INDUSTRY 4.0 TECHNOLOGIES AND SUPPLY CHAIN RESILIENCE: INSIGHTS FROM LOGISTICS AND SUPPLY CHAIN PERSPECTIVES IN PENANG

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ABSTRACT

The adoption of Industry 4.0 technologies is transforming supply chain operations by enhancing efficiency, automation, and resilience. However, logistics and supply chain firms in Penang, Malaysia, face challenges in implementing key technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, Robotics, and Blockchain. Limited adoption, high costs, and cybersecurity risks hinder digital transformation, affecting supply chain resilience. This study examines the role of Industry 4.0 technologies in strengthening supply chain resilience, focusing on key enablers and challenges. Using a quantitative approach, data was collected from 254 firms in the logistics and supply chain sector. Findings show that IoT and AI improve visibility and predictive analytics, robotics enhances operational efficiency, Big Data supports strategic planning, and Blockchain strengthens security and transparency. However, adoption barriers remain a concern. The researcher highlights the need for strategic collaboration among businesses, policymakers, and technology providers to facilitate Industry 4.0 adoption. These insights provide a foundation for companies to enhance digital transformation strategies, ensuring a more resilient and competitive supply chain.

Keywords: Supply Chain Resilience, Internet of Things (IoT), Artificial Intelligence, Robotic and Automation, Big Data Analytics, Blockchain

ABSTRAK

Penggunaan teknologi Industri 4.0 semakin mengubah operasi rantaian bekalan dengan meningkatkan kecekapan, automasi, dan ketahanan. Walau bagaimanapun, syarikat logistik dan rantaian bekalan di Pulau Pinang, Malaysia menghadapi cabaran dalam melaksanakan teknologi utama seperti *Kecerdasan buatan (AI), Internet benda(IoT), Analitik Data Besar, Robotik dan Rantaian Blok.* Kadar penerimaan yang rendah, kos tinggi, serta risiko keselamatan siber menghalang transformasi digital dan menjejaskan ketahanan rantaian bekalan. Kajian ini meneliti peranan teknologi Industri 4.0 dalam meningkatkan ketahanan rantaian bekalan, dengan memberi tumpuan kepada faktor penggerak dan cabaran utama. Pendekatan kuantitatif digunakan dengan pengumpulan data daripada 254 syarikat dalam sektor logistik dan rantaian bekalan. KajianINI menunjukkan bahawa IoT dan AI meningkatkan keterlihatan serta analitik ramalan, robotik memperkukuh kecekapan operasi, analitik data besar menyokong perancangan strategik, serta rantain blok mempertingkatkan tahap keselamatan serta ketelusan. Walau bagaimanapun, cabaran dalam pelaksanaannya masih menjadi isu utama. Kajian ini menekankan keperluan untuk kerjasama strategik antara perniagaan, pembuat dasar, dan penyedia teknologi bagi memudahkan penerapan teknologi Industri 4.0. Penemuan ini diharap dapat membantu dalam memperkukuh strategi transformasi digital serta mewujudkan rantaian bekalan yang lebih berdaya saing.

Kata kunci: *Supply Chain Resilience, Internet of Things (IoT), Artificial Intelligence, Robotic and Automation, Big Data Analytics, Blockchain*

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LIST OF ABBREVIATION

3PL	Third-Party Logistics
AGVs	Automated Guided Vehicles
AI	Artificial Intelligence
AS/RS	Automated Storage and Retrieval Systems
BDA	Big Data Analytics
DCT	Dynamic Capabilities Theory
CPS	Cyber-Physical Systems
DSCT	Digital Supply Chain Twin
IoT	Internet of Things
RPA	Robotic Process Automation
SCM	Supply Chain Management
SCR	Supply Chain Resilience
SPSS	Statistical Package for the Social Sciences

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In the logistics and supply chain management sector, there is increasing interest in the integration of Industry 4.0 technologies on supply chain resilience among logistics operations and supply chain management. Logistics and supply chains are changing the way they operate due to the adoption of Industry 4.0 technologies, such as automation, robots, Artificial Intelligence (AI), and the Internet of Things (IoT). These technologies are driving greater productivity, efficiency, and adaptability in the industry. The significance of supply chain resilience and the ability of Industry 4.0 technology to reduce supply chain risks have been emphasized by the COVID-19 pandemic. The adoption of disruptive technologies is positively correlated with supply chain performance, according to recent research examining the effects of Industry 4.0 technologies on supply chain resilience. However, the adoption of Industry 4.0 technologies in logistics and supply chain operations also faces challenges such as data security, interoperability, and standardization. This topic is of significant interest to academics, practitioners, and industry professionals, as the integration of Industry 4.0 technologies leads to improved supply chain visibility, efficiency, and cost-effectiveness, ensuring continuity and efficiency in their operations (Cano et al., 2021).

Logistics must be able to adjust to the unique demands of the new Industry 4.0 production environment since it has a direct impact on the productivity, quality of service, and customer happiness of the business. Therefore, it is doubtful that the logistics frameworks and systems in place today will be able to handle the extra complexity brought about by Industry 4.0, particularly without raising prices or sacrificing quality (Wang et al., 2020; Winkelhaus & Grosse, 2019).

It is easy to leverage digital supply chain resilience from logistics and supply chain firms to track shipments, authenticate goods, and improve quality operations across the supply chain (Hohenstein et al., 2015). IoT is valuable in integrated logistics because it can predict, manage, and improve logistical processes. Barcode and Radio Frequency Identification (RFID) technologies use radio waves to read digital data from RFID tags, QR labels, and barcodes. Many companies are switching to RFID from traditional warehouse tasks including labeling, storing, and placement allocation. The subsequent user can easily get product information via RFID tags and barcodes by attaching them to products upon receipt. Additionally, it enhances the inbound, outbound, and storage procedures in warehouses and expedites the picking process. Aside from that, Warehouse Management Systems (WMS) is an essential element of software that monitors everyday tasks in logistics. The benefits of a WMS include reduced labor costs, quicker processing times, improved warehouse output, increased inventory accuracy, and greater space utilization (Valchkov & Valchkova, 2018).

Christopher and Peck (2004) defined Resilience of the supply chain refers to its capacity to react swiftly to unforeseen shifts in supply or demand; this might be accomplished by making quick adjustments to systems and business procedures. Supply chain resilience implementation benefits companies in numerous ways. New technologies offer the potential to strengthen businesses' resilience and do away with long-standing, conventional practices. Using manual inventory monitoring techniques across many software programs and spreadsheets results in inconsistent tracking, which is laborious, repetitive, and prone to mistakes. Shipments might be partial, inaccurate, or delayed due to limited visibility in cases where inventory is difficult to detect or identify in the warehouse. Acquiring and locating the appropriate inventory is essential for effective warehouse functions and satisfying consumer experiences. The Internet of Things (IoT), blockchain item tracking, warehouse management systems, radio frequency identification, and barcode technology are a few examples of smart warehouse technologies.

Supply chain resilience can be achieved through efficient logistics management to lower transportation costs or through improved supply planning to increase stock delivery. Resilience, for example, is a method used by logistics operations to deliver high-value supply chain services and maximize performance. In this context, resilience can be understood as a supply chain capability that can mitigate the severity of supply chain vulnerabilities and work in tandem with standard risk processes. The capacity of the supply chain to adjust, react, flex, and adjust to contextual and environmental changes (Christopher & Peck, 2004; Sheffi & Rice Jr., 2005).

Logistics Industry presents unique potential and problems that are not sufficiently examined in the literature on Industry 4.0 and supply chain resilience. This study aims to bridge the gap by providing a comprehensive look at how Industry 4.0 technologies are being integrated into logistics and supply chains and the impact this has on enhancing supply chain resilience. By filling these gaps, this study improves the understanding of how logistics industry can strategically use Industry 4.0

technologies to strengthen supply chain resilience in an increasingly complex and uncertain environment. The knowledge gathered from this research can benefit research and business, providing insightful direction for future logistics procedure advancements.

1.2 Problem Statement

The increasing complexity and volatility of global supply chains have highlighted the need for businesses to adopt Industry 4.0 technologies to enhance supply chain resilience. Technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, Blockchain, and Robotics are transforming logistics and supply chain management by improving efficiency, transparency, and adaptability (Mandal.& S.Sarathy & R., 2016) . However, despite the proven benefits, logistics and supply chain firms in Penang face significant challenges in implementing these technologies effectively.

One of the primary barriers is the uneven adoption and integration of Industry 4.0 solutions across organizations. Many firms struggle with high implementation costs, technical complexity, data security concerns, and the lack of a skilled workforce to manage these advanced systems (Mandal.& S.Sarathy & R., 2016) . Additionally, there is a limited understanding of how Industry 4.0 technologies directly contribute to supply chain resilience, particularly within the logistics sector in Penang. This knowledge gap prevents businesses from making informed decisions on digital transformation strategies, leaving their supply chains vulnerable to disruptions.

The consequences of failing to adopt these technologies are severe operational inefficiencies, delays, increased costs, and an overall decline in supply chain performance. Given the increasing risks posed by global uncertainties, trade disruptions, and supply chain shocks, it is crucial to investigate how Industry 4.0 technologies can strengthen resilience, enhance flexibility, and improve real-time decision-making in logistics operations (Mandal.& S.Sarathy & R., 2016).

This study aims to address this research gap by analysing the role of Industry 4.0 technologies in enhancing supply chain resilience from the perspective of logistics and supply chain companies in Penang. By identifying the key challenges, enablers, and impact factors, the findings will provide actionable insights for businesses, policymakers, and industry stakeholders. The study will contribute to the development of strategic frameworks for digital transformation, ensuring a more resilient, efficient, and future-ready supply chain ecosystem.

1.3 Research Objectives

The objectives of this study are:

i. To investigate the impacts of the Internet of Things (IoT) on supply chain resilience.
ii. To examine the implementation of artificial intelligence (AI) on supply chain resilience.
iii. To examine how robotics and automation contribute to supply chain resilience.
iv. To examine big data implementation on supply chain resilience.

v. To examine blockchain impacts on supply chain resilience.

1.4 Research Questions

To meet the above research objectives, the following research questions were formulated:

i. Does the Internet of Things (IoT) impact the supply chain resilience?
ii. Does the implementation of artificial intelligence (AI) affect supply chain resilience?
iii. Do robotics and automation contribute to supply chain resilience?
iv. What is the effect of big data implementation on supply chain resilience?
v. Does blockchain affect supply chain resilience?

1.5 Scope of Research

The impact of Industry 4.0 technologies on Logistics and Supply Chain Management is a significant and developing area of research, and their integration into supply chain management is drawing growing attention. The scope of research in this domain involves exploring how Industry 4.0 technologies can enhance supply chain resilience within the context of Logistics operations and Supply Chain Operations. The study focused on Penang, specifically targeting the Logistics and Supply Chain companies. The company representatives should have a minimum of six months of work experience in the field.

1.6 Limitation of Research

This study may have several limitations. First, the study was carried out in Penang, Malaysia. The findings of the study may be specific to certain industries, regions, or types of operations. Generalizing the results to a broader context may be challenging. Small sample sizes can affect the representativeness of the study. The results may not be statistically significant or applicable to a larger population of the logistics and supply chain sector. Since Industry 4.0 technologies are developing so quickly, the technology in use at the time of the study may not last long. Future developments could impact the relevance of the findings. The study may identify obstacles to Industry 4.0 technology adoption by logistics and supply chain operations, but it may not provide detailed solutions for overcoming these barriers. The study may not comprehensively cover all aspects of these concerns, leaving gaps in understanding. The study may focus primarily on technological aspects and not adequately address the human factors involved in the integration of Industry 4.0 technologies, such as workforce training and acceptance.

Despite that, the long-term impacts of Industry 4.0 adoption may not be fully captured, especially if the study relies on short-term data. Longitudinal studies can be resource-intensive and may not be feasible in some cases. External factors beyond the scope of the study, such as geopolitical events, natural disasters, or global economic changes, could impact the supply chain and logistics operations. These factors fall outside the scope of this study and could affect the broader applicability of its findings.

The researcher transparently discusses these limitations in their studies, providing insights into the potential impact of the findings and suggesting directions for future research to address these limitations. This helps to enhance the credibility and applicability of the study within the academic and practitioner communities.

1.7 Significance of Research

The research aims to study the integration of Industry 4.0 technologies, which has the potential to enhance the resilience of supply chains significantly. By utilizing technologies such as IoT, big data analytics, AI, and automation, organizations can improve visibility, agility, and flexibility, enabling them to better respond to disruptions and minimize downtime.

Improved efficiency and cost savings by integrating Industry 4.0 technologies can lead to greater operational efficiency and cost savings in supply chain management. For example, real-time data analytics can facilitate better demand forecasting, optimize inventory levels, and enhance resource allocation, reducing waste and streamlining operations. Understanding the integration of Industry 4.0 technologies in Logistics and Supply Chain Management is significant as it offers insights into how these advancements can enhance operational efficiency. This research can contribute to optimizing processes, reducing costs, and improving overall performance in logistics and Supply Chain Management. (Lee et al., 2015).

Businesses that successfully adopt Industry 4.0 technology stand to benefit from a competitive edge in the marketplace. Businesses may meet changing market needs, increase customer happiness, and beat rivals in terms of agility and reactivity by strengthening the resilience of their supply chains. The study holds significance by uncovering the specific implications of Industry 4.0 technologies on supply chain resilience within the realm of Logistics and Supply Chain Management. This information is essential for directing strategic decision-making, empowering logistics operations to improve their overall resilience in a turbulent business environment and proactively navigating disruptions (Schwab, 2017).

Identifying and addressing barriers to the adoption of Industry 4.0 technologies in Logistics and Supply Chain Management is a significant contribution of this research. By shedding light on these challenges, the study can inform industry stakeholders and policymakers on strategies to overcome obstacles, facilitating a smoother integration of technologies that can elevate the competitiveness of Logistics and Supply Chain Management (Dolgui et al., 2018).

Overall, studying the integration of Industry 4.0 technologies on supply chain resilience among Logistics and Supply Chain Management is of significant importance as it provides insights and strategies for organisations to capitalise on these technologies, enhance their supply chain operations, gain a competitive edge, and ultimately deliver value to customers and stakeholders.

1.8 Definition of Key Terms

When researching the integration of Industry 4.0 technologies on supply chain resilience among Logistics and Supply Chain Management, it's essential to provide clear definitions of key terms to ensure a common understanding among readers.

i. Industry 4.0

Industry 4.0 refers to a transformative shift in business operations through advanced digital technologies, emphasizing responsiveness, decentralisation, and digitalised ecosystems (Ghobakhloo M. I.-L., 2025).

ii. Supply Chain Resilience

Resilience in the supply chain is the ability to control risks, absorb shocks, and maintain continuity to guarantee a robust reaction to unforeseen occurrences or changes in the operational environment (Wieland, 2021).

iii. Logistics

In the era of Industry 4.0, logistics operations transcend traditional practices, integrating digital technologies such as IoT, AI, and automation to create smart, adaptive systems. These innovations allow for real-time monitoring, intelligent routing, and predictive analytics, enabling logistics to become not only faster and more flexible but also more sustainable and resilient in responding to disruptions and customer demands. This shift reshapes logistics into a proactive, data-driven process that is critical to the success of modern supply chains (Wang C. N., 2024).

iv. Internet of Things (IoT)

The "Internet of Things" is a network of networked items that can exchange data and gather information because they are outfitted with sensors, software, and other technologies. Because it enables real-time tracking, monitoring, and communication throughout the supply chain, which increases visibility and control, the Internet of Things is crucial to logistics (Ben-Daya, 2019).

v. Artificial Intelligence (AI)

The term "artificial intelligence" refers to the use of computer systems to carry out operations that normally call for human intelligence. Predictive analytics, machine learning algorithms, and decision-making systems are examples of AI uses in logistics that help create more adaptable and efficient operating procedures. (Modgil, 2021)

vi. Robotics

Robotics is the study of using machines or robots to carry out tasks on their own. Robotics is used in logistics to automate material handling, order fulfilment, and warehousing activities to boost productivity, accuracy, and speed. (Banur et al., 2024)

vii. Big Data Analytics

Entails handling and analyzing massive amounts of data to find trends, insights, and patterns. Big Data analytics plays a key role in logistics by helping to improve overall operational performance, optimize supply chain processes, and make data-driven choices. (Chitta, 2017)

viii. Blockchain

Blockchain, characterized by its decentralized and immutable ledger, offers significant benefits in enhancing transparency, efficiency, and trust among supply chain stakeholders. It enables the accurate tracking of products, the verification of provenance, and streamlined processes through smart contracts, which reduce the need for intermediaries and minimize operational costs (Kshetri, 2018).

1.9 Organization of Thesis

The report for this project paper will be divided into five chapters. The detailed descriptions of each study chapter are provided below. This section will outline the research's importance and scope. The study's explanation, objectives, approach, questions, problem statement, significance, and limits will all be covered in this part.

i. Chapter 2: Literature Review

This section's main focus is the literature review. The journals and papers that helped us comprehend the subject at hand are listed in this section. This section should also further detail the relationship between the intended research and relevant studies.

ii. Chapter 3: Research Methodology

This section outlined a thorough strategy for responding to the main hypothesis and research question of the study. This chapter's objective is to provide a detailed breakdown of each phase in the process. It's so that another person can repeat the experiment. The study's design, demographic, and sample size, tools, procedures, expected data analysis, and conclusion are all included in this section.

iii. Chapter 4: Finding And Analysis

This section presents the data analysis carried out to gain more details about the research topic, "Industry 4.0 Technologies and Supply Chain Resilience: Insights from Logistics and Supply Chain Perspectives in Penang." The findings offer strong evidence and reliable facts that support the research focus. Additionally, the results provide accurate and relevant information that strengthens the overall study.

iv. Chapter 5: Discussion

This section brings together all the key findings and draws conclusions based on the overall results of the study. It also offers practical suggestions, openly discusses the study's limitations, and puts forward ideas for future research.

