INVERGE JOURNAL OF SOCIAL SCIENCES
https://invergejournals.com/
ISSN (Online): 2959-4359, ISSN (Print): 3007-2018
Volume 5 Issue 3, 2026

DIGITAL SUPPLY CHAIN TRANSFORMATION IN THE ERA OF INDUSTRY 4.0: THE ROLE OF ARTIFICIAL INTELLIGENCE, IOT, AND BIG DATA ANALYTICS IN OPERATIONAL EXCELLENCE

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DOI: https://doi.org/10.63544/ijss.v5i3.308

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Article History:
Received: 09.05.2026
Accepted: 05.06.2026
Published: 17.06.2026

Abstract

Digital supply chain transformation emerged as a critical strategic priority in the industry 4.0 era due to increasing demands for operational efficiency, agility, and data-driven decision-making. This study examined the impact of Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Analytics (BDA) on operational excellence within modern supply chain environments. A quantitative research design was employed, and primary data were collected from a sample of 350 supply chain professionals working in manufacturing, logistics, retail, and distribution organizations. Data analysis included descriptive statistics, Pearson correlation analysis, and multiple regression analysis. The descriptive results indicated high levels of agreement regarding the adoption and effectiveness of Industry 4.0 technologies, with mean values of 4.23 for Artificial Intelligence, 4.18 for Internet of Things, 4.26 for Big Data Analytics, and 4.31 for Operational Excellence. Correlation analysis revealed significant positive relationships between all study variables, with the strongest association observed between Big Data Analytics and Operational Excellence ($r = 0.768$, $p < 0.01$). Regression results demonstrated that Artificial Intelligence ($\beta = 0.312$, $p = 0.000$), Internet of Things ($\beta = 0.284$, $p = 0.000$), and Big Data Analytics ($\beta = 0.391$, $p = 0.000$) significantly influenced operational excellence. The overall model explained 71.6% of the variance in operational excellence ($R^2 = 0.716$). Big Data Analytics emerged as the most influential predictor. The findings indicated that the integration of AI, IoT, and BDA enhanced operational efficiency, visibility, responsiveness, and competitive performance. The study provided empirical evidence supporting the strategic role of Industry 4.0 technologies in achieving sustainable operational excellence and advancing digital supply chain transformation.

Keywords: Artificial Intelligence, Big Data Analytics, Digital Supply Chain Transformation, Industry 4.0, Internet of Things, Operational Excellence

1. Introduction

With Industry 4.0 comes new access to connected and intelligent, data-driven supply chain systems. The use of Artificial Intelligence (AI), the Internet of Things (IoT), and Big Data Analytics (BDA) in supply chain processes has been integrated by organizations, which provide enhanced visibility, responsiveness, and operational benefits. Digitalization of supply chains allowed companies to gather, analyse, and process a huge amount of real-time data for tasks like procurement, production, logistics and distribution. Industry 4.0 technologies were found to improve Integration and Collaboration in Supply Chain, enabling Autonomous Decision Making and overall Operational Performance (Hahn, 2020; Mithas et al., 2022). The Internet, along with the rising complexity of world markets and growing customer expectations, drove organizations to gain the ability to be competitive and resilient in the rapidly changing business climate by embracing digital

technologies.

One of the most powerful technologies to assist in digital supply chain transformation is Artificial Intelligence. By leveraging AI-based systems, it was possible to implement predictive analytics, demand forecasting, inventory optimization, and automated decision making, which minimized operational inefficiencies and boosted productivity. Companies used machine learning to analyze their supply chain data and make informed decisions that drove business strategy. Barzizza et al. (2023) reported that AI and machine learning applications made a significant impact on the agility of supply chain and quality of decisions by their ability to process huge data. In their study, Gopal et al. (2024) sought to investigate how analytics could be applied to supply chain systems to improve performance outcomes and draw factual conclusions, including the effectiveness of analytics in forecasting customer demand and further methods for managing risk.

The Internet of Things was also a key factor in the creation of real-time connectivity among supply chain stakeholders. The operational data flows from sensors, devices and communications in the Internet of Things, brought benefits in asset tracking, inventory control, and process monitoring. By linking the two concepts – IoT systems and the supply chain, organizations were able to be more visible about operating the supply chain and curbing information and time lag delays. The studies showed that the implementation of IoT increased coordination between partners on the supply chain and improved the response to operational needs (Kunrath et al., 2023; Shi et al., 2024). AI, IoT and BDA enabled predictive and prescriptive decision-making for operational excellence. Recent research proposed that organizations that applied these technologies experienced increased efficiency, flexibility, resistance and innovation (Lee et al., 2024; Sharma et al., 2023).

