The Role of Digital Manufacturing in Supporting the Smart Supply Chain: An Exploratory Study of Managers' Perspectives at Al-Kindi Factory

Yasameen Taha Abdulrazzaq, Nineveh Technical Administration Institute/Nineveh, Northern Technical University, Mosul-41001-Iraq
Email: mti.lec28.yassmeen@ntu.edu.iq

Dheyaa Muzahem Rashid, Nineveh Technical Administration Institute/Nineveh, Northern Technical University, Mosul-41001-Iraq
Email: mti.lec32.dheyaa@ntu.edu.iq

Ibrahim Abdlkhaleq Ibrahim, Nineveh Technical Administration Institute/Nineveh, Northern Technical University, Mosul-41001-Iraq
Email: mti.lec33.ibrahim@ntu.edu.iq

Corresponding Author: Yasameen Taha Abdulrazzaq, Email: mti.lec28.yassmeen@ntu.edu.iq

ABSTRACT

The present investigation seeks to analyse the contribution of digital manufacturing (DM) to the enhancement of the smart supply chain (SSC) at Al-Kindi Factory in Mosul, operating under the General Company for Communications and Power Equipment. The study is centred on the core issue of how DM can be leveraged to strengthen the SSC in order to create a manufacturing setting that improves supply chain adaptability and responsiveness to evolving market dynamics. A descriptive–analytical research design was employed to achieve the study objectives. Data were collected through a structured questionnaire, which constituted the principal tool for the empirical component of the research. The instrument was administered to managerial personnel at Al-Kindi Factory in Mosul, resulting in 90 valid responses deemed appropriate for statistical analysis. The obtained data were subsequently processed, and the proposed hypotheses were examined using established statistical software, specifically SPSS version 26. The empirical findings led to several key conclusions. Most notably, DM was shown to facilitate real-time data acquisition and processing, thereby enhancing the speed and quality of managerial decision-making and reinforcing SSC performance. This, in turn, supports cost minimisation and waste reduction. In light of these outcomes, the study puts forward a number of recommendations, including the modernisation of the examined factory through the adoption of advanced technologies such as cloud computing and the Internet of Things (IoT), with the aim of strengthening immediate communication across production lines and the broader supply chain network.

Keywords: Digital Manufacturing, Smart Supply Chain, Internet of Things

INTRODUCTION

DM is commonly known as a key pivot of the shift between traditional supply chain models to SSCs, relying on the latest technologies including the IoT, cloud computing, artificial intelligence (AI), and analytics of big data. The change contributes to the enhancement of the operational performance, reduction of the total costs, and the enhancement of the ability to predict and respond to the fluctuating demand patterns.

With the help of DM, real-time integration between the production systems and the SSC will be achieved and end-to-end visibility of operational conditions will be realised, as well as more effective control over inventory and prompt and evidence-based decision-making. Moreover, DM forms the basis of smart automation and on-demand product customisation that significantly enhances the flexibility and adaptability of the SSC to varying market conditions. Intelligent digital platforms also facilitate the integration of suppliers, manufacturers, distributors and customers in a secure and integrated eco-system. Such interconnectedness leads to reduction of wastes and consolidation of sustainability in both industrial and logistical operations. Based on this, DM is one of the core components when developing intelligent, agile, and efficient SSCs in the context of the Fourth Industrial Revolution.

The current study is organized in such a way that it has four main axes. The initial axis covers the research methodology and gives the description of the theoretical framework, including both the DM and SSC concepts. The second axis is dedicated to the empirical aspect of the research, and the ultimate axis shows the key findings and the suggestions that are put forward towards the explored manufacturing organization.

RESEARCH METHODOLOGY

Research Problem

Despite an impressive advance in DM technologies additive manufacturing, IoT, intelligent robotics, and AI their successful integration in SSCs faces numerous limitations. Such barriers are usually associated with the insufficiency of the technical infrastructure, the lack of interoperability of the systems, and the risks of data protection, as well as an enormous financial cost of digital transformation projects, and the lack of specially qualified human resources. The lack of integration may interfere with the information flow and material flow, damage the quality of the product, and increase the operation expenses. The end result of such outcomes is the hindrance of the achievement of key digitalisation goals, such as improved flexibility, real-time reaction to demand, and minimisation of waste. In this respect, the central research question can be expressed in the following way:

- To what extent are the dimensions of DM present within the investigated factory that constitutes the study sample?
- What role does DM play in supporting the SSC within the investigated factory that constitutes the study sample?

Importance of the Research

The significance of the present study is articulated through the following aspects:

1. The importance of this research originates with the growing role of DM in restructuring the traditional supply chains and moving them towards the next stage of the development in the form of SSCs that would be able to respond quickly to the changes in the market environment and demand trends. Considering the current technological advancements and the use of enabling technologies, like IoT, AI, and predictive analytics (PA), it has become possible to achieve the efficiency between manufacturing and logistics operations. This kind of integration improves operational efficiency, aids in cost reduction and organisational competitiveness.
2. In addition, the paper shows how DM-related tools and technologies could be used to strengthen SSC flexibility and responsiveness, and at the same time enhance transparency,

traceability and the quality of the decisions. These factors are especially critical in the modern business settings that are characterized by a high degree of complexity and uncertainty.

Research Objectives

1. The central objective of this study is to examine whether DM, through its core dimensions (IoT, cloud computing (CC), digital twins (DT), and 3D printing (3DP)), functions as a key enabler in supporting the SSC. In addition, the research pursues the following specific objectives:
2. To establish a comprehensive theoretical foundation that elucidates the principal concepts of DM and SSCs by critically reviewing relevant scholarly literature addressing these variables and their functional roles.
3. To define the nature, scope, and magnitude of the relationship between DM and the SSC within the context of the investigated manufacturing facility.
4. To propose practical recommendations, grounded in the empirical results obtained from the studied facility, aimed at maximising the benefits derived from DM technologies in the management and enhancement of the SSC.

Research Framework and Hypotheses

Based on the research problem and objectives, the research framework has been developed as depicted in Figure 1.