1.10 Chapter Summary

It presents an understandable justification for examining how Industry 4.0 affects supply chain resilience. Despite advancements in supply chain management, traditional models often struggle to effectively address the dynamic challenges and disruptions that characterize contemporary global markets. The limitations of existing systems underscore the need for innovative approaches to enhance supply chain resilience. While Industry 4.0 technologies have gained traction in various industries, their adoption within logistics and supply chain remains relatively limited. Understanding the factors contributing to this lag in adoption is crucial for identifying barriers and developing targeted strategies for successful integration.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Industry 4.0 is a new frontier for the global economy that might have a big impact on many different industries and alter how things are made, sold, and maintained. The notion of Industry 4.0 involves an autonomous interaction between products, machines, and operational processes both within and between businesses in an integrated corporate environment (Dolgui et al., 2018). The basic idea behind Industry 4.0 is that businesses may create intelligent networks that deliver goods to consumers and create value by dynamically integrating digital processes, systems, and machines along the whole supply chain (Hoberg & Alicke, 2016).

As supply chains become more complex and globally interconnected, the imperative to bolster resilience against disruptions becomes a strategic priority. Industry 4.0 technologies provide businesses with previously unheard-of chances to strengthen their supply chain operations. These technologies include robotics, artificial intelligence (AI), and the Internet of Things (IoT), as well as big data analytics. The synthesis of these technologies has the potential to revolutionize the way logistics and supply chain industries accomplish their responsibilities, optimizing processes, enhancing visibility, and fostering adaptability in the face of unforeseen events.

This study seeks to identify gaps, trends, and key insights that will inform our understanding of how the resilience of supply chains made possible by logistics operations and supply chain management is impacted by the incorporation of

Industry 4.0 technologies. Through this exploration, we aim to contribute to the academic discourse surrounding the transformative impact of Industry 4.0 on contemporary supply chain management and logistics practices.

2.2 Supply Chain Resilience in Logistics and Supply Chain Management

The ability of a supply chain to resume regular operating performance after being disrupted within an acceptable period is known as supply chain resilience (Brandon-Jones et al. 2014; Christopher & Peck 2004). Supply chain resilience integration creates an optimal supply chain by balancing material and capacity constraints against the demand plan to ensure efficient demand prioritization for specific organizational goals. Interfirm processes within Industry 4.0 and smart systems work together to minimise real interruptions and, to the extent possible, prevent problems in the future (Dolgui et al., 2018).

Supply chain resilience can be achieved through efficient logistics management to lower transportation costs or through improved supply planning to increase stock delivery. Resilience, for example, is a method used by logistics operations to maximise performance and deliver high-value supply chain services. In this sense, resilience can be understood as a supply chain capability that can mitigate the severity of supply chain vulnerabilities and work in tandem with standard risk processes. The capacity of the supply chain to adjust, react, flex, and adjust to contextual and environmental changes. The resilience of the supply chain is the ability to withstand and recover. This is also discussed by Dolgui et al. (2018). Resilience refers to the capacity of a supply chain to be sustained in the face of changing circumstances through the use of adaptive technologies. These are competencies that Industry 4.0 has the potential to improve.

Moreover, resilience in the supply chain is transformation. It is necessary to adapt and update current procedures and practices to handle current issues and build supply chain resilience. By developing resilience, businesses can handle the risk of supply chain interruption and carry on providing customers with goods and services (Ambulkar et al., 2014). Companies must modify their supply chain resilience plans in response to emerging difficulties to remain ahead of impending dangers. Businesses must adapt how they handle the three key components of supply chain resilience: people, technology, and procedures. To see their supply chain partners' demand and risk projections, businesses want end-to-end supply chain insight. Practically speaking, it's beneficial to be aware of your suppliers' current lead times and explain what dangers could lead to delays and disruptions in that schedule. The ability to fulfil both present and future capacity requirements on the intended delivery schedule is necessary for establishing an efficient supplier management procedure.

Table 2.1
Technological Adoption for Resilience

Concept	**Technologies**	**Samples**	**Impacts on Resilience**
Predictive Analysis	AI, Machine Learning	AI can predict demand forecasting and identify potential risk	Identify potential problems early and take action before disruption
Real-Time Monitoring	IoT, Blockchain	IoT-enabled sensors for shipment tracking	Improved response to supply chain interruptions
Automation and Robotics	Robotics, Process Automation	Automated warehouses and production lines	Enhanced efficiency and reduced human error

Source: (T. Khan et al., 2024)

2.3 Industry 4.0 Technologies and Supply Chain Resilience

The integration of Industry 4.0 technologies in logistics operations marks a significant evolution in supply chain management. Industry 4.0, characterized by the convergence of digital technologies and physical processes, introduces transformative elements such as the Internet of Things (IoT), artificial intelligence (AI), and real-time data analytics. This integration reshapes the way to operate, fostering increased connectivity, automation, and intelligence in logistics processes (Lee et al., 2015).

In the context of supply chain management, integrating Industry 4.0 technologies can have far-reaching implications. It enables seamless collaboration across the supply chain, from procurement to delivery, by leveraging real-time data and automation (GEP, 2019). This not only reduces operational costs and enhances agility but also allows for more accurate tracking and management of goods throughout the supply chain (Kannan, 2024).

Logistics service providers play a vital role in managing the movement of goods across the supply chain. By embracing Industry 4.0, these providers can optimize resource allocation, streamline transportation processes, and improve supply chain resilience. The integration of technologies like IoT, RFID, and machine learning ensures real-time visibility, reduces manual errors, and enhances the overall efficiency of logistics operations (Pfohl et al., 2015).

The impact of Industry 4.0 on supply chains shows how logistics companies could streamline their workflows and increase efficiency by implementing technology (Pfohl et al., 2015). Although the above literature does not specifically focus on Logistics 4.0, these works provide insights into the feasibility of the remaining potential benefits of Logistics 4.0 in supply chain management that this study needs to investigate to find the evidence of Industry 4.0 in logistics providers. However, the Industry 4.0 concept has its benefits and drawbacks as well (Pfohl et al., 2015). Industry 4.0 technologies in supply chain operations will present both challenges and opportunities for logistics providers. One of the challenges is the need for significant investments in technology infrastructure and employee training. For example, organisations have to create interoperability between different systems and technologies to facilitate and ensure that the data can flow seamlessly. Complexity and security risks associated with data management and cybersecurity also require consideration (Pfohl et al., 2015).

The rise of Industry 4.0 in logistics is changing the game, bringing smarter, faster, and more efficient ways to manage operations. At its core, Industry 4.0 blends cutting-edge digital tools like the Internet of Things (IoT), artificial intelligence (AI), cloud computing, big data, and robotics. By integrating automation with real-time data insights, logistics providers can track shipments with greater accuracy, make better decisions on the fly, and streamline supply chains like never before (IBM, 2022). This shift isn't just about technology; it's about creating a more connected, responsive, and resilient logistics network that keeps businesses running smoothly.

By integrating advanced technologies like the Internet of Things (IoT), artificial intelligence (AI), cloud computing, big data analytics, and robotics, companies can now optimise operations, enhance efficiency, and improve customer service (IBM, 2022). For instance, IoT adoption connects devices and allows real-time data sharing (Barreto et al., 2017). This connectivity makes it easier to track shipments, monitor equipment, and streamline logistics processes, ultimately reducing costs and improving overall performance (Abdirad & Krishnan, 2020). For example, IoT sensors and RFID tags help logistics providers keep an eye on goods, vehicles, and inventory in real time, minimising delays, cutting expenses, and boosting customer satisfaction (Jirsak, 2018).

Providing real-time updates on the location and status of shipments has become a game-changer in logistics and supply chain management, significantly improving customer satisfaction (Barreto et al., 2017). Artificial intelligence (AI) takes this a step further by optimising key operational areas such as routing, scheduling, and inventory management, ensuring that supply chains operate with maximum efficiency (Mahdavisharif et al., 2022). With AI-driven analytics, companies can predict demand more accurately, reducing inefficiencies and improving overall performance (Ghadge et al., 2020).

Despite these promising advancements, there is still a need for more in-depth research to fully grasp the long-term impact of Industry 4.0 on logistics and supply chain operations (Abdirad & Krishnan, 2020). The integration of these technologies is not just about automation but also about leveraging data for smarter decision-making and driving operational efficiency at every level (IBM, 2022) . Given the logistics and supply chain sector's critical role in global commerce, embracing these innovations can lead to substantial benefits, including cost reductions, improved responsiveness, and enhanced service delivery. The adoption of Industry 4.0

technologies offers logistics providers a significant chance to improve efficiency, elevate customer service, and stay ahead in a competitive market.

2.3.1 Internet of Things (IoT) Integration

The integration of the Internet of Things (IoT) into logistics and supply chain management has significantly transformed traditional operations, enabling real-time monitoring, enhanced decision-making, and improved efficiency (Golpîra et al., 2021). As global supply chains become increasingly complex, IoT solutions offer logistics providers the ability to track goods, monitor environmental conditions, and automate processes with minimal human intervention.

IoT technology connects physical assets such as vehicles, warehouses, and cargo to digital networks, allowing for seamless data exchange and process automation (Zhong et al., 2017). Through smart sensors, RFID tags, and GPS tracking, logistics firms can gain real-time insights into inventory levels, shipment locations, and transit conditions, reducing inefficiencies and operational costs (Golpîra et al., 2021). This increased visibility enhances decision-making, leading to better demand forecasting and streamlined supply chain operations (Winkelhaus & Grosse, 2019).

One of the most impactful applications of IoT in logistics is real-time tracking and monitoring. RFID technology and GPS sensors enable logistics companies to monitor shipments at every stage, ensuring transparency and security (Golpîra et al., 2021). Additionally, smart warehouses equipped with IoT-powered robotics and automation optimize inventory management by tracking stock levels and predicting replenishment needs (Thürer et al., 2019).

IoT also plays a crucial role in cold chain logistics, where temperature-sensitive goods, such as pharmaceuticals and perishable food items, require precise monitoring. Advanced Iot-enabled sensors allow logistics providers to track temperature fluctuations and humidity levels in real time, preventing spoilage and reducing waste (Tsang et al., 2018).

Furthermore, Iot enhances predictive maintenance in logistics fleets. Sensors installed in vehicles can monitor engine performance, tire pressure, and fuel consumption, reducing unexpected breakdowns and minimising downtime (Golpîra et al., 2021).

The future of Iot in logistics and supply chain management is expected to be driven by advancements in 5G technology, blockchain integration, and artificial intelligence (AI). With faster connectivity and enhanced data processing capabilities, logistics providers can further automate processes and leverage AI-driven analytics for smarter decision-making (Golpîra et al., 2021).

2.3.2 Artificial Intelligence (AI)

The increasing complexity of modern supply chains has driven logistics providers to explore innovative solutions to enhance efficiency, resilience, and decision-making. Among these, Artificial Intelligence (AI) has emerged as a transformative technology, offering data-driven insights, automation, and predictive analytics to optimize supply chain operations (Culot et al., 2024). AI applications in logistics range from demand forecasting and inventory management to real-time route optimization and risk mitigation. However, while AI holds immense potential, its adoption presents challenges that require strategic planning and technological advancements.

One of AI's most impactful applications in supply chain management is its ability to improve planning and decision-making. Artificial Intelligence (AI) analyze vast amounts of historical and real-time data, enabling companies to predict demand fluctuations with greater accuracy (Culot et al., 2024). By leveraging AI-powered demand forecasting, logistics providers can reduce excess inventory, minimize waste, and enhance responsiveness to market changes (Helo & Hao, 2021). Furthermore, AI-driven predictive analytics allows firms to assess supplier performance, optimize procurement strategies, and enhance overall supply chain resilience (Guida et al., 2023).

Rather than just automating routine tasks, AI brings a layer of intelligence that helps businesses anticipate disruptions, adapt to changing demand, and optimise operations in real time. Within the supply chain, AI can analyse vast amounts of data to uncover patterns, forecast future conditions, and recommend the best course of action, whether it's managing risk, planning inventory, or streamlining logistics (Ghobakhloo, 2025) . These capabilities enable supply chain managers to respond proactively to disruptions and changing market conditions, ultimately improving operational efficiency and customer satisfaction (Pessot et al., 2022).

AI has significantly transformed logistics operations by introducing intelligent automation and real-time monitoring. In warehouse management, AI-driven robotics and automation streamline order fulfillment, reducing manual labor costs and enhancing accuracy (Bodendorf, 2022). AI-powered autonomous vehicles and drones further optimize last-mile delivery by reducing transportation time and ensuring efficient parcel distribution (Meyer & Henke, 2023).

Another notable AI application in logistics is route optimization. AI-powered systems process traffic patterns, weather forecasts, and delivery constraints to determine the most efficient delivery routes (Zhu et al., 2021). By continuously learning from past deliveries, these systems improve fleet efficiency, reduce fuel consumption, and lower operational costs (Zhu et al., 2021).

Additionally, AI enhances predictive maintenance, where IoT-enabled sensors monitor vehicle performance, detect potential faults, and recommend proactive maintenance schedules. This approach minimizes unexpected breakdowns and improves overall fleet reliability (Helo & Hao, 2021).

AI has the potential to redefine logistics and supply chain management by enhancing efficiency, reducing costs, and improving decision-making. However, its successful implementation requires addressing challenges related to data quality, interoperability, cybersecurity, and workforce readiness. As AI technologies continue to advance, businesses that embrace digital transformation and invest in AI-driven solutions will gain a competitive edge in the ever-evolving global supply chain landscape.

2.3.3 Big Data Analytics

The digital revolution has significantly transformed logistics and supply chain management, with Big Data analytics emerging as a key driver of efficiency, resilience, and competitiveness. In highly dynamic logistics hubs such as Penang, the ability to process vast volumes of data in real-time has enabled businesses to optimise operations, improve demand forecasting, and enhance supply chain agility. By integrating advanced data analytics with logistics processes, companies can transition from reactive decision-making to proactive, data-driven strategies.

Big Data refers to large and complex datasets that traditional data-processing tools cannot effectively handle. These datasets are characterised by high volume, velocity, variety, and veracity (Manikas et al., 2022). In supply chain management, Big Data analytics allows organizations to process vast amounts of real-time data generated from various sources, such as IoT sensors, RFID tags, GPS tracking, social media, and transactional records (Barlette & Baillette, 2020). The integration of Big Data analytics into logistics operations enables organisations to transition from reactive decision-making to predictive and proactive strategies. Companies that leverage advanced analytics tools can optimize supply chain performance, minimize risks, and gain a competitive edge in volatile market environments.

Big Data analytics enhances supply chain resilience by providing real-time insights into potential disruptions, allowing businesses to make data-driven decisions. By analyzing historical data and identifying trends, companies can develop contingency plans and optimize resource allocation to mitigate risks. For instance, predictive analytics can forecast demand fluctuations, enabling organizations to adjust production schedules and inventory levels accordingly.

A study conducted on Emirati companies revealed that organizations with strong Big Data analytics capabilities were better prepared to handle supply chain disruptions.

These companies demonstrated improved agility by leveraging real-time data to make informed decisions, enhancing their overall supply chain resilience (Manikas et al., 2022).

One of the primary benefits of Big Data analytics in logistics is cost optimization. By analyzing transportation routes, fuel consumption, and warehouse operations, organizations can identify inefficiencies and implement cost-saving measures. Advanced analytics tools, such as machine learning algorithms, enable companies to optimize delivery routes, reducing transportation costs and improving delivery speed (Chitta, 2017).

Customer satisfaction is a key determinant of supply chain success. Big Data analytics enables businesses to enhance customer experience by providing real-time tracking updates, personalized delivery options, and improved order accuracy (Barlette & Baillette, 2020). Predictive analytics can anticipate customer demands, allowing companies to maintain optimal stock levels and reduce lead times. AI-driven chatbots and automated customer service platforms further enhance customer engagement by providing instant responses and real-time order updates.

As technological advancements continue to reshape the logistics industry, the role of Big Data analytics is expected to expand further. Emerging technologies such as blockchain, AI, and IoT will complement Big Data analytics, enhancing transparency, efficiency, and decision-making capabilities. Blockchain technology, for instance, offers secure and tamper-proof data storage, improving supply chain visibility and traceability. AI-powered predictive models will further refine demand forecasting, enabling companies to optimize production and distribution processes (Manikas et al., 2022).

2.3.4 Robotic and Automation

As global supply chains become more complex, companies are leveraging automated technologies to enhance efficiency, reduce costs, and improve operational accuracy. Robotics and automation play a crucial role in warehouse management, transportation, order fulfillment, and supply chain visibility. The use of robotics in SCM has been increasing due to the demand for faster, more efficient operations. Robotics improves supply chain performance by reducing human error, increasing productivity, and streamlining repetitive tasks. Automated Guided Vehicles (AGVs), robotic arms, and drones are among the most commonly deployed robotic solutions in warehouses and distribution centres (Banur et al., 2024).

According to Tsang et al. (2024), robotic process automation (RPA) enhances operational efficiency by automating back-office tasks such as inventory tracking, data entry, and order processing . Companies implementing RPA have reported significant improvements in accuracy, cost-effectiveness, and workforce productivity.

Automation in warehouses includes Automated Storage and Retrieval Systems (AS/RS), collaborative robots (cobots), and Goods-to-Person (G2P) systems. AS/RS systems automate inventory storage and retrieval, increasing efficiency while minimizing manual labor (Banur et al., 2024). Cobots are designed to work alongside human workers, assisting in picking, sorting, and transporting goods. These robots improve warehouse productivity by reducing workload and enhancing safety. G2P systems, on the other hand, eliminate the need for workers to move across large warehouses by bringing goods directly to them, thereby improving efficiency and order fulfillment rates (Banur et al., 2024).

Robotic Process Automation (RPA) is widely used in supply chain operations to automate repetitive, rule-based tasks such as shipment tracking, order processing, and warehouse data management (Tsang et al., 2018). Unlike traditional robotics, RPA focuses on software-based automation, allowing companies to optimize administrative workflows.

For instance, companies employing RPA for shipment tracking have seen significant reductions in manual errors and improved real-time visibility of deliveries. Automation software can access multiple carrier tracking platforms and update shipment statuses in internal databases without human intervention, enhancing supply chain transparency (Tsang et al., 2024).

Robots and automated systems significantly improve accuracy in order fulfilment, inventory management, and transportation logistics. AI-powered vision systems and sensor-based robots enhance quality control by identifying defects in products before they are shipped. Barcode scanning robots ensure precise tracking of goods, reducing misplacement and lost inventory (Banur et al., 2024).

Autonomous delivery vehicles and drones are set to revolutionize last-mile delivery operations. Companies such as Amazon, UPS, and DHL are already testing drone-based deliveries to improve delivery speed and reduce transportation costs (Banur et al., 2024).