Background of the Study

Digital transformation of the supply chain grew out of the Industrial 4.0 phenomenon, which centred on the need to integrate cyber-physical systems, intelligent automation and digital technologies into activities within supply chains. The challenges for organizations were mainly due to the lack of agility to cope with changes in the market, and the traditional supply chains were significantly dependent on manual processes and disorganized information systems. Industry 4.0 brought in a new concept in which the digital technology enabled all internet users to tie in seamlessly with suppliers, manufacturers, distributors and customers. The expectations of Industry 4.0 prompted innovation of supply chain models that are connected, automated, and decision-made using data, as explained by Hahn (2020). Old et al. (2024) demonstrated that the digital transformation of the supply chain led to a significant improvement in operation performance by empowering organizations to use smart technologies across various stages of the value chain. The importance of Big Data Analytics lies in the fact that the amount of data generated from many sources within and apart from the supply chain became unprecedented. It was becoming clear that organizations needed to derive meaningful insights from these information streams, in order to gain a competitive edge. Barzizza et al. (2023) made the argument that the advanced analytics and machine learning applications were key elements of Supply Chain 4.0 as they gave support to strategies in supply chain planning, performance optimization, and continuous improvement initiatives.

While the known advantages of digital technologies remained great, organizations still had to deal with complexity of implementation, integration of tech, cyber security fears, and training / recruiting staff for the digital economy. Previous research revealed some differences in the result of digital transformation in different industries and regions, underscoring the importance of empirical studies. In addition to technology adoption, the researchers highlighted that it is crucial for businesses to possess the necessary organizational skills, strategic integration, and data management capabilities to achieve successful digital supply chain transformation (Shi et al., 2024; Owusu-Berko, 2025). These ideas led us to explore the combined effect of AI, IoT, and BDA for enhancing operational excellence in today's supply chains.

Research Problem

Industry 4.0 technologies received significant research and practitioner focus, but empirical evidence of the impacts of these technologies together on operational excellence were still limited. Research focusing on Artificial Intelligence, Internet of Things, or Big Data Analytics were mostly devoted to these areas separately and few were devoted to looking at the impact of their integrated application in 4IR digital supply chain settings. There was a lack of in-depth guidance on how these technologies would work together to

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improve the performance, efficiency and competitiveness of operations. Recent studies identified many potential benefits of digital transformation, and found mixed results regarding implementation results in various organizational settings.

Research Objectives

1. To examine the effect of Artificial Intelligence on operational excellence in digital supply chains.
2. To evaluate the impact of the Internet of Things on operational excellence.
3. To investigate the influence of Big Data Analytics on operational excellence.
4. To assess the combined contribution of AI, IoT, and Big Data Analytics toward digital supply chain transformation and operational excellence.

Research Questions

Q1. What effect did Artificial Intelligence have on operational excellence in digital supply chains?
Q2. How did the Internet of Things influence operational excellence?
Q3. What impact did Big Data Analytics exert on operational excellence?
Q4. How did AI, IoT, and Big Data Analytics collectively contribute to digital supply chain transformation and operational excellence?

2. Literature Review

Artificial Intelligence and Operational Excellence

Artificial Intelligence (AI) was one of the integral technologies of Industry 4.0 and it has had a significant impact on the supply chain orchestration. AI-powered tools were seamlessly integrated into their systems, enhancing processes such as demand forecasting, inventory management, production planning, and decision-making. The implementation of AI systems helped companies analyze extensive amounts of operational data and provide predictive insights, which improved the efficiency and responsiveness of supply chain activities. According to studies, AI implementation in supply chains has enhanced organizational agility and efficiency with real-time analytics and intelligent automation features (Bag et al., 2021; Choi et al., 2023). The increasing use of machine learning algorithms and predictive models highlighted the significance of AI in attaining operational excellence.

AI's role in supply chain operations also enabled the automation of repetitive tasks and minimized manual involvement in routine decision-making processes. Intelligent systems facilitated in procurement management, optimization of logistics and risk assessment, while minimizing delays and inefficiency in operations. Resemer et al. (2021) proposed that AI-powered supply chains were more productive and agile, thanks to superior processing of information and better data-support based decision making. By integrating AI technologies, the organization became more competitive due to optimal use of resources and their operations.