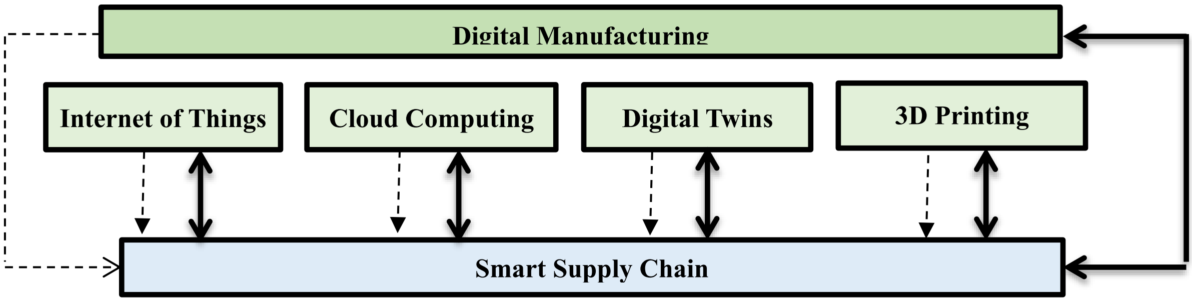

Figure 1: Hypothetical Research Plan

Research Hypotheses

H1: There is a statistically significant correlation between digital manufacturing (both collectively and individually) and the smart supply chain in the investigated manufacturing facility.
H2: There is a statistically significant causal effect of digital manufacturing (both collectively and individually) on the smart supply chain in the investigated manufacturing facility.

Research Methodology

The research used the descriptive-analytical method to define the research population and sample, describe, measure and evaluate the research variables and test the proposed model.

Data and Information Collection Methods

The researchers used both authoritative sources of Arabic and international sources relating to the issue of the research to build the theoretical framework. In the case of the empirical component, a structured questionnaire was used as the main tool of repeating information and data, and the purpose was to achieve the research goals and come up with sound conclusions.

Statistical Analysis Methods

The current research employed a collection of statistical analysis software that aligned with the objectives of the study, which was to find out the relationship among variables and test hypotheses put forward. Calculation of percentages, frequencies, means, and standard deviations were done using SPSS version 26. Also correlation and impact analysis was done and statistical hypothesis was tested on the variables being studied. One hundred questionnaires were issued and 87 were considered to be valid and the response rate was 87 % and this was utilized in the further statistical analyses.

Description of the Research Population and Sample

Somehow, Al-Kindi Factory in Mosul, which is owned by the General Company of Communications and Power Equipment, was identified as the study site in terms of research methodology. It was established in the year 1987, in Mosul, and is considered to be one of the major industrial plants in Nineveh Governorate. The factory is also specialized in thermal cameras production and was able to accomplish one project in the production of these cameras. Also, it helped in the production of sterilisation cabins that were used at hospital doors and government offices during health emergency. The portfolio of the factory consists of thermal cameras and their use in security and surveillance systems, sterilisation cabins, servicing of electrical transformers with which the company has repaired and serviced more than 700 distribution transformers of different capacity as well as manufacturing the electronic printed circuit boards (PCBs) which are used in various electronic equipments. Therefore, Al-Kindi Factory is an important part of the national industry, as it creates jobs and encourages local production, reduces the reliance on imports of communication and security devices. On the question of the research sample, the questionnaire was given to a sample population of staff at Al-Kindi Factory. Table 1 summarises the characteristics of the respondents, including gender, age, educational qualification, job position, and length of service at the facility.

Table 1. Characteristics of the individuals studied.

Sex									
Feminine					**Male**				
%	N				%	N			
31	28				69	62			
Age									
51 More		**50-41 Year**		**40-31 Year**		**30-20 Year**			
%	N	%	N	%	N	%	N		
11	10	20	18	45	39	24	21		
Academic Qualification									
Master's		**Higher Diploma**		**Bachelor's**		**Diploma**		**Preparatory**	
%	N	%	N	%	N	%	N	%	N
9	8	4	4	44	38	32	27	11	10
Number of Years of Service									
30 Years and Older		**21-30 Years**		**From 11-20 Years**		**Less than 10 Years**			
%	N	%	N	%	N	%	N		
13	11	51	44	19	17	17	15		

Source: Prepared by researchers based on questionnaire results.

Based on the data provided by participants in the first section (general information) of the questionnaire, the research sample exhibited the following characteristics:

1. Table 1 indicates that male respondents at Al-Kindi Factory considerably outnumbered female respondents, with males representing 69% and females 31%. This disparity can be attributed to the nature of work in such industrial settings, where males are generally preferred for roles demanding significant physical effort and exposure to high-risk environments.
2. The age group 31–40 years comprised the largest proportion of respondents. Those in this bracket are made up of people with experience and also energy as youths that have the advantage of rich work knowledge gained over time. Such a combination has a positive impact on the quality of the information given and the ability to match with the customer requirements. On the other hand, the participants who had the least percentage were respondents aged 51 years and onwards and constituted 11% of the sample.
3. Respondents holding a bachelor's degree constituted 44% of the sample, creating the hegemonic educational alliance. This is an indication that jobs in these manufacturing industries tend to need advanced education. Such qualified individuals would tend to have good scientific knowledge and skills, which will help them deliver the right and holistic information that can be used in line of their duties.
4. Members of the sample with 21–30 years of professional experience accounted for 44%, reflecting advanced managerial skills and technical competence, supported by extensive knowledge and expertise. The extended period of service also indicates considerable practical experience and proficiency within their respective roles.

THEORETICAL FRAMEWORK

Digital Manufacturing

The Concept of Digital Manufacturing

History of DM can be traced back, in the middle of the 20th century, during the invention of the electronic-computer in the 1940s when the first attempts were made to make use of technology to produce digital data. As computing technologies improved in the 1960s, text and image processing software programmes were produced that could process text and images digitally (Gillani et al., 2020). With the advent of the digital revolution in the 1970s and 1980s, there was a massive advancement in the creation of personal computers and graphical software, that made individuals capable of producing basic digital content including electronic documents, graphics and simple games. Then, the shift to the networked world of the 1990s and the extensive use of the Internet contributed to the distribution of digital works on a global level.

The proliferation of websites, blogs, and interactive content during this period fundamentally transformed cultural and social production (Fraile et al., 2019; Naderi et al., 2019). The trend has been ongoing into the 21st century and presently continues to evolve due to the development of smartphones, AI, and virtual reality (VR). The field of DM has widened to the development of virtual space, smart applications, creative audio-visual content and algorithmic digital arts. The digital factory or digital production is the production or development of content and products through digital technologies (Alexopoulos et al., 2020; Bastos de Miranda & Lima, 2025). DM has taken a very broad scope of outputs, including texts, pictures, videos, programs, designs and art, which were created and delivered via a variety of digital devices, i.e., smartphones and the Internet.