The integration of robotics and automation in logistics and supply chain management is revolutionizing operational efficiency, cost management, and decision-making. While the benefits are undeniable enhanced accuracy, lower costs, and improved speed challenges such as high investment costs, system integration issues, and workforce displacement must be addressed.

As the industry moves toward AI-driven automation, autonomous delivery solutions, and cloud-based RPA, businesses that strategically invest in robotics will gain a competitive edge in the evolving global supply chain landscape. Future research should focus on scalable automation solutions for SMEs, ethical considerations in robotic deployment, and AI-driven logistics decision-making.

2.3.5 Blockchain

Integrating blockchain technology in logistics and supply chain management can create many transformative benefits that enhance the transparency, efficiency, and security of operations. The use of decentralized ledgers and smart contracts in blockchain mitigates traditional challenges like fraud, inefficiencies, and data integrity issues and facilitates the creation of a more reliable supply chain ecosystem (Du, 2024).

Blockchain's most significant contribution to supply chains is its ability to enhance transparency and traceability. As emphasized by Kamilaris et al. (2019), blockchain can mitigate risks such as food fraud by providing a transparent record of food products' journeys from farm to table. Similarly, Bocek et al. (2017) highlight blockchain's potential in tracking pharmaceuticals from manufacturers to consumers, thereby combating counterfeit drugs. By recording transactions in an immutable ledger, blockchain offers a reliable source of truth, ensuring the authenticity and integrity of goods in industries where product provenance is paramount (Emon et al., 2024).

Efficiency gains are also highlighted as a crucial benefit of blockchain adoption. Through the use of smart contracts, blockchain can automate supply chain processes, reducing the reliance on intermediaries and minimizing operational costs (Francisco & Swanson, 2018). Kshetri (2017), further underscores how blockchain's ability to provide real-time data can enhance decision-making, improving supply chain responsiveness and operational efficiency. These capabilities are especially relevant in industries such as logistics, where time-sensitive transactions can significantly impact profitability and customer satisfaction.

Despite its potential, the adoption of blockchain faces several obstacles. Technological complexity is one of the primary challenges, as integrating blockchain with existing supply chain systems requires significant technical expertise and resources (Saberi et al., 2018). The lack of standardization and interoperability between different blockchain platforms complicates the implementation process, making it difficult for organizations to select suitable solutions and ensure seamless communication between systems (Kouhizadeh & Sarkis, 2018). Moreover, the high initial costs associated with setting up blockchain infrastructure, including hardware, software, and training, present a barrier, particularly for small and medium-sized enterprises (SMEs) (Khan & Khanam, 2017).

Blockchain's decentralized nature fosters greater collaboration among supply chain partners by providing a single, shared version of the truth. This transparency can reduce disputes and build trust among stakeholders (Queiroz & Wamba, 2019). However, the shift to a blockchain-based system often requires a cultural transformation, as organizations need to transition from competitive secrecy to openness and collaboration (Dolgui et al., 2017). This cultural change can face resistance, particularly from stakeholders accustomed to traditional business models and practices.

Sustainability is another area where blockchain shows promise. By providing verifiable and transparent information regarding the environmental and social impact of products, blockchain can support sustainability initiatives. Blockchain can track the carbon footprint of products and ensure that materials are ethically sourced (Emon et al., 2023). However, concerns about the energy consumption of blockchain, especially in proof-of-work systems, have raised questions about its environmental sustainability. Organizations must address these concerns by exploring more energy-efficient blockchain protocols (Upadhyay et al., 2021).

Blockchain adoption in supply chain management highlights both the transformative potential and the challenges associated with its implementation. Blockchain can enhance transparency, improve operational efficiency, and foster trust among supply chain partners. However, its adoption is hindered by technological complexities, data privacy concerns, regulatory uncertainty, and high implementation costs. To successfully implement blockchain, organizations must invest in technical expertise, address data privacy issues, and foster collaboration across the supply chain.

2.4 Underpinning Theory

Industry 4.0 technologies are reshaping global supply chains, enhancing resilience, flexibility, and adaptability in the face of disruptions. The Dynamic Capabilities Theory (DCT) provides a robust theoretical foundation for understanding how firms in the logistics and supply chain sector of Penang can leverage these emerging technologies to enhance supply chain resilience. Originally introduced by (Teece, 1997) , DCT explains how firms develop, adapt, and renew their capabilities to maintain a competitive advantage in dynamic environments. This theory is particularly relevant for examining the integration of Iot, AI, robotics, big data, and blockchain, as these technologies enhance a firm's ability to sense, seize, and reconfigure its operations in response to disruptions. As supply chains become increasingly complex and vulnerable to disruptions ranging from natural disasters to geopolitical instability, leveraging IoT, AI, robotics, big data, and blockchain becomes essential for ensuring resilience (Ivanov D. D., 2019).

One of the core principles of DCT is sensing capability, which involves identifying risks and opportunities in real time. In the context of Industry 4.0, Internet of Things (IoT) sensors and big data analytics play a crucial role in this process. IoT-enabled devices collect real-time data on inventory levels, production performance, and transportation conditions, allowing firms to anticipate potential disruptions before they escalate (Zhong R. Y., 2017). For instance, IoT sensors embedded in logistics operations can detect supply chain bottlenecks, alerting managers to take proactive measures such as rerouting shipments or adjusting inventory levels to meet fluctuating demand. This capability enables firms to make data-driven decisions, enhancing their ability to respond swiftly and effectively to disruptions.

The second component of DCT, seizing capability, refers to an organization's ability to act on the insights generated through sensing. Artificial intelligence (AI) significantly enhances this capability by enabling predictive analytics and automated decision-making. AI-powered systems analyze historical supply chain data and real-time market trends to optimize resource allocation, mitigate risks, and recommend alternative suppliers or transportation routes in case of disruptions (Wamba, 2017). AI also enhances operational efficiency by automating warehouse management, ensuring that stock levels are maintained in response to demand fluctuations. In the manufacturing sector, AI-driven predictive maintenance can anticipate equipment failures before they occur, reducing downtime and preventing disruptions in the production process (Dubey, 2018).

The final dimension of DCT, reconfiguring capability, allows firms to continuously adapt and restructure their supply chain operations in response to external challenges. Robotics and automation play a key role in this adaptability by enhancing operational flexibility. Automated production lines and robotic warehouses reduce reliance on manual labour, ensuring consistent production output even during labour shortages or disruptions (Ivanov, D & Dolgui A, 2020). Furthermore, blockchain technology enhances transparency and trust across the supply chain by creating a tamper-proof, decentralized ledger for tracking transactions and verifying supplier credentials (Queiroz, M. M., & Wamba, S. F., 2019). In industries where supply chain security and traceability are critical, such as pharmaceuticals and food supply chains, blockchain ensures compliance with regulatory standards and prevents fraudulent activities.

In the context of supply chain resilience in Penang, firms that successfully integrate these Industry 4.0 technologies into their supply chain operations will gain a competitive advantage by reducing risks, improving decision-making, and increasing agility. The ability to sense, seize, and reconfigure ensures that supply chains remain responsive and adaptive in the face of unforeseen disruptions. By applying DCT, this research provides a strong theoretical foundation for examining how firms in Penang's logistics and supply chain sector can leverage digital transformation to build more resilient supply networks.

Table 2.2
Dynamic Capabilities Theory (DCT) and Supply Chain Resilience in Industry 4.0

Research Question	DCT Explanation	Expected Outcome
Does IoT influence supply chain resilience?	IoT enhances sensing capability by providing real-time visibility and predictive analytics. IoT sensors and RFID tracking enable early identification of potential disruptions.	Improved early risk detection and response, reducing downtime and enhancing supply chain agility.
Does AI affect supply chain resilience?	AI supports seizing capability, enabling real-time automated decision-making through machine learning and predictive analytics. AI can forecast demand, optimize inventory, and automate supply chain operations.	Increased agility and proactive risk management, improving decision-making efficiency.
Do robotics and automation contribute to resilience?	Robotics and automation enhance reconfiguring capability, allowing for adaptive production and logistics. Automated systems minimize labor dependency and reduce production delays.	Enhanced operational continuity and flexibility, ensuring supply chain stability even during labor shortages.
What is the effect of big data on resilience?	Big data analytics strengthens sensing capability by processing historical and real-time supply chain data. It helps predict disruptions and optimize resource allocation.	Improved data-driven resilience strategies, allowing firms to anticipate risks and take proactive measures.

Table 2.2 (Continued)

Research Question	DCT Explanation	Expected Outcome
Does blockchain impact supply chain resilience?	Blockchain enhances reconfiguring capability by securing transactions, increasing transparency, and ensuring trust among supply chain partners. Smart contracts automate compliance and reduce transaction fraud.	Strengthened trust, traceability, and collaboration, reducing supply chain inefficiencies and security risks.

2.5 Research Framework and Summary of Research Hypotheses

This research aims to develop a conceptual framework and hypotheses to understand the relationship between Industry 4.0 technologies and supply chain resilience in the insight of logistics and supply chain management. This framework guides the systematic exploration of the research questions, ensuring a structured approach to understanding the multifaceted impact of Industry 4.0 in the specific context of logistics and supply chain. The framework explores how Industry 4.0 technologies contribute to proactive disruption management. Ivanov et al. (2018) discuss the importance of proactive strategies in managing disruptions in supply chains.

The research is grounded in the foundational principles of Industry 4.0, emphasizing the convergence of digital technologies in logistics. This concept has been extensively discussed by authors such as Garay-Rondero et al. (2019), who define Industry 4.0 as the fourth industrial revolution driven by digitalization. The integration of Industry 4.0 technologies is guided by the principles of Cyber-Physical Systems (CPS), where physical and digital elements are interconnected. Lee et al. (2015) discuss CPS as a key enabler of intelligent and adaptive systems, aligning with the vision of Industry 4.0.

The current research framework was developed based on the literature review and will depict the relationship between Industry 4.0 technologies and supply chain resilience among logistics and supply chain management. This research framework aims to provide a comprehensive understanding of the impact of Industry 4.0 technologies on supply chain resilience in logistics and supply chain management, offering valuable insights for academics, practitioners, and industry professionals.

2.5.1 Summary of Research Hypotheses

This section highlights the development of the hypotheses. The discussion that follows focuses on previous empirical findings that align with the objectives and research topics mentioned in Chapter 1. Five hypotheses were developed in this regard to examine the impact of the independent factors on the supply chain resilience among logistics and supply chain management in Penang.

i. Internet of Things (IoT) and Supply Chain Resilience

The integration of the Internet of Things (IoT) in logistics operations and supply chain management significantly enhances visibility and the ability to monitor the supply chain in real time. IoT-enabled devices, such as sensors and RFID tags, facilitate the continuous tracking of inventory, shipments, and environmental conditions. This increased visibility allows logistics providers to proactively identify disruptions, monitor the status of goods, and respond swiftly to changing circumstances. As highlighted by Ruthramathi and Sivakumar (2022), IoT's real-time monitoring contributes to improved supply chain visibility, a critical factor in building resilience.

The relationship between IoT and supply chain resilience in logistics and supply chain management is strengthened by the ability of IoT devices to support proactive risk management and predictive analytics. IoT technology helps logistics operations and supply chain management to anticipate and mitigate risks and interruptions by gathering and evaluating real-time data. Predictive analytics models that use data generated by IoT devices can help foresee potential challenges, enabling companies to implement proactive strategies before issues arise. According to Mannappan (2024), IoT's predictive capabilities contribute to proactive risk mitigation, strengthening the entire resilience of the supply chain.

The dynamic nature of IoT-driven data feeds into the adaptability and responsiveness of logistics and supply chain operations. IoT devices provide a continuous stream of information on inventory levels, equipment conditions, and transportation status. This real-time data empowers operations to dynamically adapt their strategies and respond swiftly to changes in demand, disruptions, or unforeseen events.

The traceability capabilities enabled by IoT contribute to enhanced quality control and traceability within the supply chain. IoT devices allow for the monitoring of product conditions, ensuring that goods are handled and transported within specified parameters. This level of traceability is crucial for identifying the source of disruptions, managing recalls, and maintaining the integrity of the supply chain. As discussed by Naveed et al. (2024), IoT-enabled traceability enhances the overall quality control mechanisms, a factor integral to supply chain resilience.

In conclusion, the relationship between the Internet of Things (IoT) and supply chain resilience in logistics and supply chain management is significant and multi-faceted. Enhanced visibility, proactive risk management, improved collaboration, dynamic adaptability, and traceability collectively contribute to building a more resilient and responsive supply chain.

H1: There is a significant relationship between the Internet of Things (IoT) and supply chain resilience.

ii. Artificial Intelligence (AI) Implementation and Supply Chain Resilience

The integration of Artificial Intelligence (AI) in logistics and supply chain management introduces a significant enhancement in intelligent decision-making capabilities, contributing to supply chain resilience. AI algorithms analyze vast amounts of data in real time, enabling logistics and supply chain management to make informed decisions promptly. This adaptive responsiveness is crucial for mitigating disruptions and optimizing supply chain processes. As discussed (Chen, 2019), AI-driven decision-making is foundational to building a resilient supply chain capable of dynamic adaptation.

The relationship between AI and supply chain resilience in logistics and supply chain management is underscored by the role of predictive analytics in risk management. AI algorithms leverage historical data and patterns to predict potential disruptions and risks in the supply chain. This proactive approach allows logistics and supply chains to implement preemptive strategies, helping to reduce the impact of disruptions. Research by Sheffi & Rice Jr., (2005) emphasizes the importance of predictive analytics in risk mitigation, aligning with the capabilities introduced by AI in logistics and supply chain operations.

The real-time monitoring capabilities enabled by AI technologies play a crucial role in enhancing supply chain resilience. AI-driven systems continuously track various aspects of the supply chain, offering real-time insights into inventory levels, transportation conditions, and potential disruptions. This immediate awareness allows for quick responses, minimizing the impact of any disruptions. According to Ivanov et al. (2018), real-time monitoring through AI boosts the agility and responsiveness of the supply chain, strengthening its overall resilience.

H2: There is a significant relationship between artificial intelligence implementation and supply chain resilience.

iii. Robotic and Automation Impact and Supply Chain Resilience

The integration of robotic and automation technologies in logistics and supply chain brings about a substantial improvement in operational efficiency and redundancy, fostering supply chain resilience. Automated systems can handle routine tasks with precision and speed, reducing the reliance on manual labor. This operational efficiency not only streamlines processes but also introduces redundancy by having automated systems available as backups. Automation contributes to operational excellence, a key factor in building a resilient supply chain (Woo et al., 2018).

The relationship between robotic and automation impact and supply chain resilience extends to the adaptability and scalability of operations. Robotic systems equipped with artificial intelligence can adapt to changes in demand, operating conditions, and disruptions in real time. This adaptability ensures that logistics and supply chain management can scale their operations efficiently, accommodating fluctuations in demand or unexpected events, thus emphasizing the importance of adaptive and scalable operations in building resilient supply chains (Bai, 2023).

Robots and automation impact on logistics and supply chain, significantly reducing lead times and enhancing flexibility in supply chain operations. Automated processes, such as order fulfilment and inventory management, contribute to quicker response times. The flexibility introduced by robotic systems allows logistics and supply chains to adjust operations promptly in the face of disruptions or changing market conditions. As discussed by Bai (2023), reduced lead times and increased flexibility are crucial elements of supply chain resilience, and automation plays a key role in achieving these objectives.

The collaborative nature of robotics, involving human-machine cooperation, enhances supply chain resilience in logistics and supply chain. Collaborative robots, or cobots, work alongside human operators, combining the strengths of both. This collaborative approach allows for increased flexibility in handling complex tasks, and human oversight ensures adaptability in unforeseen situations. As highlighted by Bai (2023), collaborative robotics supports a dynamic and responsive supply chain, contributing to overall resilience.

H3: There is a significant relationship between Robotic and automation implementation and supply chain resilience.

iv. Big Data Implementation and Supply Chain Resilience

Big Data Analytics (BDA) plays a significant role in enhancing supply chain resilience, particularly by integrating logistics capabilities across the supply chain. Resilience, in the context of supply chains, refers to the ability to prepare for, respond to, and recover from disruptions while maintaining the continuity of operations (Ponomarov & Holcomb, 2009). The integration of BDA into logistics processes allows companies to adapt quickly to disruptions by improving forecasting accuracy, risk identification, and strategic decision-making (Farooq et al., 2024).

BDA enables firms to leverage vast amounts of data from various sources, such as IoT devices, sensors, and transaction records, enhancing the visibility and agility of supply chains (Sundarakani et al., 2021). This integration facilitates better coordination and information-sharing across supply chain partners, allowing them to anticipate and respond to changes in demand or supply effectively (Mentzer et al., 2008). Through predictive analytics, companies can identify potential risks before they escalate into disruptions, ensuring that supply chains remain adaptable and robust in the face of crises.

Moreover, BDA enhances integrated logistics capabilities, such as demand, supply, and information management interfaces. These capabilities improve the efficiency of logistics processes, optimize resource allocation, and enhance customer satisfaction by ensuring timely deliveries and high-quality service. By applying advanced data analytics, businesses can minimize operational costs, optimize logistics routes, and improve overall decision-making processes, which directly contributes to enhanced supply chain performance.

In conclusion, the integration of BDA into supply chain management significantly strengthens resilience by improving logistics capabilities, enabling proactive decision-making, and reducing the impact of disruptions. This interplay between big data and logistics forms the foundation for a more flexible and responsive supply chain, crucial for maintaining competitive advantage in a volatile business environment.

H4: There is a significant relationship between big data implementation and supply chain resilience.

v. Blockchain and Supply Chain Resilience

Blockchain's ability to enhance transparency, traceability, and efficiency plays a pivotal role in strengthening the resilience of supply chains. Through its decentralized and immutable ledger, blockchain enables real-time tracking of goods, which helps in responding quickly to disruptions and minimizing their impact. This is particularly valuable during unforeseen events, such as natural disasters or supply chain bottlenecks, by providing accurate and accessible data that aids in decision-making (Emon et al., 2024).

Furthermore, blockchain enhances collaboration and trust among supply chain stakeholders by providing a single, transparent version of the truth. This shared visibility reduces disputes, increases cooperation, and facilitates faster responses to issues, all of which are essential components of a resilient supply chain (Queiroz & Wamba, 2019). While the adoption of blockchain is not without its challenges, such as technological complexity, regulatory uncertainty, and the high costs of implementation, the overall relationship between blockchain and supply chain resilience is highly positive and significant. These benefits make blockchain a valuable tool for improving the flexibility and sustainability of supply chains in an increasingly unpredictable global environment.