The digital supply chain transformation in the Industry 4.0 era now relies more than ever on the power of artificial intelligence, digital skills and workforce innovation for operational excellence. Previous studies have underscored the ability of AI to enhance strategic decision-making through better data-driven analysis, predictive power, automation, and organizational agility in complex business settings (Iram, et al., 2025). For the effective use of AI-driven systems, robust governance, ethical approaches to innovation are essential, as well as being ready to institutionalize new technologies, which can be impeded by organizational inertia (Ali & Rafiq-uz-Zaman, 2025). In this regard, of digital transformation, the workforce's capacity to acquire 21st-century skills, technical knowledge, flexibility, and human abilities becomes the focal point because of the need for the human workforce to be capable of functioning with intelligent technologies (Rafiq-uz-Zaman, 2022a, 2022b). Moreover, skill development and innovation for STEAM is a strategic area to meet workforce performance and business growth demand in emerging markets especially towards modernization of the supply chain. (Rafiq-uz-Zaman, 2024) AI also offers opportunities and potential hurdles for system change within the organization, while implementation barriers, digital readiness, and long-term change management must be considered (Rafiq-uz-Zaman, 2025a). Likewise, AI-based human resource management can boost the productivity of the workforce, organizational performance, and operational efficiency, which is also an essential enabler of operational excellence for digitally transformed supply chains (Rafiq-uz-Zaman, 2025b). Overall, these studies indicate that the transformation of the Industry 4.0 supply chain is not just a

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technological transformation, but a strategic, ethical and human-capability related process that relies on the adoption of AI, digital governance, upskilling of workforces and organizational practices based on innovation.

AI led to better customer satisfaction due to a better service quality and accurate demand forecasting. Businesses leveraged sophisticated analytics and AI algorithms to predict market demand and manage product inventory more efficiently. They used predictive analytics and machine learning tools to forecast market trends and optimize inventory levels. Researchers highlighted the value of AI-driven insights for proactive decision making and the ability of businesses to swiftly respond to market shifts (Kamble et al., 2020; Ivanov et al., 2022). In the context of Industry 4.0, where digital supply chains are becoming increasingly important, AI emerged as a crucial technical enabler for digital transformation and operational excellence.

Internet of Things and Operational Excellence

The Internet of Things (IoT) has been a pivotal technology for the digital transformation of supplies and value chains, facilitating the real-time interaction between physical objects, devices and actors. By using IoT technologies to gather real-time operational data in a connected fashion from sensors and monitoring devices, organizations gained visibility into their supply chain processes. We improved visibility's allowed us to manage inventory, track assets, and coordinate logistics. Prior studies showed that the implementation of the IoT increased supply chain efficiency by mitigating information gap and making the systems more responsive (Ben-Daya et al., 2019; Frederico et al., 2020).

The integral monitoring features of IoT solutions greatly enhanced operational control and optimisation of the process. Organizations used sensor-generated data to identify discontinuities, track equipment performance, and make sure products and services were delivered in accordance to timely schedule. Research studies showed that incorporation of IoT improved the quality of decision-making and helped organizations adopt a proactive approach to maintenance, which could decrease operational expenses and prevent system failures (Dolgui et al., 2020; Queiroz et al., 2021).

The close information sharing and better connections between different parts of the supply chain was made possible through IoT technologies, leading to closer collaboration. Suppliers, manufacturers, distributors and customers were able to have access to accurate and timely information which built on better coordination and reduced uncertainties. The agility and flexibility of the response to the market changes and demands were reported to be better with the help of the use of IoT in supply chains (Büyüközkan & Göçer, 2018; Bag et al., 2021).

Big Data Analytics and Operational Excellence

As a large volume of structured or unstructured data was produced by the organizations with the supply chain operations, Big Data Analytics (BDA) gained significance. BDA platforms powered businesses to unlock various deep insights from extensive data, enhancing both strategic and operational decisions. Organizations utilized sophisticated analysis to make more precise forecasts, implement strategic resource allocation, and find strategic gaps for ongoing enhancement. Research presented the positive impact of BDA capabilities on operational performance in terms of its facilitation of information visibility and improved decision quality along the supply chain (Wamba et al., 2020; Gupta et al., 2022).