DM is also a control method of the manufacturing equipment on digital signals, which transmit design information, production process information, manufacturing information, managerial information and technical capabilities. Such information is shared among manufacturing organizations through the digital networks, and the global users can post requests as the companies develop and manufacture the respective products through dynamic partnerships. To that effect, DM has become a leading type of human expression, a combination of artistic creativity and the contemporary technological potential and facilitates practically endless possibilities of innovation, distribution, and communication (Aini et al., 2024; Dallel et al., 2023; Leesakul et al., 2022). Based on the above, it is clear that DM is the practice of the complex application of digital technologies to design and manufacture products in a very efficient fashion. This will merge computing, automation, big data analytics (BDA), and AI to streamline the whole manufacturing chain and keep the operations constantly improving.

The Importance of Digital Manufacturing

DM signifies a qualitative advancement in contemporary industry, involving the integration of digital technologies such as CC, IoT, AI, and 3DP into traditional production processes. The importance of DM is reflected in several key dimensions (Alexopoulos et al., 2020; Monostori et al., 2010).

Enhancing Efficiency and Productivity

DM reduces human error, speeds up production and improves the quality of products through process automation. DM systems allow real-time performance monitoring and analysis to make prompt and accurate decisions aimed at maximising the efficiency of the operations.

Cost Reduction

DM allows companies to minimise material and energy wastage and reduce operational downtime, thereby contributing to lower production and operational costs over the long term.

Production Flexibility

The flexibility in production is high because it is achieved due to the combination of the latest technologies, including IoT, AI, and CC. This is integrated such that production lines can respond quickly to the fluctuating demand and market without time delays and widespread redesign. This flexibility allows factories to alternate quickly and effectively between the types of products or tailor the products according to the demand, which reduces waste and maximises the use of resources, thus, sustaining the production process and maintaining a solid delivery schedule.

Product Quality Improvement

Digital manufacturing can help improve the quality of the product by means of complete digitisation of the production processes that reduces the number of human mistakes on the one hand, and allows monitoring the stages of manufacturing without gaps on the other hand. This will guarantee the adherence to the set standards and the possibility to detect and fix defects in real-time, which will enhance the quality of the end product and increase customer satisfaction. In addition, the use of simulation and digital modelling technologies enhances optimisation of the product design and production processes before the real implementation and cost reduction and time-to-market.

Innovation and Accelerated Product Development

DM gives designers and engineers high-tech tools to develop and test prototypes at high speed, thus reducing the time to develop products and encouraging innovation.

Environmental Sustainability

By optimising resource utilisation, reducing waste, and minimising emissions, DM supports organisational efforts to achieve sustainable development and environmental conservation.

Supply Chain Integration

Digital technologies enable seamless connectivity among manufacturers, suppliers, and customers via an integrated digital network, enhancing transparency and strengthening SSC management.

Dimensions of Digital Manufacturing

Digital manufacturing is the use of digital technology in the overall industrial production and is one of the pillars of the Fourth Industrial Revolution. The concept is a composite of a number of interconnected dimensions that in unison lead to increased efficiency, flexibility and productivity (Alexopoulos et al., 2020; Gerrikagoitia et al., 2019; Lin et al., 2020; Yin et al., 2025). The main dimensions of DM include the utilisation of digital tools and systems, represented by the following elements:

Internet of Things (IoT)

IoT technologies used in industrial settings including manufacturing, energy, transportation, and logistics are intended to multiply productivity, efficiency, and reduction of costs. IoT is based on a network of intelligent devices and sensors that measures real-time data of equipment and machinery, and it allows monitor performance and analyze the data to make fast and correct decisions. The applications of the IoT in DM are as follows (Alexopoulos et al., 2020):

- Asset Condition Monitoring and Predictive Maintenance: Sensors gather data such as temperature, vibration, and equipment status, allowing prediction of failures before they occur, reducing unplanned downtime, extending equipment lifespan, and enhancing safety.
- Improving Product Quality: Through BDA and AI, product quality can be predicted and enhanced based on manufacturing and environmental conditions, reducing defects and increasing customer satisfaction.
- Enhancing Production Efficiency: IoT interconnects devices and industrial systems to coordinate production processes more seamlessly, minimising waste, increasing production speed, and lowering operational costs.
- Inventory and Supply Chain Management: Real-time tracking of materials and assets improves material flow, minimises delays, and strengthens supply chain control.
- Cybersecurity: Increasing connectivity among industrial devices necessitates securing data and infrastructure to maintain operational continuity.

To conclude, IoT in DM is part and parcel of the digital transformation in industry, incorporating smart devices, BDA, and AI to improve performance, efficiency, and flexibility and minimize waste and costs.

Cloud Computing (CC)

CC plays a central role in enabling smart and integrated manufacturing operations through the following aspects (Sulaiman, 2025; Yin et al., 2025):

- Providing a Flexible and Scalable Infrastructure: Resources can be expanded or reduced according to production and data requirements, supporting rapid adaptation to market changes.
- Storage and Analysis of Big Data: Massive data collected from sensors and digital machines are processed and analysed rapidly, enhancing intelligent decision-making and production processes.
- Supporting Innovation and Development: CC provides access to advanced technologies such as AI and machine learning, improving product quality, predicting failures, and enhancing predictive maintenance.
- Enhancing Collaboration and Remote Work: CC facilitates communication among teams within a single factory or across multiple sites, improving coordination and production efficiency.
- Reducing Costs and Increasing Efficiency: Minimising investment in hardware and infrastructure, CC's pay-as-you-go model makes DM more economical and effective.

Digital Twin (DT)

The DT in DM is a true virtual image of a physical product, system, or manufacturing process which is a fundamental element of digital manufacturing systems. It is the mirror of actual resources and the processes within the reality based on consistent information of sensors and IoT systems. It is important on a number of dimensions (Zhang et al., 2021; Al-Sabaawe et al., 2020):

- Improvement of Design and Product Development: DT will produce an exact digital copy of a product so it can be simulated and tested before manufacturing, error reduces, development speed and costs are minimized.
- Real-Time Performance Monitoring and Enhancement: Live data monitoring and analysis will enable DT to anticipate the faults, plan the preventive maintenance, diminish unforeseen downtime, and increase equipment lifespan.
- Enhancement of Sustainability and Reduction of Environmental Impact: DT streamlines manufacturing enhancing resource and energy use and encouraging sustainability.
- Strengthening Coordination and Transparency in the SSC: Real time and open flow of data between suppliers, manufacturers and distributors enhances coordination and minimizes cycle times.
- Product Lifecycle Management: DT is used in product lifecycle as long as in designing and manufacturing to operation in order to facilitate virtual testing and adjustments which minimizes design and tests costs.