In conclusion, as blockchain technology matures, its integration into logistics and supply chains will likely continue to enhance resilience, offering a robust foundation for managing future challenges.

H5: There is a significant relationship between blockchain and supply chain resilience.

2.6 Theoretical Framework

Figure 2.1 below shows the theoretical framework of the study. This model includes five independent variables, which are Internet of Things (IoT) Integration, Artificial Intelligence (AI) Implementation, Robotics and Automation, Big Data Analytics, and Blockchain. This study is to find out the relationship between these five IVs with the DV, which is supply chain resilience. The focus of this study is to examine how these digital innovations contribute to strengthening supply chain resilience, particularly within the logistics and supply chain sector in Penang.

The theoretical framework can be conceptualized as in Figure 2.1.

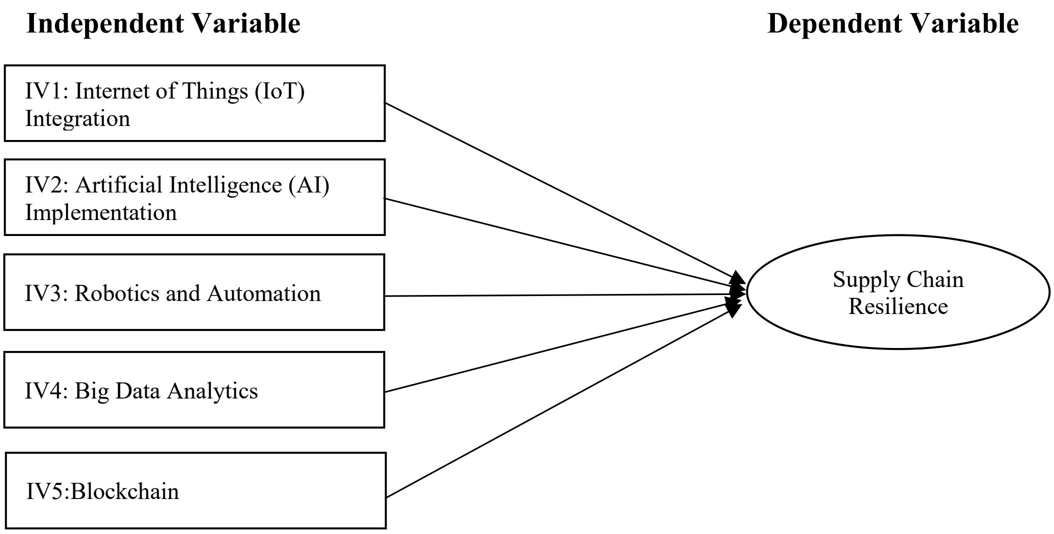

Figure 2.1
Theoretical Framework for This Study

2.7 Chapter Summary

This chapter has aimed to explore and reflect on the insights and findings of past academics, helping to shape a stronger and more well-rounded foundation for the study. It introduced and clarified the main variables involved, along with their key definitions and underlying concepts. A review of relevant past research was also provided to support the development of the study's hypotheses, which will be examined in the following chapters. In addition, this chapter outlined the theoretical framework and supporting theory that guide the overall direction of the research.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The methodology used to conduct the study is explained in this section. The study's findings described the methods and approaches utilized in the data gathering, processing, and analysis of data. In particular, the research design, target population, data collection tools, data collection processes, and data analysis are covered in the following subsections.

3.2 Research Design

This study conducted a quantitative survey in which data were obtained through a set of questionnaires. This approach was chosen because it is quick to acquire data and is low-cost, straightforward to design, and effective. The surveys were distributed with a set of questions to participants through Google Forms to collect data directly from respondents. The researcher used a primary method for collecting data directly from employees. A descriptive study is undertaken to investigate the relationship between the 4.0 industry and supply chain resilience among logistics and supply chain sector. The descriptive study allows answering the research question and meeting the research objectives. Besides that, the descriptive research approach was used when it brings quantitative data about a particular subject by explaining it from various angles.

3.3 Population, Sample, and Sampling Technique

This research draws its population data from the FMM Directory of Malaysian Industries (54th Edition), which records 436 manufacturing and logistics service companies.

According to Roscoe (1975), most research studies consider a sample size between 30 and 500 to be appropriate. Increasing the sample size improves the accuracy of survey data and findings, making them more precise. The sample size is a crucial concept in statistics.

Referring to Krejcie & Morgan,1970, Sample Size Determination Table, for a population of 420 (close to the population of 436), a minimum of 201 respondents was identified as suitable to ensure reliable representation of the population.

N	S	N	S	N	S
10	10	220	140	1200	291
15	14	230	144	1300	297
20	19	240	148	1400	302
25	24	250	152	1500	306
30	28	260	155	1600	310
35	32	270	159	1700	313
40	36	280	162	1800	317
45	40	290	165	1900	320
50	44	300	169	2000	322
55	48	320	175	2200	327
60	52	340	181	2400	331
65	56	360	186	2600	335
70	59	380	191	2800	338
75	63	400	196	3000	341
80	66	420	201	3500	346
85	70	440	205	4000	351
90	73	460	210	4500	354
95	76	480	214	5000	357
100	80	500	217	6000	361
110	86	550	226	7000	364
120	92	600	234	8000	367
130	97	650	242	9000	368
140	103	700	248	10000	370
150	108	750	254	15000	375
160	113	800	260	20000	377
170	118	850	265	30000	379
180	123	900	269	40000	380
190	127	950	274	50000	381
200	132	1000	278	75000	382
210	136	1100	285	1000000	384

Note.—*N* is population size. *S* is sample size.

Source: Krejcie & Morgan, 1970

Figure 3.1
The sample size, (Krejcie & Morgan, 1970).

To strengthen the validity of the findings and allow for possible non-responses, 300 respondents were targeted. The study collected preliminary data. From 30 firms designated for a pilot test to assess the clarity and effectiveness of the survey instrument. A total of 270 questionnaires were sent for final data collection. From the 270 questionnaires distributed, 254 were completed and returned, yielding a high response rate that not only met but exceeded the recommended sample size. This strong participation helped to enhance the credibility and generalizability of the study's results.

3.3.1 Sampling Technique

This method allows for the deliberate selection of logistics and supply chain companies with relevant Industry 4.0 implementations, ensuring that the chosen sample provides valuable insights into the integration's impact on supply chain resilience. The sample selection is based on the companies' willingness to participate and share insights into their Industry 4.0 initiatives. This research utilised quantitative analysis, with all data being collected through a structured questionnaire. This study did not set a fixed target number of respondents, as the questionnaire was distributed via social media platforms to companies listed in the FMM Directory of Malaysian Industries (54th Edition). The focus was on engaging professionals from the logistics and supply chain industry in Penang, ensuring that responses were relevant to the research.

Since the FMM Directory (54th Edition) lacked detailed information about the details on all companies in Penang, it was impractical to pre-select target respondents solely based on company-level data. As a result, the questionnaire was made accessible to professionals within relevant organisations, allowing those directly involved in supply chain and logistics operations to participate voluntarily. This approach ensured that the collected data came from individuals with first-hand industry experience, enhancing the study’s validity.

3.4 Questionnaire Design

The questionnaire is the main tool used to gather data for this study, allowing ~~us~~ to obtain dependable and precise information. The content and input from the questionnaire will help to investigate the relationship between Industry 4.0 Technologies and Supply Chain Resilience: insights from Logistics and Supply Chain Perspectives in Penang.

To obtain the necessary data, this study was carried out by giving questionnaires to respondents. The required abstract information was converted into a collection of clear, measured responses through questionnaires. The questionnaire consists of three (4) sections: Section A, Section B, Section C and Section D.

Section A covers the demographic profile of the respondents. The details questioned in this section will be gender, ethnic background, age, course, current job related to the field of study, and scale of operation. The choice is given, and the respondent needs to tick the answer that is relevant to them.

Section B questions delve into the specific Industry 4.0 technologies integrated into the supply chain operations. This section explores the adoption of technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Robotics, Big Data Analytics and Blockchain, which questions related to independent variables. Utilize Likert scale questions to quantitatively measure the extent of integration for specific Industry 4.0 technologies (Iot, AI, Robotics and Automation, Data Analytics and Blockchain).

Section C covers the items on dependent variables and employs scaled questions to measure perceptions regarding the impacts of Industry 4.0 integration on various aspects of supply chain resilience, such as responsiveness and adaptability. Use a structured format with Likert scale questions to quantify the challenges encountered during the integration process.

Lastly, Section D focuses on assessing the adoption level of Industry 4.0 technologies within companies, gathering insights from direct participants to understand how extensively these technologies are being used and whether any Industry 4.0 technologies have been adopted by their organizations.

The methodology proposed by Kulkarni et al. (2016), a five-point Likert scale to measure respondents' attitudes, opinions, and perceptions. The data is primarily evaluated by scoring the responses according to this scale, providing valuable insights into the subject matter. A summary of the sections is presented in below table.

Table 3.1
Variables and Sources

Section	Dimension	Sources
A	Demographic	
B	Internet of Things (IoT) Integration	Ruthramathi & Sivakumar, 2022)
	Artificial Intelligence (AI) Implementation	(Modgil et al., 2021)
	Robotics and Automation	(Parshuramkar et al., 2024)
	Big Data Analytics	(Papadopoulos et al., 2016)
	Blockchain	(Susanto et al., 2024)
C	Supply Chain Resilience	(Mandal et al., 2016)
D	What Is the Current Adoption Level of IR 4.0 Technologies in Your Company?	

3.5 Pilot Test

Before using any survey, it is crucial to test it to ensure its effectiveness. Conducting a pilot study enhances the validity of the research and provides insights that can help in planning and refining the main investigation. This preliminary test not only verifies the reliability of the research instrument but also allows for adjustments and improvements to the questionnaire (Abd Gani et al., 2020). To improve the overall quality of the study, feedback from the pilot study can guide necessary modifications. To achieve this, 30 questionnaires were distributed as part of the pilot phase. These 30 questionnaires were shared via Google Forms through an online platform to respondents who are working in the Logistics and supply chain sector in Penang.

3.6 Data Collection Technique

Primary and secondary data sources are the two categories of sources used in research. Primary data is information that is gathered directly from respondents, individuals, or groups, whereas secondary data is information that is gathered from already-published sources, such as books, journals, government publications, websites, and articles. (Sekaran, 2006). Primary data for this study will be gathered through the use of a self-administered questionnaire. Surveys and questionnaires are effective tools for collecting quantitative data. These can be designed to gather information on the extent of Industry 4.0 technology integration, perceived impacts on supply chain resilience, challenges faced, and strategies employed. Quantitative data can be organized using multiple-choice questions and closed-ended questions with Likert scales. This approach can clear up concerns, is less expensive, is easy to use, and has a high return rate. Gather data on the integration levels of Industry 4.0

technologies (Variable 1) and the corresponding measures of supply chain resilience (Variable 2). Ensure that the data is representative and covers the relevant aspects of technology integration and resilience.

3.6.1 Primary Data

Primary data refers to information gathered directly from individuals, organizations, or specific respondents. For this study, the main data was collected through an online questionnaire. The opinions and insights of the respondents play a key role in the foundation of the data collected for the research. The primary data for this investigation consists of the responses and feedback provided by 254 logistics and supply chain companies from Penang.

3.6.2 Secondary Data

Secondary data refers to information that has been gathered from sources that were previously published, such as books, articles, journals, newspapers, and other relevant materials. This method of data collection allows for the review and analysis of data that has already been compiled by other researchers. In the context of this study, the secondary data consists of earlier articles and journals that are related to the research topic.

3.7 Data Analysis Technique

The data analysis method used in this research provided a detailed overview of the statistical procedures employed. The data was processed using the Statistical Package for the Social Sciences (SPSS), version 29, a specialised software chosen for its ability to perform the necessary calculations with precision. SPSS is a statistical tool that helps streamline and accurately analyze data. It generates a wide range of outputs that are essential for the research process. By utilising SPSS, the data was efficiently processed to answer the research questions effectively. On the other hand, the analysis was done in the aspect of Industry 4.0 Technologies and supply Chain Resilience: insights from Logistics and Supply Chain Perspectives in Penang to examine variables such as Internet of Things (IoT) Integration, Artificial Intelligence (AI) Implementation, Robotic and Automation, Big Data Analytics, Blockchain and supply chain resilience. To evaluate the data collected from the questionnaires, descriptive statistics will be used to measure the frequencies, percentages, and mean values.

3.7.1 Descriptive Analysis

Descriptive analysis is commonly used to highlight the key features of the data in a study. It provides clear summaries of the graphical representations, sample data, and measurement methods used in the research. While different techniques can be applied to present the study model, descriptive analysis plays a crucial role in making large amounts of data easier to understand (Kopcha & Alger, 2014). Typically, it helps to outline the demographic profile, such as gender, age, education level, and work experience. This information is usually displayed as percentages and frequencies. For each variable, central tendency measures like the mean, mode, average, and standard deviation are calculated.

3.7.2 Reliability Analysis

Reliability refers to the consistency and stability of a test or data collection method, ensuring that the results remain dependable over time. One of the most commonly used tests for reliability is Cronbach's coefficient alpha, often simply called Cronbach's alpha. This test is widely used in various research projects to assess how consistent respondents' answers are across the different items included in a measurement. A Cronbach's alpha value between 0.7 and 0.9 is typically considered good, indicating that the measurement tool is reliable. According to (Streiner D. L., 2003) , higher values of alpha suggest a higher level of internal consistency among the items of the scale.

As seen in Table 3.2, based on the data presented in the table, the reliability analysis for the pilot test indicates that the measurement scales used in this study exhibit strong internal consistency. Cronbach's Alpha values were computed for six key variables, namely Internet of Things (IoT) Integration, Artificial Intelligence (AI) Implementation, Robotics and Automation, Big Data Analytics, Blockchain, and Supply Chain Resilience.

Among these, IoT Integration demonstrated the highest reliability with a Cronbach's Alpha value of 0.914, followed closely by AI Implementation at 0.908. Both of these variables fall within the "Excellent" reliability range, signifying a high degree of consistency in the responses related to these constructs.

Robotics and Automation recorded a Cronbach's Alpha of 0.863, while Blockchain scored 0.868, both categorized under the "Good" reliability level. Similarly, Big Data Analytics and Supply Chain Resilience achieved values of 0.841 and 0.874, respectively, also indicating good internal consistency.

Overall, these findings suggest that the survey instrument used to assess Industry 4.0 technologies and their impact on supply chain resilience is both reliable and well-structured. The high reliability scores imply that the selected items for each construct are appropriate and effectively capture the intended dimensions, ensuring the credibility of the study's results.

Table 3.2
Reliability for Pilot Test

Variables	Cronbach's Alpha	N of items	Reliability Level
Internet of Things (IoT) Integration	0.914	5	Excellent
Artificial Intelligence (AI) Implementation	0.908	4	Excellent
Robotics and Automation	0.863	4	Good
Big Data Analytics	0.841	3	Good
Blockchain	0.868	3	Good
Supply Chain Resilience	0.874	4	Good

Table 3.3
Cronbach's Alpha

Cronbach's Alpha	Strength of Association
a ≥ 0.9	Excellent
0.7 ≤ a < 0.9	Good
0.6 ≤ a < 0.7	Acceptable
0.5 ≤ a < 0.6	Poor
< 0.5	Unacceptable

Source: (Cronbach's alpha in SPSS: Definition, formula, and interpretation, 2025)

3.7.3 Pearson Correlation Analysis

The results of the correlation analysis will provide insights into the strength and direction of the relationship between the independent and dependent variables. A positive correlation would indicate that the integration of Industry 4.0 technologies is associated with higher levels of supply chain resilience, while a negative correlation would suggest the opposite This variable represents the level of integration of various Industry 4.0 technologies, including but not limited to the Internet of Things (IoT), Artificial Intelligence (AI), Robotics, Big Data Analytics and Blockchain. This variable measures the overall resilience of the supply chain, considering its ability to adapt to disruptions, recover from shocks, and maintain operational continuity. Evaluate the correlation coefficients to understand the strength and direction of the relationship between the integration of Industry 4.0 technologies and supply chain resilience.

Correlation coefficients range from -1 to 1, with 1 indicating a perfect positive correlation, -1 indicating a perfect negative correlation, and 0 indicating no correlation. A positive correlation coefficient suggests a positive linear relationship between the integration of Industry 4.0 technologies and supply chain resilience. This would imply that as the level of technology integration increases, supply chain resilience also tends to increase. negative correlation coefficient would suggest a negative linear relationship, indicating that higher levels of technology integration are associated with lower levels of supply chain resilience. A correlation coefficient close to 0 would suggest a weak or no linear relationship between the variables. This research can offer quantitative insights into the type and degree of the relationship between supply chain resilience in Logistics Operations and the incorporation of Industry 4.0 technology by using correlation analysis.

3.8 Summary of the Chapter

The research methodology chapter outlines the approach used to explore the impact of Industry 4.0 technologies on supply chain resilience, focusing specifically on logistics and supply chain management in Penang. The study utilized a quantitative approach, where data was gathered through structured questionnaires distributed to employees in the logistics and supply chain sector. The data was collected using a self-administered questionnaire via Google Forms, ensuring the inclusion of various demographic factors and industry-specific technologies.

The Likert scale, a five-point scale ranging from "strongly disagree" to "strongly agree," was employed to measure respondents' perceptions and attitudes regarding the adoption of Industry 4.0 technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), Robotics, Big Data Analytics, and Blockchain. This scale provided a clear method to quantify responses and ensure reliable data collection on the degree of technology integration within companies.

To process and analyze the data, the Statistical Package for the Social Sciences (SPSS) version 29 was used. This software was chosen for its robustness in handling complex statistical calculations. Descriptive statistics were utilized to summarize the data, such as frequencies, percentages, and mean values. Reliability analysis, using Cronbach's alpha, ensured the consistency and reliability of the measurement tools.

The data collected was also analyzed using Pearson correlation to examine the relationships between Industry 4.0 technology integration and supply chain resilience.

Overall, this chapter sets the foundation for a thorough understanding of how technological advancements impact logistics and supply chain operations, helping to improve resilience through predictive analytics, real-time data integration, and automation.