Big Data Analytic and Industry 4.0 technology enabled the integration of Big Data Analytics with technologies to help organizations do things better under uncertainty and face market changes with flexibility. Normal decisions composed of analytics helped to oversee the risks, refine processes and measure performance in supply chain networks. Akter et al., (2021) and Dubey et al., (2020) noted that organizations with high analytical capabilities that used and utilised information well, have a greater level of operational efficiency and competitive advantage. Humongous Data Analytics improved co-operation and information sharing among the various parties involved in the value chain. Organizations leveraged Analytical platforms to combine data from various sources in order to gain holistic understanding about performance. It was indicated that BDA played a tremendous role in innovation, operational flexibility and supply chain resilience, which were made possible through data-driven decision making and continuous performance evaluation (Gunasekaran et al., 2021; Mikalef et al., 2020).

Research Hypotheses

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https://invergejournals.com/
ISSN (Online): 2959-4359, ISSN (Print): 3007-2018
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H1: Artificial Intelligence (AI) has a significant positive effect on Operational Excellence in digital supply chains.

H2: Internet of Things (IoT) has a significant positive effect on Operational Excellence in digital supply chains.

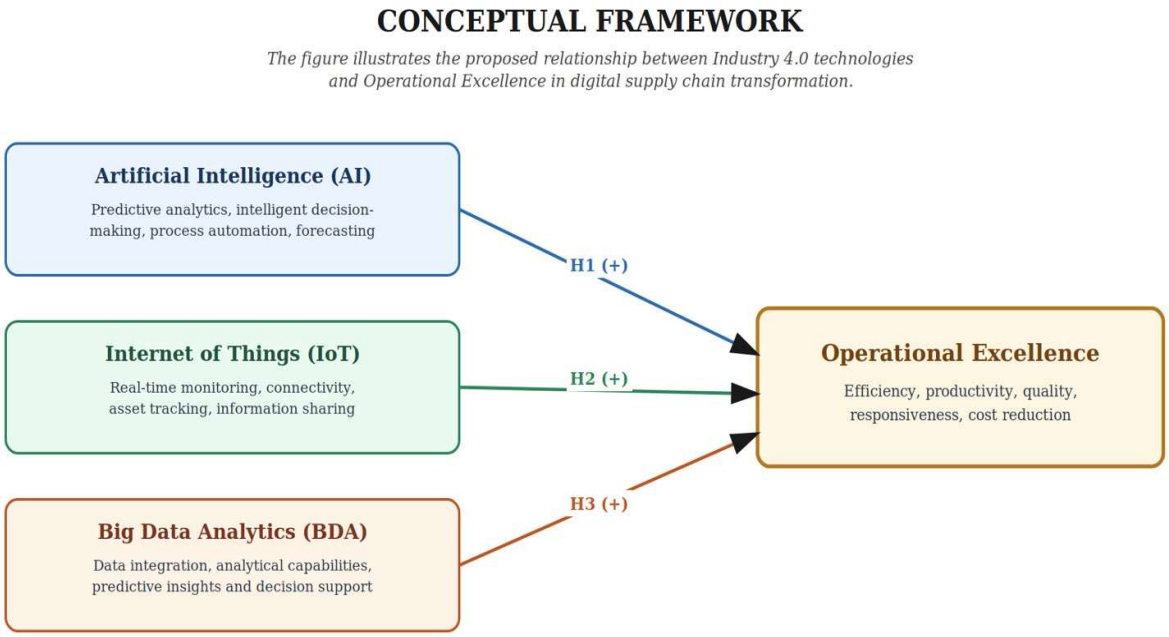
H3: Big Data Analytics (BDA) has a significant positive effect on Operational Excellence in digital supply chains.