Three-Dimensional Printing (3DP)

3DP is a manufacturing technology that constructs 3D objects by sequentially adding material layers with high precision. The digital model is sliced into layers, printed sequentially until the final object is formed. Key features include (Lin et al., 2020; Moore et al., 2019):

- Capability to Manufacture Complex and Interconnected Shapes: Enables production of geometries difficult or impossible with traditional methods.
- Material Waste Reduction: Significantly reduces material wastage compared to conventional manufacturing, which can discard over 90% of raw materials.
- Speed and Precision in Production: Allows rapid, accurate manufacturing with flexible design modifications.
- Lower Costs: Particularly cost-effective for complex shapes, small-batch production, and prototyping.
- Versatility in Material Usage: Supports diverse materials such as thermoplastics, photopolymers, metals, and ceramics, depending on the 3DP technology applied.

Smart Supply Chain

Concept of the Smart Supply Chain

The idea of the SSC started developing as the world of digital technologies appeared, and the business environment is changing at the beginning of the twenty-first century. With growing complexity in the market, changing consumer behaviours and growing global competition, firms needed more responsive, faster and flexible supply chains (Aini et al., 2024).

To begin with, the supply chains were based on the traditional systems that were centered on storage and production and did not interdependent with each other. Nevertheless, the introduction of Enterprise resource planning (ERP) and supply chain management (SCM) systems in 1990s initiated the initial phases of digitisation and organisation. However, these systems did not serve effectively to sustain rapidly changing times. As technologies, including the Internet, sensors, tracking systems, and data analytics were implemented in the first decade of the new millennium, the idea of the SSC started to emerge and allowed collecting data at different stages of the supply chain to make a decision (Guo & Mantravadi, 2024). In 2015 (around the time of the Fourth Industrial Revolution (Industry 4.0)) the SSC was recognised as a unifying system that connects all parts of the supply chain with the help of modern technologies, including AI, IoT, intelligent robotics, predictive analytics, and Blockchain. This change has enabled firms to become more efficient, predictable and immediate to any type of changes making the SSC a very important strategic resource in the contemporary competitive world (Wu et al., 2016).

The SSC uses innovative technologies to provide unprecedented benefits in reduction of costs, product quality, delivery process and flexibility. It allows the best gathering and use of information to make various decisions. Electronic systems and information technology increases customer focus on the buyers and suppliers and improves the management of upstream and downstream channels as well as delivery of value adding products, services and information to customers and stakeholders (Hamid & Eshag, 2025; Lee et al., 2023). To conclude, the SSC is a digitally intertwined supply chain that uses modern technologies to overcome a smooth and smart flow of materials and information (Al-Akidi & Niebal Younis, 2024). It will ensure timely and effective reaction to market variation and customer needs, therefore, enhancing competitiveness and reducing wastage of resources.

Objectives of the Smart Supply Chain

Smart supply chains are geared towards daily growth of the integrated operations of an organisation by electronically surveying the creation and delivery of products. The SSC is better than the traditional supply chain in the ability of integrating activities both external and internal to the company, with an aim of producing products that bring value to the organisation (Ali & Aljuboury, 2023). It therefore involves co-ordination as well as sharing of information between the company and all the parties involved in a way that generates competitive advantage to the stakeholders. The SSC is characterized with the following goals (Chbaik et al., 2022; Movahed et al., 2023; Zhang et al., 2022):

- Enhancing Operational Efficiency: By automating and using data analytics, they want to ensure that there is less waste and better utilisation of resources like time, materials, and energy.
- Achieving Comprehensive Visibility and Transparency: Providing the ability to monitor and track all the stages of the supply chain in real-time whether suppliers or end-customers.
- Improving Responsiveness and Adaptability: Enabling quick reaction to the market conditions, including demand variations, internal and external supply shocks, thus enhancing the capability to react speedily and precisely in meeting the customer demands.
- Enhancing Coordination and Integration: Strengthening collaboration and instantaneous information exchange among suppliers, manufacturers, and distributors, reducing cycle times and increasing operational transparency.
- Raising Product and Service Quality: Enhancing the smooth flow of delivering goods or services as specified and demanded by constant monitoring and processes adjustment.
- Supporting Sustainability: Minimising environmental impact by optimising energy and material usage and adopting environmentally friendly manufacturing practices.
- Enabling Smart Decision-Making: Utilising data and predictive analytics to improve planning and operations, thereby enhancing overall supply chain performance.

Features and Benefits of the Smart Supply Chain

The smart supply chain is a qualitative breakthrough in the supply chain and manufacturing management that provides an impressive competitive advantage to manufacturing and industrial organisations. A detailed elaboration of its major advantages is given below (Liu et al., 2021; Wang et al., 2022; Zaviša, 2023):

- Risk Prediction and Crisis Management Improvement: Predictive analytics and real-time data allow predicting demand changes or possible equipment crashes and provide a chance to take proactive steps to minimize the crisis risk and minimize unexpected outages.
- Process Automation and Reduction of Human Intervention: Automation reduces human errors and speeds up the storage transport and distribution operation resulting in reduced cost of operation and high productivity.
- Inventory Management Enhancement: The SSC can be used to monitor and automatically update the inventory levels to minimize stock out or overstock conditions and decrease the cost of storage.
- Enhancing Transparency: The level of transparency through technologies like IoT is very high throughout all supply chain levels, which allow tracking of products, maintain quality and safety, and enhance compliance with regulations.
- Improving Customer Experience: Real-time shipment tracking and accurate delivery estimates enhance customer satisfaction and foster loyalty.
- Reducing Waste and Achieving Sustainability: Intelligent data analysis identifies and

minimises sources of waste in energy and resources, supporting environmental objectives and promoting sustainable manufacturing.
- Flexibility and Rapid Response to Changes: The SSC enables the organisations to respond swiftly to abrupt changes in the market or the supply chain and minimise the effects of disruption thereby maintaining business continuity.
- Improving Product Quality and Reducing Defects: The smart systems constantly check the quality of goods and identify deviations or problems upon their occurrence and lower the level of returns and improve the image of the organisation.
- Enhancing Collaboration Among Partners: Digital allow sharing information between suppliers, manufacturers, and distributors in real-time, enhancing coordination, minimizing cycle times, and making operations more efficient.
- Achieving Tangible Financial Savings: The efficiency of the operations, waste minimisation, and enhanced inventory management leads to reduction in the operating costs and higher annual profits of the organisation.