CHAPTER 4

FINDING AND ANALYSIS

4.1 Introduction

This chapter presents the empirical findings of the study, beginning with a summary of respondent profiles. This section outlines the demographic details of the participants and any relevant factors that could influence the results. A total of 254 responses were successfully collected from the 270 questionnaires distributed randomly to capture a diverse range of perspectives. The data was analysed using SPSS, focusing on key aspects related to Industry 4.0 technologies and supply chain resilience, particularly within the logistics and supply chain sectors in Penang. The analysis included descriptive statistics, reliability testing, Pearson's correlation, and multiple regression to draw meaningful insights.

4.2 Pilot Test Result

A reliability test was conducted using a sample of 30 responses. According to the Cronbach's Alpha values, all questions are reliable to be asked to the respondents as the values are in excellent and good categories which is the values are above 0.8. This indicates that the questionnaire is well-structured and suitable for gathering responses from participants.

Table 4.1
Reliability results for pilot test

Variables	**Cronbach's Alpha**	**N of items**	**Reliability Level**
Internet of Things (IoT) Integration	0.914	5	Excellent
Artificial Intelligence (AI) Implementation	0.908	4	Excellent
Robotics and Automation	0.863	4	Good
Big Data Analytics	0.841	3	Good
Blockchain	0.868	3	Good
Supply Chain Resilience	0.874	4	Good

4.3 Descriptive Analysis for Demographic Information

4.3.1 Demographic Profile

Table 4.2
Respondent's Gender

		Frequency	**Percent**	**Valid Percent**
Valid	Female	130	51.2	51.2
	Male	124	48.8	48.8
	Total	254	100.0	100.0

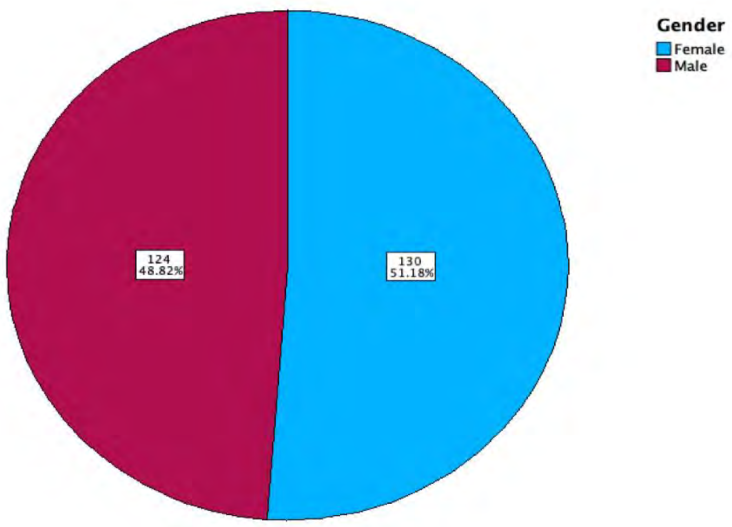

Figure 4.1
Respondent's Gender

Table 4.2 and figure 4.1 show that 254 respondents were involved in this survey and the breakdown of the respondents. There are 130 (51.2%) Female respondents and 124 (48.8%) Male respondents who participated in this study.

4.3.2 Respondent's Age

Table 4.3
Respondents' Age

		Frequency	Percent	Valid Percent
Valid	21 to 30	115	45.3	45.3
	31 to 40	90	35.4	35.4
	41 and over	27	10.6	10.6
	Under 20	22	8.7	8.7
	Total	254	100.0	100.0

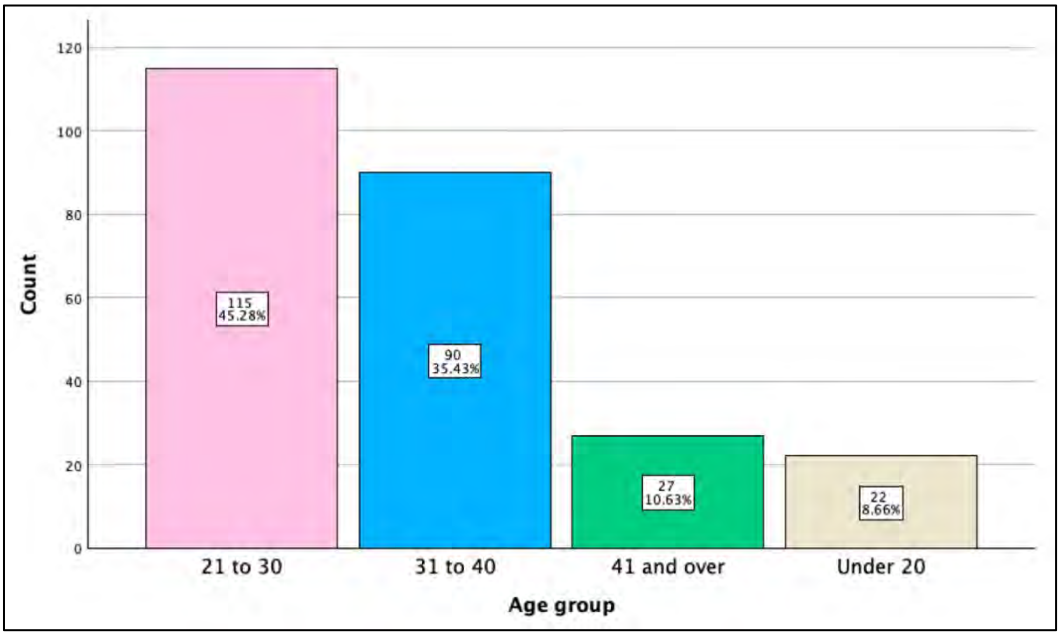

Figure 4.2
Respondents' Age

Table 4.3 and Figure 4.2 provide an overview of the respondents' age groups. From 254 of respondents, 115 (45.3%) respondents are aged group between 21 to 30 years old, 90 (35.4%) respondents are aged group between 31 to 40 years old. Meanwhile, 22 (8.7%) respondents are aged under 20 years old.

4.3.3 Respondents' Education Level

Table 4.4
Respondents' Education Level

		Frequency	**Percent**	**Valid Percent**
Valid	Bachelor's Degree	158	62.2	62.2
	Diploma	76	29.9	29.9
	Master's Degree and above	18	7.1	7.1
	Secondary School	2	.8	.8
	Total	254	100.0	100.0

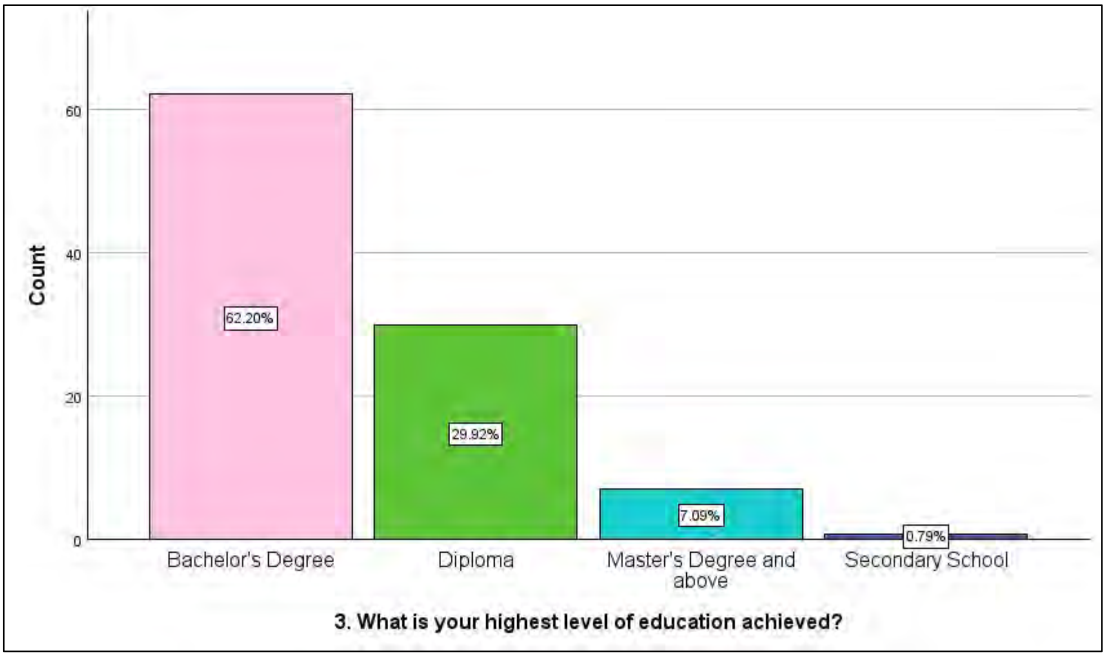

Figure 4.3
Respondents' Education Level

In terms of the highest education level, 158 respondents (62.2%) hold a Bachelor's Degree, followed by 76 respondents (29.9%) with a Diploma. Additionally, 18 respondents (7.1%) possess a Master's Degree or higher, while 2 respondents (0.8%) have completed Secondary School.

4.3.4 Respondent's Job Position

Table 4.5
Respondent's Job Position

		Frequency	Percent	Valid Percent
Valid	Assistant Engineer	1	.4	.4
	Executive	68	26.8	26.8
	Inventory Analyst	12	4.7	4.7
	Logistics Coordinator	1	.4	.4
	Manager	14	5.5	5.5

Table 4.5 (Continued)

	Frequency	Percent	Valid Percent
Manager, Executive, Supervisor, Inventory Analyst, Planners	1	.4	.4
Manager, Executive, Supervisor, Planners	1	.4	.4
Planners	12	4.7	4.7
Production Assistant	4	1.6	1.6
Production Planner	4	1.6	1.6
Supervisor	129	50.8	50.8
Supply Chain Coordinator	5	2.0	2.0
Warehouse Assistant	2	.8	.8
Total	254	100.0	100.0

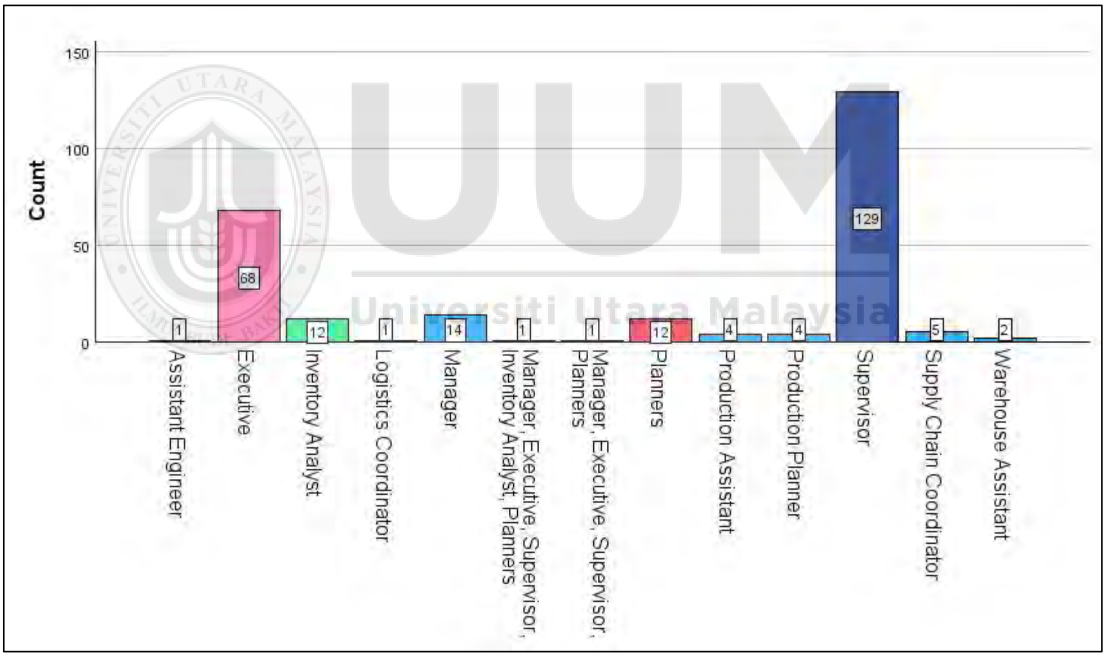

Figure 4.4
Respondent's Job Position

In terms of job position, the majority of respondents, 129 (50.8%), hold the position of Supervisor, followed by 68 respondents (26.8%) as Executives. Additionally, 12 respondents (4.7%) work as Inventory Analysts, while another 12 respondents (4.7%) are Planners. Other roles include Managers (14 respondents, 5.5%), Supply Chain

Coordinators (5 respondents, 2.0%), Production Assistants and Production Planners (each with 4 respondents, 1.6%), and Warehouse Assistants (2 respondents, 0.8%). A few respondents hold combined roles in management, supervision, and planning.

4.3.5 Types of services offered by a company

Table 4.6
Types of services offered by a company

		Frequency	Percent	Valid Percent
Valid	Automotive Industry	11	4.3	4.3
	Freight Forwarding	13	5.1	5.1
	Logistics & Transportation	24	9.4	9.4
	Logistics & Transportation, Warehousing and Inventory	29	11.4	11.4
	Manufacturing Industry	76	29.9	29.9
	Warehousing and Inventory	101	39.8	39.8
	Total	254	100.0	100.0

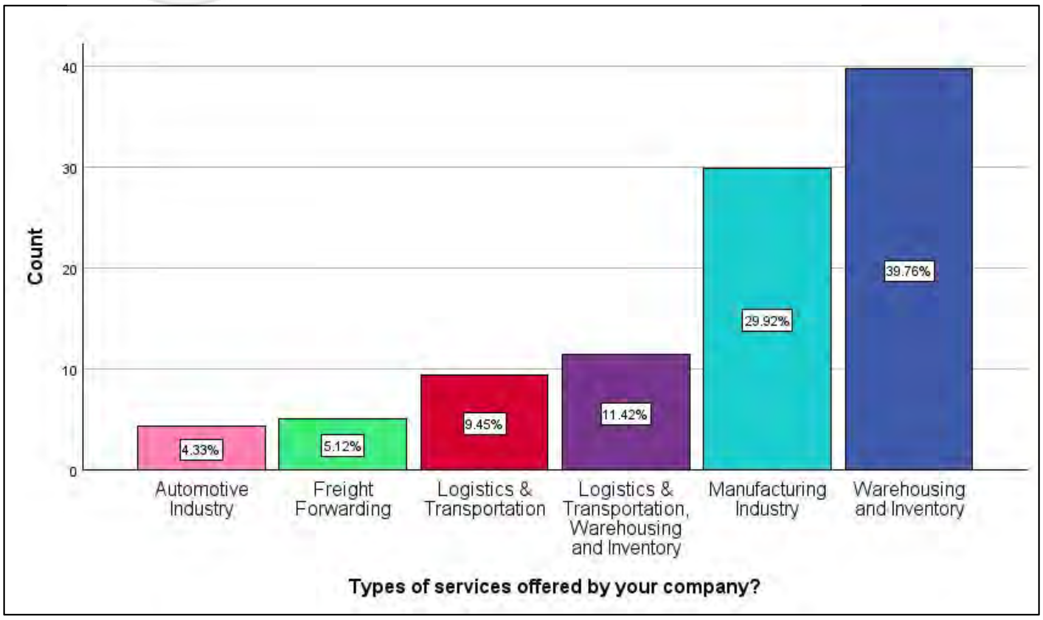

Figure 4.5
Types of Services Offered by Company

For the types of services offered by the respondents' companies, the majority, 101 respondents (39.8%), are involved in warehousing and inventory services. This is followed by 76 respondents (29.9%) engaged in the manufacturing industry, and 29 respondents (11.4%) again working in logistics and transportation, warehouse and inventory. Additionally, 24 respondents (9.4%) provide logistics and transportation services, while smaller percentages represent companies involved in freight forwarding, automotive industry services. Freight Forwarding and the Automotive Industry contribute smaller but still meaningful portions, with 13 (5.1%) and 11 (4.3%) responses, respectively.

4.3.6 Types of Ownership of Respondents Organizations

Table 4.7
Types of Ownership of Respondents Organizations

		Frequency	Percent	Valid Percent
Valid	Foreign-Owned Company	52	20.5	20.5
	Local and Foreign Joint Venture/Domestic-Foreign Partnership	48	18.9	18.9
	Partnership	38	15.0	15.0
	Private Limited Company	55	21.7	21.7
	Public Corporation/Public Limited Company	31	12.2	12.2
	Sole proprietorship/Personal enterprise	30	11.8	11.8
	Total	254	100.0	100.0

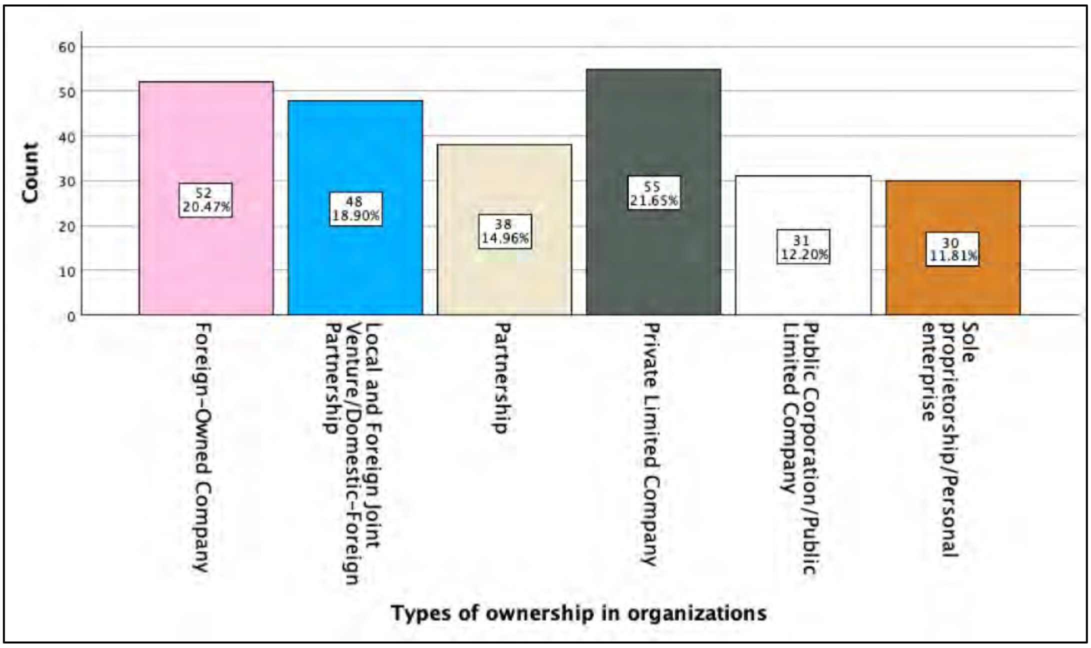

Figure 4.6
Types of Ownership of Respondents Organizations

In terms of types of ownership, 55 (21.7%) respondents are private limited companies, 52 (20.5%) respondents are foreign-owned companies and 31 (12.2%) respondents are public corporations/public limited companies. The cumulative percentage accounts for 100% of the respondents.