Conceptual Framework Model

The conceptual framework proposed depicts the relationship that is hypothesized between the independent variables of Artificial Intelligence (AI), Internet of Things (IoT) and Big Data Analytics (BDA) and the dependent variable of Operational Excellence, in the setting of the digital supply chain transformation. The structure is built on the tenets of Industry 4.0, which focus on intelligent automation, current connectivity and information-driven decision-making. AI plays a key role in operational efficiency by leveraging predictive analysis, machine learning, demand forecasting, and process automation. Through IoT, assets can be monitored in real time, tracked, information can be shared, and visibility can be increased along one or more supply Chain networks, which helps improve operational performance. Big Data Analytics is assisting organizations in overcoming the challenge of turning tremendous amount of operational data into informative insights which can be used for strategic planning, risk management and constant performance improvement. The three Industry 4.0 technologies suggested in the framework can further enhance the organizational competence, with a high degree of impact on operational excellence. With the integration of AI, IoT and BDA, organizations achieve more efficiency, agility, reactivity, productivity and service quality in supply chain operations. A direct positive influence is indicated in the model by the arrows from each independent variable to operational excellence. The framework is based on the notion that the greater the level of technological use, the better the operational performance and the more competitive the performance.

Figure 1

Conceptual Framework Model



3. Research Methodology

Research Design

This is a quantitative research design to explore the impact of three key technologies in the field of

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digital supply chain transformation namely Artificial Intelligence (AI), Internet of Things (IoT) and Big Data Analytics (BDA) on operational excellence. A cross sectional survey method was used to obtain the data from the respondents in a large number for the specific period. In quantitative approach the relations between variables of the study were measured objectively and were detected in statistical analysis of the hypotheses set in the study.

Population of the Study

The target groups targeted were Supply Chain, Logistics and procurement managers, Operations managers, Digital Transformation experts and Manufacturing staff, Retail and Distribution. The respondents had relevant knowledge and hands-on experience of applying AI, IoT and Big Data Analytics to supply chain tasks. The membership of the chosen population was instrumental in the discussions on how a digital technology can help to enhance efficiency and the performance of the organization.

Sample Size and Sampling Technique

For the study, a sample size of 350 people was chosen. The respondents were professionals from organizations where digital technologies were used in any of their activities within the supply chain. The respondents who have sufficient knowledge and experience in the field of Industry 4.0 technologies and Supply Chain Management were selected using purposive sampling technique. The sample method guaranteed participants had the knowledge to give valid and appropriate feedback on digital supply chain transformation and operational excellence.

Data Collection Method

Structured questionnaire was used to gather primary data. There were two sections of the questionnaire. First section was about demographic data including gender, age, level of education, type of organization and professional experience. In the second section, the study variables such as Artificial Intelligence, Internet of Things, Big Data Analytics and Operational Excellence were measured. The 5 point likert scale from Strongly Disagree (scale 1) to Strongly Agree (scale 5) was used with this form of questionnaire. Data was collected using internet-based survey tools, and directly from professionals in related industry sectors. The survey was voluntary and respondents gave information based on their experiences at work.

Measurement of Variables

This study was conducted with following three independent variables and one dependent variable. Artificial Intelligence was expressed using the predictive analytics, intelligent decision-making, process automation and forecasting questions. The Internet of Things was assessed by indicators that represent the real-time monitoring, connectivity, asset tracking, and sharing of information. Three items encompassed in Big Data Analytics were used in the assessment of Big Data Analytics: (1) data integration, (2) analytical capabilities, and (3) predictive insights and decision support systems. The variables operational excellence was captured at replacing it with the dependent variable are indicators such as: efficiency; productivity; improvement in quality; improvement in responsiveness; reduction in costs. All the measurement items were developed from literature and adapted to the purpose of digital supply chain transformation in the context.

Data Analysis Techniques

Data collected were analysed with Statistical Package for Social Sciences (SPSS). Data from respondents were summarized using descriptive statistics such as frequencies, percentages, means and standard deviations. Pearson correlation analysis was used to investigate the correlation between the study variables. The Multiple Regression Analysis (MR) was used to measure the influence of Artificial Intelligence, IoT, and Big Data Analytics on Operational Excellence. The criterion for statistical significance of the results of hypothesis testing was set at 0.05. The statistical analyses supported, from an empirical perspective, the role of Industry 4.0 technologies towards the operational excellence within a digital supply chain environments.

4. Results and Analysis

Descriptive Statistics Analysis

Description

The analysis provided an overview of respondents' perceptions regarding Artificial Intelligence, Internet of Things, Big Data Analytics, and Operational Excellence within digital supply chain environments.