Dimensions of the Smart Supply Chain

The dimensions of the SSC can be summarised as follows (Aini et al., 2024):

- Efficiency: Means the capability of the supply chain to perform well at a very low cost and at the same time deliver their products or services to the customers at the right time and of the desired quality.
- Adaptability: shows how the supply chain can be flexible enough to meet the demands of any change in the market, demand or supply and how the supply chain can modify processes and production to suit the new conditions.
- Alignment: Means the extent of integration and alignment of objectives and operations between the entire supply chain partners (suppliers, manufacturers, distributors, and others) with the aim of maximising value among all of them and enhance superior service provision to the final consumer.
- Smart Factory: Focuses on automation and integration between industrial equipment and systems to collect and analyse data and improve operations.
- Digital Thread: Follows the life cycle of the digital data and information of the product, starting with design, all the way to delivery, maintaining a connection between the engineering and operational processes.
- Value Chain Management: Aims to enhance integration across all stages of the supply chain from supplier to end customer, reducing costs and increasing customer satisfaction.

The Field Aspect

Description and Diagnosis of Research Variables

The section will provide a summary and diagnosis of the research variables according to the views of a sample of employees at Al-Kindi Factory. Data analysis was performed with the help of the statistical program SPSS V26 with the help of which the percentages, frequencies, means, and standard deviations were determined. Also, the associations, impacts, and statistical hypotheses among the variables under study were checked. It is also remarkable that out of 100 questionnaires distributed 90 of them were considered valid to analyze and this is a response rate of 90. The details of the analysis results are as follows:

Description and Diagnosis of Digital Manufacturing Variables

In this section, the presented views of the surveyed sample with references to the statements used to define the dimensions of the first independent variable, DM, are presented. Table (2) illustrates the related results as follows:

- Internet of Things Dimension: The IoT dimension is represented by the sub-variables (X1–X3). The highest agreement percentage among these sub-variables, contributing to a positive assessment, was for variable X3, which reached 71.3%. This variable reflects the statement: "The factory management is keen on using IoT in its production processes due to its impact on improving productivity, reducing costs, and monitoring performance." This is supported by a mean value of 3.7586 and a standard deviation of 0.76197. Conversely, the lowest agreement percentage was for variable X2, at 50.5%, related to the statement: "The factory management applies predictive maintenance before breakdowns occur, which in turn reduces unplanned downtime," indicated by a mean value of 3.4253 and a standard deviation of 1.0301.
- Cloud Computing Dimension: The sub- variables (X4-X6) depict the CC dimension. Variable X4 had the highest agreement percentage among other sub-variables that led to the positivity of this dimension standing at 90.4% in agreement. This variable is as follows: The management at the factory is engaged in the storage and analysis of big data using sensors and digital machines so that accurate and fast processing and analysis can be done. This makes smart decisions and streamlines production processes better. This is supported by a mean value of 4.1724 and a standard deviation of 0.5748. Conversely, the lowest agreement percentage was for variable X5, which reached 44.8%, regarding the statement: "The factory management reduces costs and increases efficiency by minimising the need for investment in hardware and infrastructure," evidenced by a mean value of 3.4253 and a standard deviation of 1.0301.
- Digital Twins Dimension: The sub-variables (X7 -X9) reflect the DT dimension. The maximum level of agreement between the sub-variables that helped to make this dimension positive was X9 that had reached 76 %. This variable reads as follows: The factory management uses the help of DTs to model the different scenarios to predict the demand where the DT has now become a key component of the digital transformation strategy in the industry, which puts the manufacturers at a considerable competitive edge in the market. It is reinforced by a mean of 3.9655 and a standard deviation of 0.75403. On the other hand, the percentage of agreement is the lowest with variable X7 with a percentage of 56.3 indicating that the statement: The factory management has a virtual model to monitor and comprehend the performance of physical assets and constantly predict performance patterns was accepted by the mean value of 3.5632 and a standard deviation of 0.85862.
- 3D Printing Dimension: The sub-variables (X10 -X12) depict the 3PD dimension. The greatest percentage of agreement between the sub-variables that lead to the positivity of this dimension was on variable X12 which had the greatest of 69%. This variable says: The management of the factory tries to minimize the waste of materials by 3DP in comparison to the traditional production by wasting materials, but is able to produce higher production speed and precision with possibilities to make designs easily amenable. This is supported by a mean value of 3.7586 and a standard deviation of 0.90175. Conversely, the lowest agreement percentage was for variable X10, which reached 57.4%, regarding the statement: "The factory management enhances the value created by facilitating the manufacturing of complex parts," indicated by a mean value of 3.5747 and a standard deviation of 0.78807.

Table 2: Description and Diagnosis of Digital Manufacturing Variables

Variable	Symbol	Response Scale										Arithmetic Mean	Standard Deviation
		Strongly Agree		Agree		Somewhat Agree		Disagree		Strongly Disagree			
		N	%	N	%	N	%	N	%	N	%		
Internet of Things	X1	10	11.5	38	43.7	36	41.4	2	2.3	1	1.1	3.5977	0.76947
	X2	13	14.9	31	35.6	29	33.3	10	11.5	4	4.6	3.4253	1.0301
	X3	10	11.5	52	59.8	20	23	4	4.6	1	1.1	3.7586	0.76197
Cloud Computing	X4	22	22.60	25	67.8	5	5.7	1	1.1	-	-	4.1724	0.57480
	X5	4	4.6	35	40.2	37	42.5	11	12.6	-	-	3.3678	3.3678
	X6	10	11.5	47	54.0	24	27.6	6	6.9	-	-	3.7011	0.76424
Digital Twins	X7	8	9.2	41	47.1	30	34.5	8	9.2	-	-	3.5632	0.78801
	X8	6	6.9	48	55.2	26	29.9	4	4.6	3	3.4	3.5632	0.85862
	X9	17	19.7	49	56.3	19	21.8	1	1.1	1	1.1	3.9655	0.75403
3D Printing	X10	9	10.3	41	47.1	28	32.2	9	10.3	-	-	3.5747	0.78807
	X11	21	24.1	39	44.8	18	20.7	9	10.3	-	-	3.7586	0.90175
	X12	14	16.1	46	52.9	19	21.8	8	9.2			3.7586	0.83479

Source: Prepared by the researchers based on the results of statistical analysis using SPSS v26 software.

