring the intricate and interconnected nature of textile supply chains that complicate the application of new technologies.

"Budgetary Constraints" is identified as the sixth major challenge, reflecting the monetary hurdles that companies face in investing in Industry 4.0 technologies. This is followed by "Collaboration and Trust," which highlights the need for strong partnerships and trust among supply chain partners. "Ethical Challenges" rank eighth, indicating concerns about the ethical implications of adopting new technologies. Lastly, "Data Overload and Management" is ranked ninth, pointing to the challenges associated with handling and analyzing the large volumes of data produced by I4.0 technologies. Overall, the BWM findings provide a structured and prioritized list of challenges, offering valuable insights for stakeholders in the textile sector to address these issues strategically and effectively in their Industry 4.0 implementation efforts.

4.4 Findings of DEMATEL Method

Based on table 4.4, challenges are put into cause-and-effect groups. The cause group includes Inadequate Technical Skills of Workers (B1), Lack of Awareness of Workers (B2), Technological Infrastructure Limitations (B5), Data Overload and Management (B6), and Budgetary Constraints (B8). These challenges have a positive Rm - Cm value, indicating they exert more influence on other challenges than they receive. These challenges act as fundamental drivers that impact the effectiveness and efficiency of the entire system. Conversely, the effect group comprises Skills Gap and Workforce Training (B3), Supply Chain Complexity (B4), Collaboration and Trust (B7), and Ethical Challenges (B9). These challenges have a negative Rm - Cm value, meaning they are more influenced by other factors. They are the outcomes or consequences of the issues originating from the cause group. Addressing the challenges in the cause group can potentially alleviate the challenges in the effect group, leading to overall system improvement.

4.5 Practical Recommendations

Invest in lifelong learning and development programs to bring workers to the newest technologies within Industry 4.0.

For Policy Makers:

Offer incentives for companies to accept I4.0 technologies. Encourage industries to collaborate with educational institutions in the identification, designing, and development of required training programs.

Develop and design courses and training programs in the technologies specialized in Industry 4.0. Engage industry stakeholders in defining curricula according to expressed needs.

Mitigate Budgetary Constraints through Strategic Funding: The flexibility to access other sources of funding, such as public-private partnerships, grants, and subsidies, would greatly relieve the cost burdens. At the same time, straightforward returns on investment in Industry 4.0 investments will most probably attract investors and stakeholders. The financial plan and resource allocation have to be maximized to ensure continuing investments in these technological upgrades.

CHAPTER 5

CONCLUSION

The systematic application of the Best Worst Method (BWM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodologies has yielded critical insights into the supply chain challenges plaguing the implementation of Industry 4.0 within the textile sector. The ranking provided by BWM highlights dearth of awareness and knowledge, legacy infrastructure, and technical limits as the foremost hurdles.

Furthermore, the DEMATEL analysis has elucidated the causal relationships among these challenges and differentiate them into cause-and-effect groups, pinpointing low skills among workers, lack of awareness, technological infrastructure limitations, data overload, and budgetary constraints as significant contributors. These findings underscore the imperative for targeted interventions aimed at addressing challenges at their root causes.

Effective management strategies must be implemented to prioritize technological upgrades and workforce training initiatives. Management commitment is crucial in securing the necessary resources and advocating for the importance of addressing these challenges to top administration. Additionally, engaging experienced consultants for tailored training programs is essential to bridge the skills gap among employees.

Collaboration among industry stakeholders, policymakers, educators, and researchers is paramount in fostering a conducive environment for skill development and professional ethics. By working together, these stakeholders can drive the necessary changes to ensure the sustainability and competitiveness of the textile sector in the era of Industry 4.0.

In conclusion, this thesis serves as a blueprint for action, providing a systematic framework for identifying, prioritizing, and addressing supply chain challenges in the textile sector. By leveraging the insights gleaned from BWM and DEMATEL analyses, stakeholders can embark on a collective journey towards a technologically advanced, ethically sound, and resilient textile industry.

5.1 Limitations and Future Scope

While this study endeavors to shed light on supply chain challenges in the application of I4.0 within the textile sector, several limitations must be acknowledged. Firstly, the findings are based on a sample of industry experts, potentially limiting the representation of diverse perspectives within the sector and introducing bias. Secondly, although the Best Worst Method (BWM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodologies provided a robust analytical framework, their reliance on subjective judgments and assumptions could introduce variability into the results. Lastly, the context-specific nature of the study confines the generalizability of findings solely to the textile industry, possibly restricting their applicability to other sectors or industries. These limitations suggest avenues for upcoming research and emphasize the need for caution in interpreting the results within their specific context

As this study contributes to understanding supply chain challenges in I4.0 implementation within the textile sector, it also illuminates avenues for future research and exploration. Long studies trailing the development of these challenges over period could provide valued intuitions into their persistence, emergence, and potential mitigation strategies. Furthermore, comparative analyses with other industries or sectors would bid wider perspectives and facilitate the development of more robust and transferable solutions. Exploring advanced analytical techniques, such as machine learning algorithms or system dynamics modeling, holds promise for enhancing predictive capabilities and informing strategic decision-making, alongside fostering cross-disciplinary partnership among academe, industry, and representatives, could drive sustainable innovation and transformative change in the textile sector and beyond. These future research directions aim to build upon the foundation laid by this study and contribute to advancing knowledge and practice in I4.0 adoption and SCM.

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My name is Hamish Ali, I have completed my Bachelor of Technology in Textile Engineering from Government Central Textile Institute (GCTI) Kanpur in 2021. At present, I am pursuing Master of Technology in Industrial Engineering and Management from Delhi Technological University, New Delhi.

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