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Table 1

Descriptive Statistics of Study Variables (n = 350)

Variables	Mean	Std. Deviation
Artificial Intelligence	4.23	0.61
Internet of Things	4.18	0.65
Big Data Analytics	4.26	0.58
Operational Excellence	4.31	0.54

The descriptive statistics showed a good level of consistency among the respondents about adopting and the effectiveness of Industry 4.0 technologies in supply chain operations. Big Data Analytics recorded the highest mean value (M = 4.26, SD = 0.58), followed closely by Artificial Intelligence (M = 4.23, SD = 0.61) and Internet of Things (M = 4.18, SD = 0.65). The findings indicated that the respondents feel that the digital technologies have played a significant role in improving organizational efficiency and operational performance. The mean score of the dimension "Operational Excellence" was highest (M = 4.31, SD = 0.54), indicating that organisations had good operational performance based on digital supply chain initiatives. The relatively lower standard deviations were observed while indicating the uniformity of perception among the respondents, and the understanding about the benefits of Industry 4.0 technologies was common. The results showed that the organizations are increasingly leveraging AI, IoT, and Big Data Analytics to gain deeper insight into their resources, automate tasks more efficiently, more accurately forecast their requirements, and optimize the allocation of resources. Positive mean values in all of the items indicated that digital transformation projects had a significant impact on improving the operations and gaining competitive advantage.

Correlation Analysis

Description

Pearson correlation analysis was conducted to examine the strength and direction of relationships among Artificial Intelligence, Internet of Things, Big Data Analytics, and Operational Excellence.

Table 2

Correlation Matrix of Study Variables

Variables	1	2	3	4
1. Artificial Intelligence	1			
2. Internet of Things	0.642	1		
3. Big Data Analytics	0.687	0.659	1	
4. Operational Excellence	0.731	0.695	0.768	1

Note: $p < 0.01$

The correlation explored positive many relationships between all the study variables. There was a strong positive correlation between Artificial Intelligence and Operational Excellence ($r = 0.731$, $p < 0.01$), suggesting that the more the companies use these AI technologies, the more the operational excellence of their companies improves. There was also a strong positive relationship between Internet of Things and Operational Excellence ($r = 0.695$, $p < 0.01$). The findings suggested that real-time monitoring, asset tracking and better connectivity contribute to the operativeness and process efficiency. The highest correlation ($r = 0.768$, $p < 0.01$) with Operational Excellence was found with Big Data Analytics. This finding revealed the significance of using analytics as decision-making tools to enhance the performance of an organization. The results indicated that the organizations with advanced analytical skills enjoyed superior operational performances through their accurate forecasting, optimal use of resources and proactiveness in managing their operations.

Multiple Regression Analysis

Multiple regression analysis was performed to evaluate the influence of Artificial Intelligence, Internet of Things, and Big Data Analytics on Operational Excellence.

Table 3

Regression Analysis Results

Predictor Variables	Beta (β)	t-value	p-value

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Artificial Intelligence	0.312	7.24	0.000
Internet of Things	0.284	6.58	0.000
Big Data Analytics	0.391	8.76	0.000

Model Summary	**Value**
R	0.846
R²	0.716
Adjusted R²	0.712
F-value	291.37
Significance	0.000

The regression results showed that all three independent variables have significant effect on Operational Excellence. The effect of Artificial Intelligence was positive and significant (β = 0.312, t = 7.24, p = 0.000) demonstrating that the use of AI in practices had a positive influence on operation efficiency, productivity, and decision-making in the practices. The other technology with a positive and statistically significant impact was Internet of Things with a value of β = 0.284, t = 6.58, p = 0.000. This discovery implied that organisations gained from real-time connection and enhanced visibility all through supply chain activities. The variable that has the highest correlation with the variables in this study is Big Data Analytics given the score of β = 0.391, t = 8.76 and p = 0.000. The findings showed excellent improvements in organizational performance with the process of data-driven decision making. The model accounted for 71.6% of the variance in Operational Excellence (R^2 = 0.716) and the significant F-value (291.37, p = 0.000) indicated the overall strong regression model. The findings indicated that the combination of AI, IoT, and Big Data Analytics was a key factor in making supply chains operations so effective during the digitally revolution.