Description and diagnosis of variables related to the smart supply chain.

This section involved describing the opinions of the surveyed sample regarding the dependent variable, SSC, based on the statements used to characterise it, represented by items (X19–X30). Table (3) indicates that the highest agreement percentage, adding to the favorable evaluation of this dimension, is associated with item X26 with a score of 93.1%. This fact is mentioned: The SSC flexibility in the factory allows it to react efficiently to the unpredictable alterations in the external or internal environment, including fluctuations in the demand, or alterations in the policies of the suppliers or the customers. It is supported by the mean value of 4.1609 and a standard deviation of 0.568010. On the other hand, the least percentage of agreement across the sub-variables was registered with respect to item X30, which stood at 47.1%. This statement is relevant to this item since management of factories depends on the supply chain to gain high performance at a minimum cost without compromising timely delivery of products or services to customers at the desired quality as indicated by a mean value of 3.5057 and a standard deviation value of 0.86096.

Table 3: Description of Smart Supply Chain Variables and Diagnosis

Variable	Symbol	Response Scale										Arithmetic Mean Somewhat Agree%	Standard Deviation Strongly Agree N
		Strongly Agree		Agree		Somewhat Agree		Strongly Agree		Agree			
		N	%	N	N	%	N	N	%	N	N		
Smart Supply Chain	X19	20	23.0	45	51.7	16	18.4	6	6.9	-	-	3.8161	.81453
	X20	22	25.3	46	52.9	19	21.8	-	-	-	-	4.0345	.68960
	X21	12	13.8	45	51.7	24	27.6	6	6.9	-	-	3.7241	.78784
	X22	5	5.7	44	50.6	34	39.1	4	4.6	-	-	3.5747	.67569
	X23	27	31.0	51	58.6	9	10.3	-	-	-	-	4.2069	.61262
	X24	11	12.6	37	42.5	25	28.7	14	16.1	-	-	3.5172	.91324
	X25	26	29.9	44	50.6	15	17.2	2	2.3	-	-	4.0805	.75048
	X26	21	24.1	60	69.0	5	5.7	1	1.1	-	-	4.1609	.56801
	X27	31	35.6	48	55.2	8	9.2	-	-	-	-	4.2644	.61870
	X28	20	23.0	56	64.4	10	11.5	1	1.1	--	-	4.0920	.62193
	X29	19	21.8	47	54.0	18	20.7	2	2.2	1	1.1	4.0000	.90219
	X30	10	11.5	31	35.6	35	40.2	11	12.6	-	-	3.5057	.86096

Analysis of Correlation Relationships Between Digital Manufacturing (Combined and Individual) and the Smart Supply Chain in the Researched Factory

This part deals with the validation of the main hypothesis which is that there is statistically significant correlation between DM (both combined and individual dimensions) and SSC in the factory studied. Data from Table (4) reveal a statistically significant correlation between combined DM and SSC, with a correlation coefficient of 0.693**. This finding shows the relevance and robustness of the correlation existing between the two variables, which proves that the main hypothesis can be accepted. The hypothesis supports the argument that the 6R dimensions are able to describe and forecast SSC, which means that technological and environmental orientations exist at the majority of production stages.

Correlation effect Between Each Dimension of Digital Manufacturing and the Smart Supply Chain

On correlation between each dimension of DM and SSC, analysis outcomes in the same table suggest that there is a strong correlation between each dimension of DM that included IoT, CC, DT, and 3DP with SSC. The high correlation coefficients demonstrate this fact with the highest correlation value of reduction variable at 0.631**. that is statistically significant. Further, all sub-correlations are considered significant at the levels below 0.05, meaning that the management of the factory is actively implementing modern technologies in order to simplify the operating environment and processes in order to minimize waste, improve performance, and sustain SSC. These findings indicate that the sizes of DM can predict and explain SSC, hence the hypothesis of the main hypothesis is accepted.

Table 4: Correlations Between Digital Manufacturing (Combined and Individually) and the Smart Supply Chain

Independent Variable / Dependent Variable	Digital Manufacturing				Overall Index
	Internet of Things	Cloud Computing	Digital Twins	3D Printing	
Smart Supply Chain	0.631**	0.571**	0.613**	0.447**	0.693**

Source: The table was prepared by the researchers based on the results of the calculator; N = 90, *P ≤ 0.05.

Analysis of the Impact Relationships Between Digital Manufacturing (Combined and Individual) and the Smart Supply Chain in the Researched Factory

The test of the second major research hypothesis, which holds that there is a statistically significant effect of DM (combined and individual) on SSC in the factory being studied, is the subject of the analysis. As shown in Table (5), there is a significant effect of DM on SSC, with a calculated F-value of 79.021, exceeding the critical value of 2.1750 at degrees of freedom (1, 88) and a significance level of 0.05. The coefficient of determination (R^2) is 0.714, it corresponds to the fact that 71% of the variations observed in SSC are explained by DM and the remaining 29% is explained by other variables which are not considered in this study. This proves that SSC in the factory studied depends greatly on the embodied aspect of DM. In this connection, the second principal hypothesis stating the presence of the statistically significant effect between DM and SSC in the factory under study can be accepted.

Table 5: Impact of Digital Manufacturing (Combined) on the Smart Supply Chain

Independent Variable / Dependent Variable	Digital Manufacturing		R^2	F	
	B_0	B_1		Calculated	Tabulation
Smart Supply Chain	**0.629**	**0.694 (8.889)**	**0.714^a^**	**79.021**	**2.1750**

Source: The table was prepared by the researchers based on the results of the electronic calculator. ( ) indicates the calculated t-value; df = 1, 88; N = 90; P < 0.05.