4.3.7 Number of Full-Time Employees in Organizations

Table 4.8
Number of Full-Time Employees in Organizations

		Frequency	Percent	Valid Percent
Valid	< 50	29	11.4	11.4
	100 - 149	53	20.9	20.9
	150 – 199	50	19.7	19.7
	200 Above	80	31.5	31.5
	50 - 99	42	16.5	16.5
	Total	254	100.0	100.0

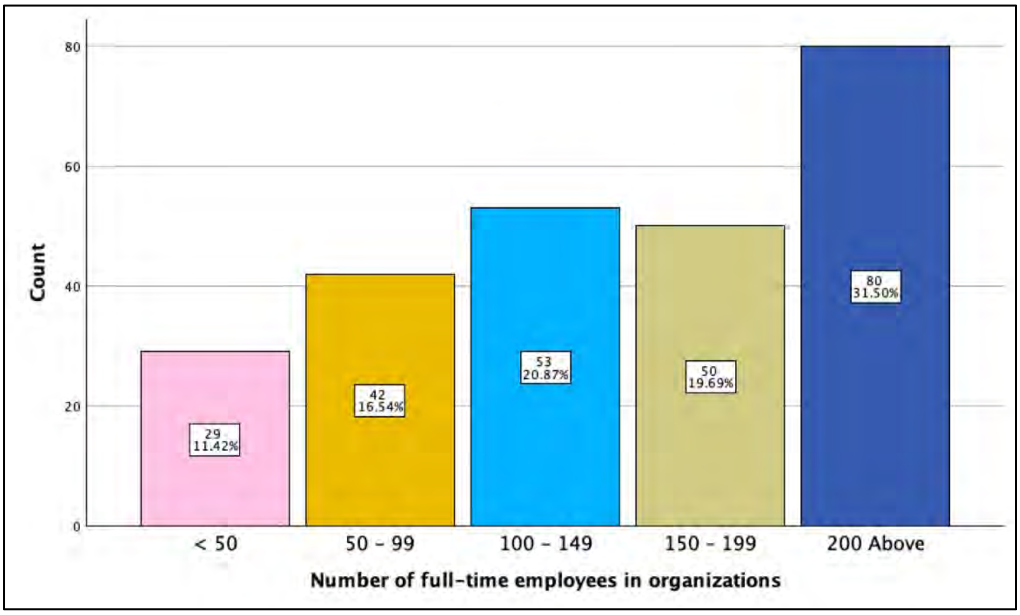

Figure 4.7
Number of Full-Time Employees in Organizations

There are 80 (31.5%) respondents who answered the number of full-time employees of 200 and above employees, 53 (20.9%) respondents answered 100-149 employees and 29 (11.4%) respondents answered less than 50 employees. The cumulative percentage accounts for 100% of the respondents.

4.3.8 Years of -Company Operating In Malaysia

Table 4.9
Years of Respondents Company Operating In Malaysia

		Frequency	Percent	Valid Percent
Valid	>20 years	22	8.7	8.7
	0-5 years	73	28.7	28.7
	11-15 years	45	17.7	17.7
	16-20 years	26	10.2	10.2
	6-10 years	88	34.6	34.6
	Total	254	100.0	100.0

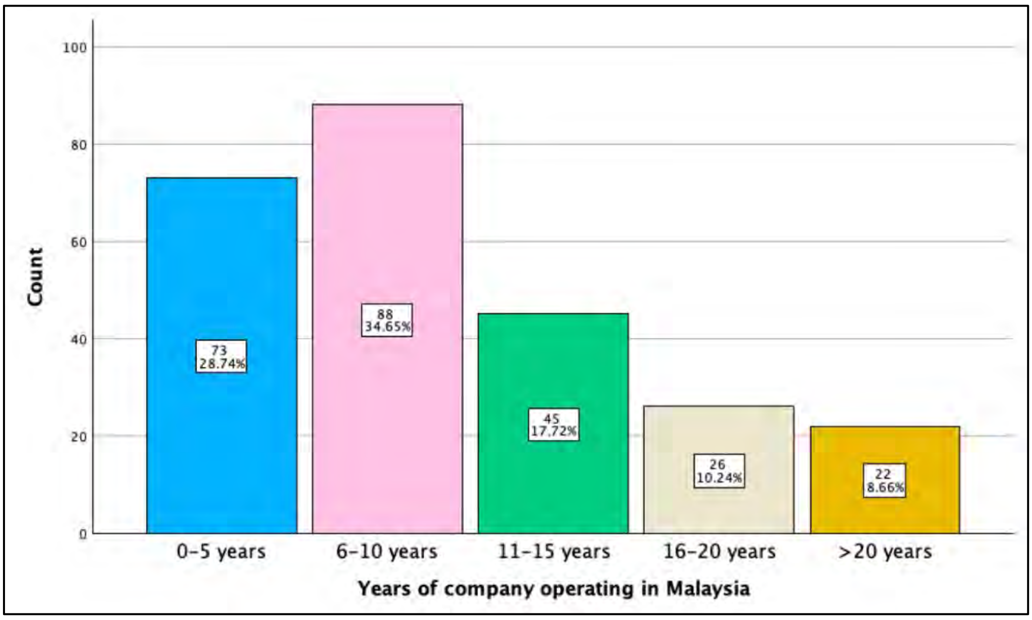

Figure 4.8
Years of Respondents' Company Operating In Malaysia

Apart from that, there are 88 (34.6%) respondents answered the company is operation 6-10 years, 73 (28.7%) respondents answered 0-5 years, and 45 (17.7%) respondents answered 11-15 years. The cumulative percentage accounts for 100% of the respondents.

4.4 Descriptive Analysis for Variables

In the descriptive analysis, data from all variables are summarized and examined based on frequency, mean, and standard deviation. This method helps in identifying patterns and trends within the dataset. The study explores the impact of technologies such as the Internet of Things (IoT), Artificial Intelligence, robotics and automation, big data implementation, and blockchain on supply chain resilience. To assess these factors, a five-point Likert scale was used to evaluate each item.

4.4.1 Internet of Things (IoT) Integration

Table 4.10
Descriptive Statistics for Internet Of Things (IoT)

Items	N	Minimum	Maximum	Mean	Std Deviation
IoT1	254	1	5	3.90	1.083
IoT2	254	1	5	3.81	1.133
IoT3	254	1	5	3.88	1.158
IoT4	254	1	5	3.80	1.101
IoT5	254	1	5	3.92	1.113
Overall	254	1	5	3.86	0.813

The table presents descriptive statistics for the integration of the Internet of Things (IoT), which is considered an independent variable in the study titled *Industry 4.0* Technologies and Supply Chain Resilience: Insights from Logistics and Supply Chain Perspectives in Penang. There are 5 items under Internet of Things (IoT) Integration, each evaluated based on a sample of 254 respondents. The table provides key statistical measures, including the minimum and maximum values (both ranging from 1 to 5), the mean scores, and the standard deviations for each item. The mean values for individual items range between 3.80 and 3.92, indicating generally positive perceptions toward IoT integration. The standard deviations vary from 1.083 to 1.158, reflecting a moderate level of variability in responses. The overall mean score of 3.86 with a standard deviation of 0.813 suggests a relatively consistent agreement among respondents regarding IoT's role in supply chain resilience. These findings provide insights into how IoT is perceived within the logistics and supply chain sectors in Penang, highlighting its potential impact on strengthening supply chain resilience in the context of Industry 4.0.

4.4.2 Artificial Intelligence (AI) Implementation

Table 4.11
Descriptive Statistics for Artificial Intelligence (AI) Implementation

Items	N	Minimum	Maximum	Mean	Std Deviation
AI1	254	1	5	3.85	1.102
AI2	254	1	5	3.78	1.181
AI3	254	1	5	3.84	1.132
AI4	254	1	5	3.78	1.196
Overall	254	1.75	5	3.81	0.878

The descriptive analysis in Table 4.11 provides statistical insights into the implementation of Artificial Intelligence (AI) within the study titled "Industry 4.0 Technologies and Supply Chain Resilience: Insights from Logistics and Supply Chain Perspectives in Penang." The table presents key descriptive statistics, including the number of respondents (N = 254), minimum and maximum values, mean scores, and standard deviations for four independent variables (AI1, AI2, AI3, AI4) that assess AI implementation. The mean values across the four AI implementation items range from 3.78 to 3.85, indicating a generally positive perception of AI adoption in logistics and supply chain operations. The overall mean score is 3.81, reflecting a consistent and moderate level of AI implementation across respondents. The standard deviation (SD) values range between 1.102 and 1.196 for the individual AI implementation items, indicating moderate variability in responses.

The overall standard deviation (0.878) is lower, suggesting a more consistent perception of AI implementation when considering the combined responses.

4.4.3 Robotics and Automation

Table 4.12
Robotics and Automation

Items	N	Minimum	Maximum	Mean	Std Deviation
RA1	254	1	5	3.72	1.235
RA2	254	1	5	3.80	1.155
RA3	254	1	5	3.77	1.154
RA4	254	1	5	3.78	1.183
Overall	254	1	5	3.76	0.891

The descriptive statistics in Table 4.12 provide valuable insights into how employees in the logistics and supply chain industry perceive the implementation of Robotics and Automation in the context of Industry 4.0. The mean scores suggest a generally positive outlook, but the variations in responses indicate differences in acceptance levels among employees. There are 4 items under Robotics and Automation. RA2 obtained the highest mean of 3.80 and the lowest mean was on RA1 with the mean of 3.72. Employees may find this specific technology easier to use or more beneficial in their daily tasks.

4.4.4 Big Data Analytics

Table 4.13
Big Data Analytics

Items	N	Minimum	Maximum	Mean	Std Deviation
BDA1	254	1	5	3.81	1.107
BDA2	254	1	5	3.94	1.039
BDA3	254	1	5	3.81	1.116
Overall	254	1	5	3.86	0.891

Based on the table 4.13 showed BDA2 obtained the highest mean of 3.94 and the lowest mean was on BDA1 and BDA3 with the mean of 3.81.BDA3 has the highest SD (1.116), suggesting that opinions about this aspect of big data analytics vary the most among employees. While most employees acknowledge the potential benefits of data-driven decision-making, their level of acceptance depends on several factors. Some employees embrace Big Data Analytics because they see its advantages in improving efficiency, forecasting demand, and optimizing supply chain operations. Those who find it easy to use and integrate into their daily tasks are more likely to support its implementation.

4.4.5 Blockchain

Table 4.14
Blockchain

Items	N	Minimum	Maximum	Mean	Std Deviation
B1	254	1	5	3.84	1.092

Table 4.14 (Continued)

Items	N	Minimum	Maximum	Mean	Std Deviation
B2	254	1	5	3.76	1.188
B3	254	1	5	3.82	1.191
Overall	254	1	5	3.81	0.879

Table 4.14 showed there are 3 items under Blockchain. B1 obtained the highest mean of 3.84, and the lowest mean was on B2 with the mean of 3.76.If blockchain systems are easy to integrate into existing processes and do not require significant changes in workflow, employees are more likely to embrace them.

4.4.6 Supply Chain Resilience

Table 4.15
Supply Chain Resilience

Items	N	Minimum	Maximum	Mean	Std Deviation
SCR1	254	1	5	3.88	1.039
SCR2	254	1	5	3.85	1.123
SCR3	254	1	5	3.83	1.108
SCR4	254	1	5	3.76	1.176
Overall	254	1	5	3.83	0.827

The table presents a descriptive analysis of Supply Chain Resilience, which is considered a dependent variable in the study on Industry 4.0 Technologies and Supply Chain Resilience. There are 4 items under Supply Chain Resilience. SCR1 obtained the highest mean of 3.88 and the lowest mean was on SCR4 with the mean of 3.76. SCR2 and SCR3 had mean scores of 3.85 and 3.83, respectively, reflecting a generally positive perception of supply chain resilience. Employees likely recognize the organization's ability to withstand disruptions and maintain smooth operations. As Industry 4.0 technologies become more prevalent, employees who see automation, artificial intelligence, and blockchain improving supply chain functions may be more confident in resilience measures.

4.5 Reliability Test

Table 4.16
Reliability Analysis for Variables

Variables	**Cronbach's Alpha**	**N of items**	**Reliability Level**
Internet of Things (Iot) Integration	0.778	5	Good
Artificial Intelligence (AI) Implementation	0.758	4	Good
Robotics and Automation	0.747	4	Good
Big Data Analytics	0.643	3	Acceptable
Blockchain	0.633	3	Acceptable
Supply Chain Resilience	0.730	4	Good

This table presents the results of a reliability test using Cronbach's Alpha to assess the consistency of different variables in a study. A total of 254 samples were analyzed. Cronbach's Alpha values indicate the internal consistency of the items measuring each variable, with a threshold of 0.7 generally considered good for reliability level. According to Hair 2014, it is acceptable if reliability values are between 0.60 and 0.70. The variables tested include Internet of Things (IoT)

Integration, Artificial Intelligence (AI) Implementation, Robotics and Automation, Big Data Analytics, Blockchain, and Supply Chain Resilience. Most of these variables exhibit Cronbach's Alpha values above 0.7, signifying good reliability. However, Big Data Analytics (0.643) and Blockchain (0.633) these scores fall under the "acceptable" range. Yet they are still categorized as acceptable and reliable based on the study's criteria.

In summary, the findings suggest that the questionnaire items used to measure these variables are consistent and suitable for further research or data collection.

4.6 Pearson Correlation Result and Analysis

4.6.1 The Correlation analysis between Internet of Things (IoT) Integration and Supply Chain Resilience.

Table 4.17
The Correlation between Internet of Things (IoT) Integration and Supply Chain Resilience.

Variables		**Internet of Things (IoT) Integration**	**Supply Chain Resilience**
Internet of Things (IoT) Integration	Pearson Correlation	1	.768**
	Sig. (2-tailed)		<.001
	N	254	
Supply Chain Resilience	Pearson Correlation	.768**	1
	Sig. (2-tailed)	<.001	
	N		254

**. Correlation is significant at the 0.01 level (2-tailed).

Based on the table, there is a strong positive correlation, which is 0.768 (p<.001), between IoT Integration and Supply Chain Resilience. A correlation coefficient of 0.768 suggests that as IoT integration increases, supply chain resilience also improves. This means that companies that effectively implement IoT technologies tend to have more resilient supply chains. The p-value (<0.001) confirms that this correlation is statistically significant, meaning that the relationship is unlikely to be due to chance.

4.6.2 The Correlation Analysis between Artificial Intelligence (AI) Implementation and Supply Chain Resilience.

Table 4.18
The Correlation between Artificial Intelligence (AI) Implementation and Supply Chain Resilience.

Variables		**Artificial Intelligence (AI) Implementation**	**Supply Chain Resilience.**
Artificial Intelligence (AI) Implementation	Pearson Correlation	1	.701**
	Sig. (2-tailed)		<.001
	N	254	
Supply Chain Resilience.	Pearson Correlation	.701**	1
	Sig. (2-tailed)	<.001	
	N		254

**. Correlation is significant at the 0.01 level (2-tailed).

Based on the table, the Pearson correlation coefficient for AI Implementation and Supply Chain Resilience is 0.701, which indicates a strong positive correlation. The p-value (<0.001) indicates that this result is highly significant. This means the findings are not just a coincidence, but rather, there is clear evidence that AI adoption contributes to improving supply chain resilience.

4.6.3 The Correlation Analysis between Robotics and Automation and Supply Chain Resilience.

Table 4.19

The Correlation between Robotics and Automation Implementation and Supply Chain Resilience.

Variables		**Robotics and Automation**	**Supply Chain Resilience**
Robotics and Automation	Pearson Correlation	1	.788**
	Sig. (2-tailed)		<.001
	N	254	
Supply Chain Resilience	Pearson Correlation	.788**	1
	Sig. (2-tailed)	<.001	
	N		254

**. Correlation is significant at the 0.01 level (2-tailed).

Based on the table, there is a significant strong positive linear relationship between Supply Chain and Robotics and Automation with the Pearson correlation of 0.788 (p<.001).The correlation value of 0.788 suggests a strong positive link between automation and supply chain resilience. This means that companies that use more robotics and automated systems tend to have supply chains that handle disruptions better and operate more smoothly.

The p-value (<0.001) shows that this finding is not a coincidence. It means that the connection between automation and supply chain strength is real and reliable, not just due to random factors.

4.6.4 The Correlation Analysis between Big Data Analytics and Supply Chain Resilience.

Table 4.20

The Correlation between Big Data Analytics Implementation and Supply Chain Resilience.

Variables		Big Data Analytics	Supply Chain Resilience
Big Data Analytics	Pearson Correlation	1	.776*
	Sig. (2-tailed)		<.001
	N	254	
Supply Chain Resilience	Pearson Correlation	.776*	1
	Sig. (2-tailed)	<.001	
	N		254

**. Correlation is significant at the 0.01 level (2-tailed).

Based on the table, there is a significant strong positive linear relationship between Supply Chain and Big Data Analytics with the Pearson correlation of 0.776 ($p<.001$). The Pearson correlation coefficient of 0.776 indicates that Big Data Analytics plays a crucial role in strengthening supply chain resilience. The closer the value is to 1, the stronger the relationship, showing that companies that integrate data-driven decision-making tend to have more resilient supply chains.

4.6.5 The Correlation Analysis between Blockchain and Supply Chain Resilience.

Table 4.21
The Correlation between Blockchain and Supply Chain Resilience.