Hypotheses Testing

Table 4

Hypotheses Testing Results

Hypothesis	Relationship	Beta (β)	p-value	Result
H1	Artificial Intelligence → Operational Excellence	0.312	0.000	Supported
H2	Internet of Things → Operational Excellence	0.284	0.000	Supported
H3	Big Data Analytics → Operational Excellence	0.391	0.000	Supported

The results of hypothesis testings supported all hypotheses to be tested. H1 suggested that AI had a positive effect on Operational Excellence and the statistical findings provide a significant positive effect. The study showed that the use of AI systems had helped to improve their forecasting accuracy, automate repetitive tasks, and provide better strategic decision-making skills. H2 studied the IoT and Operations Excellence linkage. The results showed there is a positive and significant effect; thus, it proved IoT technologies support the improvements of supply chain visibility, operational co-ordination and real-time monitoring. These enhancements directly helped improve an organization's performance. H3 showed to have the most robust evidence in relation to all of the hypotheses of its impact on Operational Excellence based on the Big Data Analytics. The results showed that organisations implementing 'data skills' to use and make better informational choices and evidence-based decisions outperformed others in their operations.

5. Discussion

This study showed a strong impact of Artificial Intelligence, Internet of Things and, Big Data Analytics in digitally transformed supply chains on operational excellence. Descriptive statistics showed a high mean score for each of the variables, demonstrating that there was high level of agreement among the respondents on the strategic importance of the technologies that encompass Industry 4.0. When paired with the findings of the latest research that proved the ability of AI technologies to enhance forecasting and forecasting precision, automate decision-making processes and optimize operational performance, it's impossible not to see the positive impact of Artificial Intelligence on operational excellence. The use of AI mechanisms improved the responsiveness of the organization by quickly handling large amounts of data and providing predictive

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ISSN (Online): 2959-4359, ISSN (Print): 3007-2018
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information that helped in strategic planning and resource allocation (Min, 2023; Nguyen et al., 2024).

The research findings also showed that Internet of Things technologies had a positive impact on operational excellence. The transformative impact of IoT highlighted the importance of collecting data in real time, tracking assets, and providing better visibility in supply chain networks. The growing need in the business world for other devices to be interconnected, to enable better tracking of business activities, and better coordination between partners in the supply chain, relied on sensor based technologies. The findings align with Lee et al. (2023), who found that IoT-based systems helped to enhance operational transparency and responsiveness in complex supply chain environments. Real-time connectivity allowed organizations to act swiftly in response to disruptions, and to provide better quality decision-making by providing continuous information exchange, according to Ivanov et al. (2023).

The use of Big Data Analytics proved to be the key enabler for operational excellence, underscoring the critical role data plays in today's supply chains. The results indicated that organizations that were successful in collecting data, coupling it together and analysing it, demonstrated better operational results. Advanced analytical tools helped in forecasting demand, optimizing inventory, assessing risks and improving processes. This fact resonated with Bag et al., (2023) who proposed that one of the improvements that allows an organization to be agile and competitive is its capability to provide analysis and evidence for decision making. Baryannis et al. (2022) highlighted how predictive analytics and machine learning applications could drive improved operational efficiency by leveraging data and generating business intelligence.

The correlation analysis revealed there were strong positive relationships between all the variables which showed that Artificial Intelligence, Internet of Things and Big Data Analytics was interdependent rather than independent technologies. With these technologies interwoven, there were possibilities for organizations to create a digital ecosystem that would bolster their supply chain. Data coming from the IoT (Internet of Things) devices were fed into AI applications and data from Big Data Analytics gave strategic insight to support decisions in operations. The results are consistent with that of Queiroz et al. (2022) who reported on the enhancement of supply chain resilience and adaptability using digital technology integration. Cichosz et al. (2023) suggested the successful application of digital transformation was based on the implementation of a series of previously mentioned Industry 4.0 technologies that compliment each other and both improve the organizational's capabilities and the outcome of the activities.

The regression analysis showed that the proposed model accounted for a significant amount of variance in operational excellence, confirming the effectiveness for the application of Industry 4.0 technologies in the improvements of the organization and its performance. The scale of the impact of the model was stark, indicating that investments in AI, IoT and Big Data Analytics had a measurable operational impact. The results were consistent with the idea that a digital transformation was a necessity for strategic progress and not merely a technological trend. We analysed the results for organizations that have introduced advanced digital technologies for activities in the supply chain processes and found that these organizations have improved their efficiency, flexibility, responsiveness and customer satisfaction. Kache and Seuring (2023) report competitive advantages of digitally enabled supply chains being derived from better information processing and operational coordination.