Relationships of Each Dimension of Digital Manufacturing (Individually) on the Smart Supply Chain in the Researched Factory

The data presented in Table (6) illustrate the impact of each individual dimension of DM on SSC, with varying degrees of influence. By examining the values of the standardised coefficients (β) and the corresponding t-tests, it is evident that the first dimension, IoT, exerts the strongest influence on SSC, with a β value of 0.661 and a calculated t-value of 4.483. This t-value exceeds the critical t-value of 1.697, indicating statistical significance at the 0.05 level. Conversely, the 3DP dimension exhibits a comparatively lower impact, with a β value of 0.506 and a calculated t-value of 3.071. This t-value is also more than the critical value of 1.697 which proves to be significant on the level of 0.05. In this regard, it is possible to adopt the second primary hypothesis, according to which the statistically significant impact of every single dimension of DM on SSC in the factory under study is significant.

Table 6: The Impact of Each Dimension of Digital Manufacturing (Individually) in the Smart Supply Chain

Dependent Variable / Independent Variable		Smart Supply Chain		R2	F	
		Bo	B1		Calculated	Tabulation
Digital Manufacturing	Internet of Things	0.603	0.661 (4.483)	0.553[a]	18.648	2.710
	Cloud Computing	0.543	0.414 (3.894)			
	Digital Twins	0.476	0.654 (3.441)			
	3D Printing	0.427	0.506 (3.071)			

Source: The table was prepared by the researchers based on the results of the electronic calculator. ( ) indicates the calculated t-value; N = 90; P < 0.05; df = 4.85.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The outcomes of the descriptive and diagnostic study in the macro level of the dimensions of DM and SSC demonstrated material positive tendencies in the sample individuals in the factory under consideration. The results are an acceptable amount of acceptance and willingness, which means that the favorable environment exists and offers real chances of the successful acceptance and use of DM technologies and SSC in the factory.
2. The outcomes of the descriptive and diagnostic analysis showed that the management of the factory pays much attention to the use of IoT technologies in its production process and strategic decision-making. Another thing that was also visible is that it can be inferred that the management can use the storage and analysis of big data created by sensors and other digital machinery, which allows fast and very precise data processing. It is this high level of analytical power that leads directly to the quality of sound decision-making as well as an increase in the production operation efficiency and effectiveness which transfers to the overall performance of the factory.
3. Flexibility of SSC in the factory under study allows finding quick and responsive reaction to the change of the market situation and efficiently respond to the needs of consumers, as the balance between demand and supply can change abruptly.
4. Digital transformation is one of the primary drivers of the increased responsiveness and flexibility to the changes in demand by adopting digital models and superior simulation technologies. These tools allow the precise prediction of the future changes in demand and

allows organisations to react to changes in the production processes and supply chains in a rapid and efficient manner. Thus organisations also enhance their capacity to respond to the changing market needs thus enhancing their competitiveness and sustainability in dynamic business environments.

5. The DM technologies improve the inventory control by tracking the items in real-time with the help of sensors and minimizing the manual errors and maximizing the accuracy of the data. They also use predictive analytics and AI to predict the demand, as well as optimise inventory levels, along with automating the reorder process and storage organisation. This integration enhances efficiency and minimizes the costs of operation.
6. Digital systems increase transparency and give real-time information exchange between suppliers, manufacturers, and distributors, which helps to coordinate the processes and decreases the production cycle time. Such integration promotes the collaboration between SSC partners making them more efficient and flexible in meeting market needs.

Recommendations

1. To implement digital infrastructure of the studied factory, the management should enhance the factory with CC and IoT technologies and update them to provide the real-time communication between the production lines and the SSC.
2. It is necessary to invest in AI and predictive analytics technologies and incorporate AI algorithms to process big data and enhance production, inventory and distribution-related decisions in the investigated factory.
3. The transition to an on-demand production system involving the application of such technology as 3DP should be promoted to decrease wastage and provide more specific customer needs, which will make the SSC smarter and more adaptable in the researched factory.
4. The management of the factory under study is to ensure that the SSC has a single digital platform through the implementation of a central digital system that oversees all participants in communication (suppliers, manufacturers, distributors) to inform in real time and has operational consistency.
5. It is highly essential to improve cybersecurity in digital supply chains and establish superior techniques of securing data and digital systems against cyberattacks as more and more smart platforms are implemented in the factory under study.
6. To use DT simulation models, the management of the factory under the study should consider developing virtual digital models of factories and SSCs to simulate and test different scenarios, without taking a toll on the real operations. The smart digital indicators that will assist in monitoring the efficiency of SSC and the realization of the continuous improvement should be used to measure the performance.

REFERENCES

Aini, B. K., Chen, M.-C., & Isnaini, M. M. r. (2024). Identifying Barriers of Implementing Smart Supply Chain Management in Electronics Industry: A Literature Review. In *Lecture Notes in Mechanical Engineering* (pp. 293-303): Springer Nature Singapore. http://dx.doi.org/10.1007/978-981-97-6492-1_24

Al-Akidi, K. A. K. I., & Niebal Younis, M. (2024). Strategic Planning and Its Implications for Some Supply Chain Activities an Exploratory Study of the Opinions of a Sample of Administrative Leaders in the Oil Sector in Nineveh Governorate. *NTU journal for Administrative and Human Sciences (JAHS)*, *4*(2), 159-185.

https://doi.org/10.56286/dq8hap03

Alexopoulos, K., Nikolakis, N., & Chryssolouris, G. (2020). Digital Twin-Driven Supervised Machine Learning for the Development of Artificial Intelligence Applications in Manufacturing. *International Journal of Computer Integrated Manufacturing*, *33*(5), 429-439. https://doi.org/10.1080/0951192x.2020.1747642

Al-Sabaawe, Y. M., Husien, W. A., & Hammadi, A. A. (2020). Three Phases Strategy Of Electronic Management Application "A Proposed Model". In 2020 2nd Annual International Conference on Information and Sciences (AiCIS) (pp. 148-156). IEEE. https://DOI10.1109/AiCIS51645.2020.00033.