Variables		**Blockchain**	**Supply Chain Resilience**
Blockchain	Pearson Correlation	1	.726**
	Sig. (2-tailed)		<.001
	N	254	
Supply Chain Resilience	Pearson Correlation	.726**	1
	Sig. (2-tailed)	<.001	
	N		254

**. Correlation is significant at the 0.01 level (2-tailed).

Based on the table, there is a significant strong positive linear relationship between Supply Chain and Blockchain with the Pearson correlation of 0.726 ($p<.001$). A correlation coefficient of 0.726 shows a strong positive link between blockchain technology and supply chain resilience. In other words, as more companies start using blockchain in their supply chain operations, their ability to handle disruptions, adapt to challenges, and maintain smooth operations also improves significantly. This suggests that blockchain plays a key role in making supply chains stronger and more reliable. Since the p-value is less than 0.001, we can be highly confident that this result is not just a coincidence. This means that the connection between blockchain and supply chain resilience is real and significant.

4.7 Hypothesis Testing

Table 4.22

Hypothesis testing results for variables

Hypothesis	Description	Pearson correlation	Result
H1	Internet of Things (IoT) has a significant relationship with supply chain resilience	0.768 ($p<.001$)	Supported
H2	Artificial intelligence (AI) has a significant relationship with supply chain resilience	0.701 ($p<.001$)	Supported
H3	Robotics and Automation have a significant relationship with supply chain Resilience	0.788 ($p<.001$)	Supported
H4	Big data has a significant relationship with supply chain resilience	0.776 ($p<.001$)	Supported
H5	Blockchain has a significant relationship with supply chain resilience	0.726 ($p<.001$)	Supported

The table presents the hypothesis testing results for different Industry 4.0 technologies and their impact on supply chain resilience. The Pearson correlation values, which measure the strength and direction of the relationship, all indicate a strong positive correlation, with statistical significance at $p < 0.001$. The first hypothesis (H1) tests the impact of the Internet of Things (IoT) on supply chain resilience. With a Pearson correlation of 0.768, the findings confirm that IoT adoption significantly improves the ability of supply chains to adapt to changes and recover from disruptions. This is likely due to real-time data tracking, automation, and enhanced communication between different parts of the supply chain. The second hypothesis (H2) focuses on Artificial Intelligence (AI) and its role in supply chain resilience. The correlation value of 0.701 suggests a strong positive relationship, indicating that AI-powered tools, such as predictive analytics and machine learning, contribute to better decision-making, efficiency, and adaptability within the supply chain.The third hypothesis (H3) examines the influence of robotics on supply chain resilience. With a 0.788 correlation the highest among all tested technologies, robotics demonstrates a very strong positive effect. This implies that the automation of processes through robotics significantly enhances operational efficiency, reduces errors, and minimizes disruptions.The fourth hypothesis (H4) assesses the role of Big Data Analytics in supply chain resilience. A correlation value of 0.776 confirms that analyzing large volumes of data allows companies to anticipate risks, optimize operations, and improve overall supply chain performance. The ability to extract meaningful insights from data contributes to proactive problem-solving and better strategic planning.

The final hypothesis (H5) explores the impact of blockchain technology on supply chain resilience. With a correlation of 0.726, blockchain also shows a strong positive relationship, highlighting its role in enhancing transparency, security, and trust within supply chains. The decentralized and tamper-proof nature of blockchain ensures greater traceability and reliability in transactions, making supply chains more resilient to fraud, delays, and inefficiencies. Overall, the results confirm that all five technologies- IoT, AI, robotics, big data analytics, and blockchain play a crucial role in strengthening supply chain resilience. The statistical significance ($p < 0.001$) of these correlations indicates that these relationships are highly reliable and not due to random chance. The findings emphasize that companies adopting Industry 4.0 technologies are better equipped to handle uncertainties, improve efficiency, and maintain stability in their supply chain operations.

4.8 Summary of the Chapter

This chapter presents the findings and analysis of the study, focusing on the relationship between Industry 4.0 technologies and supply chain resilience. The results are derived from statistical tests, including Pearson correlation analysis and hypothesis testing, to determine the impact of various technological advancements on supply chain robustness.

The correlation analysis indicates a strong positive relationship between different Industry 4.0 technologies and supply chain resilience. Specifically, the study finds that Robotics and Automation have the highest correlation (0.788), followed closely by IoT (0.768), Big Data Analytics (0.776), Blockchain (0.726), and Artificial Intelligence (0.701). These findings suggest that implementing these technologies significantly enhances the resilience of supply chains by improving efficiency, decision-making, and adaptability in the face of disruptions.

Hypothesis testing further confirms these results, showing that all five technological factors have a statistically significant positive impact on supply chain resilience. The p-values for each correlation are below 0.001, indicating strong reliability in the findings. This suggests that the integration of Industry 4.0 technologies is not just a trend but a critical strategy for businesses aiming to strengthen their supply chain operations.

Overall, this chapter provides clear evidence that digital transformation through Industry 4.0 technologies plays a vital role in enhancing supply chain resilience. The findings highlight the importance of embracing technological advancements to mitigate risks, improve operational efficiencies, and maintain stability in supply chains, especially in unpredictable environments.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Introduction

This chapter provides a detailed analysis of the findings discussed in Chapter 4, focusing on the empirical results of the study. It explores the impact of Industry 4.0 Technologies and Supply Chain Resilience: insights from Logistics and Supply Chain Perspectives in Penang. The chapter is structured into four main sections. It begins with an overview of the key findings, followed by a summary. Next, the study's limitations are addressed, along with recommendations for future research. Finally, the chapter concludes by summarizing the overall discussion.

5.2 Key Findings

The findings discussed in Chapter 4 offer valuable insights into the key factors that impact supply chain resilience, particularly from the perspectives of logistics and supply chain management. This study aimed to examine the connection between the research questions and the study's results, which are outlined as follows.

Table 5.1
Overview of the Findings

Research Objectives	**Research Questions**	**Findings**
1)To investigate the impacts of the Internet of Things (IoT) on supply chain resilience.	1)Does the Internet of Things (IoT) impact the supply chain resilience?	IoT has a strong and significant positive impact on supply chain resilience

Table 5.1 (Continued)

Research Objectives	Research Questions	Findings
2)To examine the implementation of artificial intelligence (AI) on supply chain resilience**.**	2)Does the implementation of artificial intelligence (AI) affect supply chain resilience?	AI has a strong and significant positive influence on supply chain resilience
3)To examine how robotics and automation contribute to supply chain resilience.	3)Do robotics and automation contribute to supply chain resilience?	Robotics and automation have positively influenced supply chain resilience
4)To examine big data implementation on supply chain resilience**.**	4)What is the effect of big data implementation on supply chain resilience?	Big Data Analytics has a slightly lower positive relationship and thus contributes positively to supply chain resilience.
5)To examine blockchain impacts on supply chain resilience	5)Does blockchain affect supply chain resilience?	Blockchain technology and the lowest positive relationship thus contribute positively to supply chain resilience.

5.3 Summary of the Findings

5.3.1 Internet of Things (IoT) and Supply Chain Resilience

The study aimed to investigate how the integration of the Internet of Things (IoT) enhances supply chain resilience in logistics and supply chain management. Specifically, it examined the role of IoT-enabled tracking, predictive analytics, and real-time monitoring in improving supply chain adaptability, risk management, and operational efficiency. The research employed quantitative analysis, utilizing statistical techniques such as Pearson correlation analysis and hypothesis testing. Data collection was conducted through surveys, focusing on the use of Iot in logistics and supply chain operations. The study analyzed key metrics such as supply chain visibility, predictive capabilities, and response time to disruptions .

The findings revealed several critical insights. One of the most significant benefits of IoT integration is enhanced visibility and real-time monitoring. IoT-enabled sensors, RFID tags, and tracking systems allow businesses to monitor inventory, shipments, and environmental conditions. (Supply Chain Dive, 2025) .This real-time data enables companies to quickly identify potential disruptions and take corrective measures before issues escalate. Such transparency is crucial for ensuring smoother operations and reducing losses due to delays or mismanagement.

Another key insight was the role of IoT in risk mitigation and predictive analytics. The study found that companies utilizing IoT for data collection and predictive maintenance were better prepared to handle sudden supply chain disruptions, such as delays in raw material supply, equipment breakdowns, or transportation bottlenecks. By analyzing patterns in supply and demand, IoT-enabled systems helped businesses anticipate issues before they escalated into major operational challenges. This proactive approach led to improved decision-making, allowing firms to make real-time adjustments to their logistics strategies (Kohut, 2024).

The research also highlighted the strong correlation between IoT adoption and supply chain resilience, showing that organizations that invested in IoT solutions were more adaptable and better equipped to handle disruptions. The statistical analysis indicated that IoT-enabled companies experienced greater operational stability, improved response times, and stronger supplier collaboration, which are all critical factors in ensuring a resilient supply chain.

The findings highlight the critical role of IoT in strengthening supply chain resilience. By providing real-time insights, enabling predictive analytics, and improving risk management, IoT technology allows businesses to react more effectively to unexpected disruptions. The study suggests that organizations should prioritize IoT adoption to enhance visibility, improve decision-making, and increase overall operational resilience. Additionally, future research should explore potential challenges such as data security, integration costs, and interoperability issues.

5.3.2 Artificial Intelligence (AI) and Supply Chain Resilience

The research aimed to explore the impact of Artificial Intelligence (AI) on supply chain resilience, focusing on how AI-driven technologies contribute to operational efficiency, risk mitigation, and adaptive decision-making in logistics and supply chain management. The study seeks to understand the relationship between AI implementation and the ability of supply chains to adapt and recover from disruptions.

The analysis found a strong positive correlation between AI and Supply Chain Resilience. This showed that companies leveraging AI in their supply chains experience greater adaptability and stability in response to disruptions. Enhanced Decision-Making Through Predictive Analytics AI-powered tools, such as machine learning algorithms and predictive analytics, enable businesses to forecast potential risks and optimize supply chain planning. This proactive approach allows for more efficient risk mitigation and strategic decision-making (Aljohani, 2023).

The descriptive analysis provided insights into the respondents' perceptions of AI in supply chain resilience. The study reported a mean score of 3.85 on a five-point scale, indicating a generally positive view of AI's role in improving logistics operations. The standard deviation values ranged between 0.7 and 1.1, suggesting moderate variability in responses, meaning while most respondents acknowledged AI's benefits, some organizations faced challenges in full-scale implementation .

However, the study also reminds us that the successful implementation of AI requires addressing challenges like ensuring data quality, strengthening cybersecurity, and investing in workforce training. The study suggests that businesses should focus on the strategic adoption of AI in logistics, as it holds the promise of transforming supply chain resilience in a rapidly evolving global market.

5.3.3 Robotic and Automation and Supply Chain Resilience

Based on a strong Positive Correlation Between Robotics, Automation, and Resilience, organisations leveraging robotics experience greater efficiency, lower risks, and enhanced adaptability . Operational Efficiency and Error Reduction, such as robotic process automation (RPA), automated guided vehicles (AGVs), and warehouse robotics, significantly reduce human errors and improve supply chain operations (Bensinger, 2025) . Companies using robotics reported faster order fulfilment, better inventory tracking, and more precise demand forecasting. The descriptive analysis provided insights into respondents' perceptions of robotics in supply chain resilience. The mean score for automation's effectiveness was 3.90 on a five-point scale, reflecting a highly positive reception. The standard deviation ranged from 0.75 to 1.05, indicating some variation in views, likely due to differences in automation adoption levels across industries. However, most respondents acknowledged the substantial benefits of robotics in improving supply chain resilience.

The findings highlight that robotics and automation are not just tools for enhancing efficiency but are now essential for ensuring supply chain stability in an increasingly unpredictable global market. Companies that have successfully integrated robotics, such as automated storage and retrieval systems (AS/RS), robotic process automation (RPA), and smart logistics platforms, experience faster decision-making, better inventory control, and reduced dependency on manual labor. These benefits allow businesses to respond more effectively to sudden disruptions, such as supplier delays, labor shortages, and fluctuating customer demand (Supply Chain Tech News., 2023).

5.3.4 Big Data implementation on supply chain resilience

The study aimed to explore how Big Data Analytics (BDA) enhances supply chain resilience by improving forecasting, risk identification, and decision-making. Quantitative research was gathering responses from 254 respondents from logistics and supply chain employees, The data was analyzed using Pearson correlation analysis and hypothesis testing to evaluate the relationship between BDA adoption and supply chain resilience. The analysis revealed a Pearson correlation coefficient, which indicates a significant positive relationship between Big Data Analytics and supply chain resilience. This suggests that companies leveraging data-driven decision-making demonstrate higher adaptability, efficiency, and preparedness for disruptions.

The study found that Big Data Analytics significantly reduced operational costs by improving logistics processes, route optimization, and warehouse management. By analyzing large volumes of supply chain data, firms were able to streamline operations and enhance overall efficiency. The descriptive statistics revealed that the mean score for Big Data Analytics effectiveness was 3.86, reflecting a generally positive perception among supply chain professionals. The standard deviation ranged from 0.89 to 1.11, indicating moderate variability in responses. The highest-rated factor was Big Data's role in predictive analytics (mean = 3.94), showing that respondents strongly believe in its ability to enhance risk management and forecasting .

To fully leverage Big Data, businesses should focus on investing in analytics infrastructure, training employees in data-driven decision-making, and ensuring robust cybersecurity measures (Mucci, 2024) . The research suggests that collaborative data-sharing among supply chain partners can further enhance resilience by creating more transparent and interconnected supply chains.

5.3.5 Blockchain Impacts on Supply Chain Resilience.

The study aimed to explore the role of blockchain technology in enhancing supply chain resilience by improving transparency, security, and efficiency in supply chain operations. Blockchain Strongly Enhances Supply Chain Resilience. The analysis showed a strong positive relationship of Pearson correlation. This suggests that businesses implementing blockchain technology experience improved security, operational efficiency, and adaptability to supply chain disruptions . Improved Transparency and Traceability The blockchain's decentralized and tamper-proof ledger enables real-time tracking of goods, ensuring that all transactions are recorded accurately. This reduces fraud, eliminates errors, and enhances trust among supply chain stakeholders. The descriptive analysis revealed that respondents overall perceive blockchain as beneficial for supply chain resilience. The mean score for blockchain's effectiveness was 3.82, indicating a positive perception of its role in logistics. The standard deviation ranged from 0.85 to 1.10, suggesting moderate variability in responses, likely due to differences in adoption rates across industries. The highest-rated aspect was blockchain's impact on security and fraud prevention (mean = 3.91), highlighting its importance in protecting sensitive supply chain data .

The findings confirm that blockchain technology is a valuable tool for enhancing supply chain resilience, particularly in ensuring transparency, reducing fraud, and improving transaction security. Businesses that integrate blockchain experience fewer disputes, stronger supplier relationships, and greater efficiency in managing disruptions.

5.3.6 Adoption of Industry 4.0 Technologies Through Section D: Insights from Open-ended Responses

Section D of the questionnaire served a vital role in providing an open-ended and practical perspective on how Industry 4.0 technologies are currently being adopted across logistics and supply chain organisations in Penang. This section captured real-time insights from respondents on the extent to which technologies like IoT, AI, Robotics, Big Data Analytics, and Blockchain are implemented in their operations, categorised as low, medium, or high adoption. What made this section particularly valuable was the flexibility it offered. Rather than restricting participants to a predefined scale or a tightly scoped answer set, respondents had the space to indicate the presence of "other technologies" they were adopting as well. Interestingly, over 86% of respondents selected this option, indicating that many organisations are exploring beyond the commonly discussed pillars of Industry 4.0. This emphasizes the dynamic and evolving nature of digital transformation, where many companies are going beyond traditional IR 4.0 pillars to adopt innovations that fit their specific operational needs.

To relate Section D (the adoption level of IR 4.0 technologies in companies) to the Dynamic Capabilities Theory (DCT), we can interpret the data through the lens of a firm's ability to sense, seize, and transform the three foundational pillars of DCT (Teece D. J., 2007).

The chart shows significant medium to high adoption of Iot Sensors and Robotics & Automation, suggesting that companies have successfully sensed the strategic value of these technologies. However, technologies like Blockchain and AI show more skewed adoption (mostly low), indicating that firms may still be in the opportunity-identification phase, reflecting hesitation or lack of market clarity (Queiroz & Wamba, 2019) . Companies with strong sensing capabilities are quicker to experiment with and adopt new IR 4.0 technologies. Those lagging may lack market intelligence systems, leadership foresight, or strategic visioning tools. The high adoption levels in Robotics & Automation and Big Data Analytics suggest that companies are actively reallocating resources, upskilling their workforce, and making necessary investments. Lower adoption in Blockchain reflects resource constraints or misalignment with current business models, hindering the “seizing” phase (Queiroz & Wamba, 2019).DCT is an organisation’s capacity to reconfigure its assets and capabilities over time, which the data indicates that a sizable number of firms are exploring "Other" IR 4.0 technologies, and 86.6% reported adopting additional tech. This points toward active transformation, flexibility, and adaptation, a sign of robust dynamic capabilities (Gupta, 2020).