One of the other key take-outs from the results was regarding organizational resilience/adaptability. Uncertainties of market volatility, fluctuation in market demands, global disruptions have become a challenge to the supply chains. By harnessing AI, IoT and Big Data Analytics, organisations are able to detect potential threats, track working conditions and take proactive measures to mitigate risk. This helped to build organisational resilience and minimise exposure to unforeseen disruption. In a study conducted by Belhadi et al. (2024), digital technologies were found to contribute to supply chain sustainability and resilience, leveraging on the use of intelligent monitoring and predictive risk management systems. The findings of Gupta et al., 2023 similarly indicated that use of data-driven technologies enhanced organisational readiness and enabled quicker response to changes in the environment.

The results indicated an increasing importance of digital competencies and technological skills in modern companies. For Industry 4.0 technologies to be successful investments in the infrastructure, employee skills, and data management systems were needed. The organizations with powerful technology capabilities

had the most positive impact in digital transformation projects and had more satisfaction with operational performance. For digital transformation, Tortorella et al (2023) concluded that organizational readiness, technological maturity, are significant elements that played an influence on outcomes of digital transformation. The positive impacts found in this study were a strength in that the benefits that companies who had sufficient technological resources and strategic commitment from smart companies, benefitted significantly from the use of AI, IoT, and Big Data Analytics Overall.

6. Conclusion

This study focused on investigating the contribution of Artificial Intelligence (AI), Internet of Things (IoT) and Big Data Analytics (BDA) in improving operational excellence in the context of digital supply chain transformation in the era of Industry 4.0. The results showed all three technologies were statistically significant and positive in the respect of operational excellence. The descriptive analysis revealed a high level of technology uptake and a positive attitude from respondents towards technology to improve supply chain performance. The findings from the correlation analysis showed that there were very high positive correlation among AI, IoT, BDA and operational excellence. The subsequent regression results also confirmed that the variables Artificial Intelligence ($\beta = 0.312$, $p < 0.001$), Internet of Things ($\beta = 0.284$, $p < 0.001$) and Big Data Analytics ($\beta = 0.391$, $p < 0.001$) had significant impacts on operational excellence. Big Data Analytics turned out to be the most powerful predictor, underscoring the need for data-driven decision making in today's supply chain. The model had a high explaining power—the R^2 is 0.716. The study found the utilization of Industry 4.0 technologies helped to boost the supply chain's efficiency, responsiveness, visibility, and competitiveness, helping to ensure sustainable operational excellence.

7. Recommendations

Organizations need to invest in AI technologies more significantly for better forecasting, automation, and increased strategic decision making capabilities. Management needs to create detailed digital transformation plans involving the adoption of AI, IoT and Big Data Analytics at the heart of supply chain activities. Companies need to focus on integrating IoT technologies to enhance visibility, supply chain management, and asset tracking in real time within their supply chain networks. In addition, there is a need to improve the data management infrastructure within an organization to make sure that the organization is getting every benefit of using the Big Data Analytics and can facilitate evidence-based decision making. More and more consideration should be given to employee training and digital skills development in order to be able to use and adopt technologies successfully. It is essential for organizations to have robust cybersecurity policies and procedures in place, along with data governance, to ensure the protection of digital assets and operational reliability. There is a need to encourage collaborative partnerships among supply chain stakeholders to make information exchange, technological integration and innovation possible.

8. Future Directions

In future, digital supply chain transformation can involve the use of emerging technologies like blockchain, digital twins, cloud computing and machine learning that should be explored and studied. Harmonised and comparative studies of various industries and geographical areas could give a more general picture on the effectiveness of the Industry 4.0 technologies. Other moderating or mediating factors that can be studied are such as organizational culture, technological readiness, innovation capability and supply chain resilience. Some long-term studies might shed more light on the long-term impact of digital transformation interventions on performance of operation. Sustainability outcomes of AI, IoT and Big Data Analytics may also be studied in the future, such as sustainability goals in terms of environmental performance, carbon reduction or circular economy practises. These lines of research could also contribute to expanding research on the role of technology in achieving operational excellence in more digitalized environments of the supply chain.

Acknowledgments

The authors would like to thank the participants and the respective universities for their support and cooperation in conducting this study.

Contribution of Authors

All the authors participated in the ideation, development, and final approval of the manuscript, making significant contributions to the work reported.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Informed Consent

Informed consent was obtained from all individual participants included in the study.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of 1964 Helsinki declaration and its later amendments.

Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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