Bastos de Miranda, G., & Lima, F. (2025). Artificial Neural Network Applied to Virtual Commissioning and Control of a Robotic Cell. *IEEE Latin America Transactions*, *23*(4), 301-311. https://doi.org/10.1109/tla.2025.10930373

Chbaik, N., Khiat, A., Bahnasse, A., & Ouajji, H. (2022). The Application of Smart Supply Chain Technologies in the Moroccan Logistics. *Procedia Computer Science*, *198*, 578-583. https://doi.org/10.1016/j.procs.2021.12.289

Dallel, M., Havard, V., Dupuis, Y., & Baudry, D. (2023). Digital Twin of an Industrial Workstation: A Novel Method of an Auto-Labeled Data Generator Using Virtual Reality for Human Action Recognition in the Context of Human–Robot Collaboration. *Engineering Applications of Artificial Intelligence*, *118*, 105655. https://doi.org/10.1016/j.engappai.2022.105655

Fraile, F., Sanchis, R., Poler, R., & Ortiz, A. (2019). Reference Models for Digital Manufacturing Platforms. *Applied Sciences*, *9*(20), 4433. https://doi.org/10.3390/app9204433

Gerrikagoitia, J. K., Unamuno, G., Urkia, E., & Serna, A. (2019). Digital Manufacturing Platforms in the Industry 4.0 from Private and Public Perspectives. *Applied Sciences*, *9*(14), 2934. https://doi.org/10.3390/app9142934

Gillani, F., Chatha, K. A., Sadiq Jajja, M. S., & Farooq, S. (2020). Implementation of Digital Manufacturing Technologies: Antecedents and Consequences. *International Journal of Production Economics*, *229*, 107748. https://doi.org/10.1016/j.ijpe.2020.107748

Guo, D., & Mantravadi, S. (2024). The Role of Digital Twins in Lean Supply Chain Management: Review and Research Directions. *International Journal of Production Research*, *63*(5), 1851-1872. https://doi.org/10.1080/00207543.2024.2372655

Hamid, A. A., & Eshag, E. A. E. (2025). Does Green Purchasing Mediate The relationship between Smart Supply chain and Green Performance Of pharmaceutical Companies In sudan: Implications for Underdevelopment Countries. *International Journal of Productivity and Performance Management*, *74*(9), 3103-3130. https://doi.org/10.1108/ijppm-10-2024-0703

Lee, K. L., Wong, S. Y., Alzoubi, H. M., Al Kurdi, B., Alshurideh, M. T., & El Khatib, M. (2023). Adopting Smart Supply Chain and Smart Technologies to Improve Operational

Performance in Manufacturing Industry. *International Journal of Engineering Business Management*, *15*. https://doi.org/10.1177/18479790231200614

Leesakul, N., Oostveen, A.-M., Eimontaite, I., Wilson, M. L., & Hyde, R. (2022). Workplace 4.0: Exploring the Implications of Technology Adoption in Digital Manufacturing on a Sustainable Workforce. *Sustainability*, *14*(6), 3311. https://doi.org/10.3390/su14063311

Lin, J., Zhu, Z., Cheung, C. F., Yan, F., & Li, G. (2020). Digital Manufacturing of Functional Materials for Wearable Electronics. *Journal of Materials Chemistry C*, *8*(31), 10587-10603. https://doi.org/10.1039/d0tc01112f

Liu, C., Ji, H., & Wei, J. (2021). Smart Supply Chain Risk Assessment in Intelligent Manufacturing. *Journal of Computer Information Systems*, *62*(3), 609-621. https://doi.org/10.1080/08874417.2021.1872045

Monostori, L., Csáji, B. C., Kádár, B., Pfeiffer, A., Ilie-Zudor, E., Kemény, Z., & Szathmári, M. (2010). Towards Adaptive and Digital Manufacturing. *Annual Reviews in Control*, *34*(1), 118-128. https://doi.org/10.1016/j.arcontrol.2010.02.007

Moore, D. G., Barbera, L., Masania, K., & Studart, A. R. (2019). Three-Dimensional Printing of Multicomponent Glasses Using Phase-Separating Resins. *Nature Materials*, *19*(2), 212-217. https://doi.org/10.1038/s41563-019-0525-y

Movahed, A. B., Movahed, A. B., & Nozari, H. (2023). Opportunities and Challenges of Smart Supply Chain in Industry 5.0. In *Advances in Business Information Systems and Analytics* (pp. 108-138): IGI Global. http://dx.doi.org/10.4018/979-8-3693-0159-3.ch006

Naderi, A., Bhattacharjee, N., & Folch, A. (2019). Digital Manufacturing for Microfluidics. *Annual Review of Biomedical Engineering*, *21*(1), 325-364. https://doi.org/10.1146/annurev-bioeng-092618-020341

Sulaiman, S. (2025). The Role of Cloud Computing in Improving Production Costs and the Speed of Financial Reports: A Case Study of Iraq Steel Karbala. *NTU journal for Administrative and Human Sciences (JAHS)*, *5*(2), 176-202. https://doi.org/10.56286/wmq0xe68

Wang, L., Deng, T., Shen, Z.-J. M., Hu, H., & Qi, Y. (2022). Digital Twin-Driven Smart Supply Chain. *Frontiers of Engineering Management*, *9*(1), 56-70. https://doi.org/10.1007/s42524-021-0186-9

Wu, L., Yue, X., Jin, A., & Yen, D. C. (2016). Smart Supply Chain Management: A Review and Implications for Future Research. *The International Journal of Logistics Management*, *27*(2), 395-417. https://doi.org/10.1108/ijlm-02-2014-0035

Yin, J., Ma, R., & Ge, S. (2025). Predicting Task Bottlenecks in Digital Manufacturing Enterprises Based on Spatio-Temporal Graph Convolutional Networks. *Frontiers of Engineering Management*, *12*(4), 736-753. https://doi.org/10.1007/s42524-025-4030-5

Zaviša, Ž. (2023). The Importance and Benefits of Applying Smart Technologies in the Supply Chain: The Case of Ab 'Rokiškio Sūris'. *PUBLIC SECURITY AND PUBLIC ORDER*, *35*(2024). https://doi.org/10.13165/pspo-24-35-25

Zhang, G., Yang, Y., & Yang, G. (2022). Smart Supply Chain Management in Industry 4.0: The Review, Research Agenda and Strategies in North America. *Annals of Operations Research*, *322*(2), 1075-1117. https://doi.org/10.1007/s10479-022-04689-1

Zhang, L., Zhou, L., & Horn, B. K. P. (2021). Building a Right Digital Twin with Model Engineering. *Journal of Manufacturing Systems*, *59*, 151-164. https://doi.org/10.1016/j.jmsy.2021.02.009