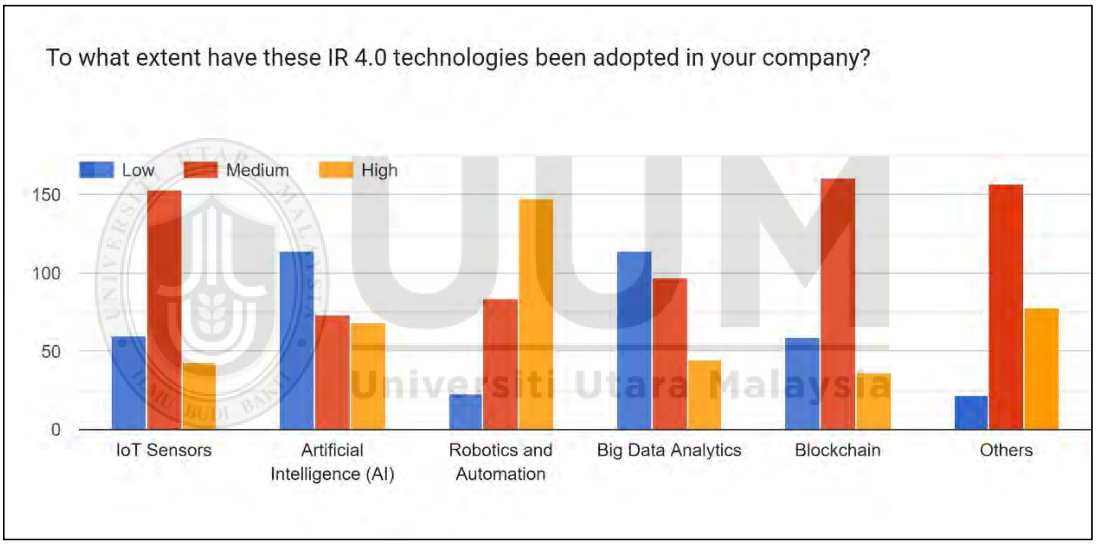

Figure 5.1
IR 4.0 technologies have been adopted in the respondent's company

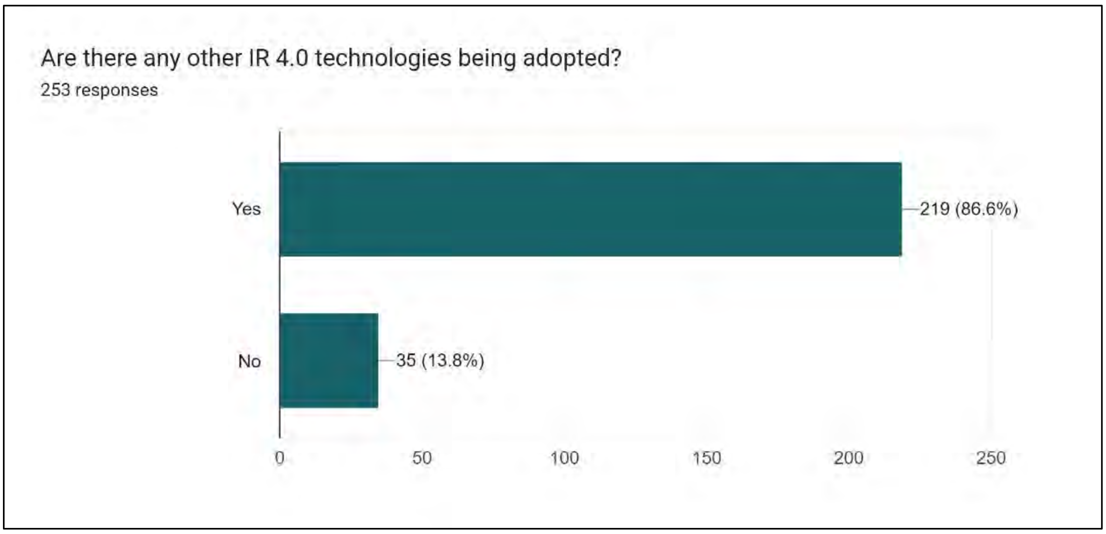

Figure 5.2
Adoption of Additional Industry 4.0 Technologies Within the Organisation

5.4 Limitations of Research

While this study provides valuable insights into the impact of Industry 4.0 technologies on supply chain resilience, several limitations should be acknowledged.

Firstly, the study was conducted within a specific geographic region, Penang, Malaysia, which may limit the generalizability of the findings. Since supply chain operations and Industry 4.0 technology adoption vary across different countries and industries, the results may not fully reflect global trends. Future research should consider a broader sample across multiple regions and industries to gain a more comprehensive understanding .

Secondly, the sample size of this study consisted of 254 respondents, which, while providing useful insights, may not fully represent the entire supply chain management workforce. A larger and more diverse sample could strengthen the study's findings and reduce potential biases. Future studies should aim for a more extensive sample size to improve the generalizability of the results .

Another limitation lies in the data collection method. The research primarily used a structured questionnaire distributed through Google Forms, which, while efficient, may introduce self-reporting biases. Respondents might have overstated or understated their organizations' adoption levels of Industry 4.0 technologies, either due to social desirability bias or a lack of full awareness of their company's digital transformation. Additionally, some participants may have been hesitant to provide critical feedback about their organizations due to confidentiality concerns .

To address these concerns and enhance the depth of understanding, the study also incorporated qualitative research methods, including in-depth interviews and case studies. These qualitative approaches provided richer insights into the challenges, experiences, and real-world applications of Industry 4.0 technologies in supply chain resilience. However, due to resource constraints, the number of interviews and case studies was limited, potentially restricting the breadth of qualitative data. Future research should consider expanding qualitative components by conducting more extensive interviews and longitudinal case studies to capture the evolving nature of Industry 4.0 adoption over time .

Additionally, the rapid evolution of Industry 4.0 technologies presents another challenge. Given the continuous advancements in AI, blockchain, IoT, robotics, and big data analytics, some findings may become outdated as newer technologies emerge. Longitudinal studies that track the long-term impact of Industry 4.0 adoption would provide a more dynamic and up-to-date perspective on how these technologies influence supply chain resilience .

Lastly, while the study highlights barriers to technology adoption, such as high implementation costs, data security risks, and workforce adaptation challenges, it does not provide detailed strategies for overcoming these issues. Future research should focus on developing practical implementation frameworks and policy recommendations to guide organizations in navigating these challenges effectively .

Despite these limitations, the study makes a significant contribution by providing empirical evidence on the relationship between Industry 4.0 technologies and supply chain resilience. Addressing these limitations in future research will help further refine strategies for digital transformation and enhance the adaptability of supply chains in an increasingly volatile global environment.

5.5 Recommendations for Future Research

As industries continue to embrace Industry 4.0 technologies to enhance supply chain resilience, there remains a need for further research to address existing gaps and improve practical implementation strategies. This study has provided important insights, but several areas require deeper exploration to support businesses in successfully navigating digital transformation.

One of the main limitations of this study was its focus on supply chain operations within Penang, Malaysia. While the findings offer valuable perspectives, the adoption of Industry 4.0 technologies can vary significantly based on geographical, economic, and regulatory factors. Future research should consider a broader, cross-country analysis to compare adoption rates, challenges, and success stories in different regions and industries (Parry, 2023) . This would allow for a more comprehensive understanding of how businesses worldwide leverage these technologies to enhance their supply chain resilience.

Although this study gathered data from 254 respondents, a larger and more diverse sample size would strengthen the generalizability of the findings. Future research should aim to include a wider range of supply chain professionals across various levels of expertise, from frontline workers to top management. Additionally, studying organizations of different sizes, from startups to multinational corporations, would provide a more holistic view of how Industry 4.0 technologies impact supply chain resilience in different business environments (Bauer, 2021).

The rapidly evolving nature of Industry 4.0 technologies means that their effects on supply chain resilience may change over time. This study provides a snapshot of the current landscape, but future research should focus on longitudinal studies that track how companies adapt to technological advancements, overcome barriers, and refine their strategies. Observing these changes over an extended period would offer deeper insights into the long-term benefits and challenges associated with Industry 4.0 adoption. A study on the future of Industry 4.0 and supply chain resilience after the COVID-19 pandemic underscores the need for ongoing research in this area. (Spieske, 2021)

While this study identified key barriers such as high costs, cybersecurity risks, and integration difficulties, it did not delve deeply into practical solutions for overcoming these obstacles. Future research should focus on case studies of companies that have successfully implemented Industry 4.0 technologies, highlighting best practices, lessons learned, and strategies that others can adopt. This would provide organizations with actionable guidance on how to navigate the complexities of digital transformation. (Spieske, 2021)

This study primarily relied on quantitative data, which is useful for identifying trends and correlations but may not fully capture the human and organizational factors influencing Industry 4.0 adoption. Future research should incorporate more in-depth interviews and case studies with industry leaders, technology providers, and frontline workers (Chiarini, 2021). By understanding firsthand experiences, decision-making processes, and resistance to change, researchers can offer more nuanced recommendations tailored to real-world challenges.

As companies integrate AI, robotics, and automation into supply chain operations, concerns about job displacement and workforce adaptation continue to grow. Future research should explore how businesses can implement these technologies while ensuring a balanced approach to workforce development. This could include studying reskilling programs, employee perceptions of automation, and strategies for maintaining human-machine collaboration in modern supply chains (Krachtt, 2017).

The successful adoption of Industry 4.0 technologies depends not only on technological readiness but also on government policies, regulatory frameworks, and industry standards. Future studies should examine how regulations impact the adoption and scalability of emerging technologies in supply chains. Additionally, exploring policy recommendations for supporting digital transformation, such as incentives for technology adoption, cybersecurity guidelines, and data protection laws, could help governments and industry stakeholders create a more favorable ecosystem for innovation (Bauer, 2021).

As Industry 4.0 continues to reshape supply chain management, ongoing research is essential to guide businesses in overcoming challenges and maximizing the benefits of digital transformation. Future studies should adopt a broader geographical scope, employ a mix of qualitative and quantitative research methods, and focus on real-world implementation strategies. By addressing these areas, researchers can contribute to building more adaptive, efficient, and resilient supply chains in the years to come.

5.6 Overall Conclusion of The Study

This study has provided a comprehensive understanding of how Industry 4.0 technologies, including IoT, AI, robotics, big data analytics, and blockchain, contribute to strengthening supply chain resilience. As businesses face increasing uncertainties due to global disruptions, market fluctuations, and operational risks, integrating these advanced technologies has proven to be a crucial factor in maintaining efficiency, agility, and competitive advantage.

The findings confirm that companies that invest in digital transformation experience significant improvements in areas such as real-time tracking, predictive analytics, process automation, and secure data management. These advancements not only enhance supply chain visibility and decision-making but also allow businesses to anticipate risks and respond to disruptions more effectively (Ivanov D. &., Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability, 2020) . However, despite these benefits, the research also highlights practical challenges that must be addressed, including high implementation costs, integration complexities, workforce adaptation, and cybersecurity risks.

Moreover, while quantitative data has provided valuable statistical insights into the positive correlation between Industry 4.0 adoption and supply chain resilience, qualitative perspectives, such as real-world case studies and employee experiences, are equally important in understanding the human and operational impact of digital transformation. Businesses must not only invest in technology but also focus on training their workforce, fostering organizational adaptability, and developing industry-wide best practices to ensure sustainable and inclusive adoption of these technologies (Kumar, 2022).

Looking ahead, organizations that proactively embrace Industry 4.0 technologies will be better positioned to navigate future uncertainties, optimize operations, and build long-term resilience. However, to fully realize the potential of these advancements, further collaboration between businesses, policymakers, and technology providers is essential. With strategic planning, proper investment, and continuous innovation, supply chains can become more intelligent, responsive, and future-ready, ultimately driving greater efficiency, reliability, and growth in the ever-evolving global marketplace.

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APPENDICES

Appendix A
Questionnaire

Universiti Utara Malaysia

Research Questionnaires Survey

Dear Respondents,

Hi, my name is Sathiya D/O Vadivelu, and I'm currently in my final semester, working on my final year project (thesis) under the supervision of Dr. Fadhilah Zahari. My research explores Industry 4.0 technologies and supply chain resilience, focusing on insights from logistics and supply chain perspectives in Penang. This study aims to better understand how these emerging technologies impact supply chain efficiency and adaptability.

Thank you for taking the time to participate in my research study. Your insights are incredibly valuable and will play a key role in shaping my research.

The questionnaire includes a brief demographic section followed by questions about supply chain practices in your organization. It should only take a few minutes to complete, and I truly appreciate your honest and thoughtful responses. Your feedback is essential to the success of this study.

Your privacy is important to me. Rest assured that all the information you provide will remain strictly confidential. Please feel free to share your opinions openly and honestly.

Thank you again for your time and contribution!

Sathiya D/O Vadivelu

sathiyadynamic@gmail.com
011-36271829

Email *

Valid email

2. **Section A: Demographic** *

Please click the answer

1. What is your gender?

Mark only one oval.

- Male
- Female

3. **2. What is your age group?** *

Mark only one oval.

- Under 20
- 21 to 30
- 31 to 40
- 41 and over

4. **3. What is your highest level of education achieved?** *

Check all that apply.

- [ ] Secondary School
- [ ] Diploma
- [ ] Bachelor's Degree
- [ ] Master's Degree and above
- [ ] Other: __________

5. **4. What is your designation?** *

Check all that apply.

- [ ] Manager
- [ ] Executive
- [ ] Supervisor
- [ ] Inventory Analyst
- [ ] Planners
- [ ] Other: ____________________

6. **5. Types of services offered by your company?** *

Check all that apply.

- [ ] Logistics & Transportation
- [ ] Manufacturing Industry
- [ ] Warehousing and Inventory
- [ ] Automotive Industry
- [ ] Freight Forwarding
- [ ] Other: ____________________

7. **6. What types of ownership do your organizations have?** *

Mark only one oval.

- ( ) Public Corporation/Public Limited Company
- ( ) Local and Foreign Joint Venture/Domestic-Foreign Partnership
- ( ) Foreign-Owned Company
- ( ) Private Limited Company
- ( ) Partnership
- ( ) Sole proprietorship/Personal enterprise

8. **7. Number of full-time employees in your organizations?** *

Mark only one oval.

- < 50
- 50 - 99
- 100 - 149
- 150 – 199
- 200 Above

9. **8. How many years has your company been operating in Malaysia?** *

Mark only one oval.

- 0-5 years
- 6-10 years
- 11-15 years
- 16-20 years
- >20 years

Section B (Independent Variables)

Please indicate the extent to which your organization agrees or disagrees with the statements provided by selecting a response on a **linear scale**: **Strongly Agree**, **Agree**, **Neutral**, **Disagree**, **or Strongly Disagree.**

Internet of Things (IoT) Integration

Definition

An "Internet of Things" is a network of networked items that can exchange data and gather information because they are outfitted with sensors, software, and other technologies. Because it enables real-time tracking, monitoring, and communication throughout the supply chain, which increases visibility and control, the Internet of Things is crucial to logistics.

10. Our IoT systems track goods and assets in real time, improve inventory management, and help prevent lost or misplaced items in logistics and production.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

11. We use IoT devices to monitor equipment health in logistics and production, predicting maintenance needs before failures occur

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

12. We use IoT to connect systems in logistics operations and supply chain, like WMS and transportation, streamlining communication and optimizing logistics operations.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

13. We generate vast data to analyze supply chain performance, identify trends, optimize routes, and forecast demand, boosting efficiency.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

14. We use IoT in logistics and supply chains to automate tracking and monitoring, reducing manual work, speeding up responses, and lowering costs.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Artificial Intelligence (AI) Implementation

Definition

The term "artificial intelligence" refers to the use of computer systems to carry out operations that normally call for human intelligence. Predictive analytics, machine learning algorithms, and decision-making systems are examples of AI uses in logistics that help create more adaptable and efficient operating procedures.

15. Our AI analyzes barcode data to predict customer behavior and market demand, helping logistics and supply chains align with customer needs.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

16.

Our AI tools make shipment tracking easier by predicting delivery times, identifying delays, and assessing risks based on trends, improving planning and coordination.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

17.

Our AI predicts issues, automates inventory, and adapts logistics to keep the supply chain running smoothly, even during crises like COVID-19.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

18.

Our AI improves spend visibility, speeds up decision-making with categorized data, and reduces costs by minimizing human effort.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Robotics and Automation

Definition

Robotics is the study of using machines or robots to carry out tasks on their own. Robotics is used in logistics to automate material handling, order fulfillment, and warehousing activities to boost productivity, accuracy, and speed.

19. We use robotic automation to cut costs, reduce waste, speed up production, and keep inventory balanced, preventing overstocking and shortages *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

20. We use robotics and automation to analyze real-time data, helping companies adapt quickly, speed up orders and deliveries, and improve demand forecasting for better inventory management. *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

21. We use robotics and automation to use resources wisely, cut waste, and support sustainability by keeping inventory precise and preventing overproduction. *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

22.

We use automation systems to enhance quality control by using automated inspections to prevent defects, cut return costs, and ensure products meet standards, making the supply chain more reliable.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Big Data Analytics

Definition

It entails handling and analyzing massive amounts of data to find trends, insights, and patterns. Big Data analytics plays a key role in logistics by helping to improve overall operational performance, optimize supply chain processes, and make data-driven choices.

23.

Our Big Data improves supply chain visibility, helping logistics operations optimize operations. It identifies weak points like production inefficiencies or poor decisions, enabling more agile and smarter adjustments.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongle Agree

24.

Our Big Data Analytics (BDA) helps identify key trends in large datasets, helping logistics operations make better supply chain decisions and understand customer preferences and market demand.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongle Agree

25.

Our big data strengthens the supply chain by aligning logistics with operation goals and improving market position and operational efficiency.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Blockchain

Definition

Blockchain technology raises the resilience of a supply chain by enhancing traceability, transparency, and data security. It for smart contracts and real-time information sharing, which are indispensable (for managing risks throughout the entire supply chain and improving collaboration).

26.

Our Blockchain gives all participants real-time access to the same data, allowing them to track goods throughout the supply chain, leading to improved visibility and accountability

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

27.

We are using blockchain transparency to eliminate intermediaries, giving all parties direct access to shared data, streamlining processes, and reducing errors.

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

28.

We use blockchain with cryptography to secure data, ensuring transactions remain unchanged, reducing fraud, and building trust among stakeholders

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Section C (Dependable Variable)

Supply Chain Resilience

Definition
The ability of a supply chain system, in this example, third-party logistics operations, to anticipate, adapt to, and successfully recover from disruptions is known as supply chain resilience. Resilience in the supply chain is the ability to control risks, absorb shocks, and maintain continuity in order to guarantee a robust reaction to unforeseen occurrences or changes in the operational environment.

29.

Our firm's supply chain is well prepared for unexpected events

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

30.

Our firm's supply chain is able to adequately respond to unexpected disruptions by quickly restoring operations

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

31.

Our firm's supply chain has the ability to maintain control over structure and function during a disruption

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

32.

Our firm's supply chain has the ability to maintain control over structure and function during a disruption

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Section D

What Is the Current Adoption Level of IR 4.0 Technologies in Your Company?

33. To what extent have these IR 4.0 technologies been adopted in your company? *

Check all that apply.

	Low	Medium	High
IoT Sensors	☐	☐	☐
Artificial Intelligence (AI)	☐	☐	☐
Robotics and Automation	☐	☐	☐
Big Data Analytics	☐	☐	☐
Blockchain	☐	☐	☐
Others	☐	☐	☐

34. Are there any other IR 4.0 technologies being adopted? *

Check all that apply.

☐ Yes
☐ No

Thank you for taking the time to share your insights with us. Your responses are incredibly valuable and will play a key role in shaping our research. I truly appreciate your participation, and your input will make a meaningful impact on the success of this study.

Rest assured, all the information you've provided will be kept strictly confidential. Your time and contribution are greatly appreciated. Thank You.