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Published in:
Seafood 4.0

DOI:
10.1016/B978-0-443-33750-5.00008-1

2025

Document Version:
Publisher's PDF, also known as Version of record

CHAPTER SIX

Digital twins and cloud computing

Pankaj B. Pathare[a], Hrishikesh Patil[b], Nilesh Nirmal[c], Jennifer Mignonne de Waal[d], Sandeep Jagtap[d,e], Naveen Kumar Mahanti[f], Piyush Sharma[g] and V. Arun Prasath[g]

[a]Department of Soils, Water and Agricultural Engineering, College of Agricultural & Marine Sciences, Sultan Qaboos University, Muscat, Oman
[b]School of Engineeing, University of Guelph, ON, Canada
[c]Institute of Nutrition, Mahidol University, Nakhon Pathom, Thailand
[d]Division of Engineering Logistics, Faculty of Engineering, Lund University, Lund, Sweden
[e]Sustainable Manufacturing Systems Centre, Cranfield University, United Kingdom
[f]Post Harvest Technology Research Station, Dr. Y.S.R. Horticultural University, Andhra Pradesh, India
[g]Department of Food Process Engineering, National Institute of Technology, Rourkela, Odisha, India

6.1 Introduction

Seafood is highly perishable and prone to rapid degradation due to its high water content, rich nutrient composition, and susceptibility to microbial and enzymatic activity. Given these challenges, innovative solutions are essential to ensure quality, safety, and sustainability. The Fourth Industrial Revolution, commonly referred to as Industry 4.0, plays a crucial role in addressing these issues within the seafood sector. The application of Industry 4.0 technologies along the seafood supply chain is known as Seafood 4.0. In recent years, the sector has undergone significant transformations driven by key Industry 4.0 components, including artificial intelligence (AI), robotics, the Internet of Things (IoT), big data, augmented reality, cybersecurity, and blockchain. Three industrial revolutions occurred prior to Industry 4.0, which made it possible to apply major advancements and technological improvements in a variety of industrial and agricultural sectors. The shift from manual to steam-powered mechanized labor and manufacturing marked the first industrial revolution (IR 1.0), which took place in the late eighteenth century. The second (IR 2.0) was the first to use electrical power for mass production and emerged in the late 19th century. The introduction of electronics and information technology in the early 1970s marked the beginning of the third industrial revolution (IR 3.0), leading to the integration of automation in production processes (Echegaray et al., 2022).

Seafood 4.0: Digital, Physical, and Biological Realms from Sea to Table
DOI: https://doi.org/10.1016/B978-0-443-33750-5.00008-1

The application of cutting-edge technology like cloud computing, AI, deep learning, and IoT is spreading beyond conventional industries and entering the seafood sector. According to Janssen et al. (2017), one such technology is the digital twin (DT), which is essentially a digital replica of the real world that records data in real time for use in making decisions. DTs have become widely used in many different industries as a result of the advent of Industry 4.0 supporting technologies, including sensors, IoT, cloud computing, big data analytics, and augmented and virtual reality (Ivanov & Dolgui, 2021). The capacity of DTs to transmit real-time information from the physical entity and virtually replicate the physical system is one of their key features.

Cloud computing has made it possible to increase parallel computing, scalability, accessibility, data security, visualization, and integration of resources and their storage. Cloud computing provides configurable computing resource sharing pool services to help clean big data, structure, and integrate enormous amounts of data, so that effective data can meet the needs of users. In aquaculture, cloud computing is mainly used to collect data generated from production, processing, and sales and store the generated data before processing and analysis (Yongqiang et al., 2019).

Application of Industry 4.0 technologies in the seafood sector can improve processing efficiency, quality control, and traceability with unprecedented possibilities, especially through the combination of DTs and cloud computing. Innovations in AI, IoT, blockchain, DTs, and cloud computing are expected to bring about a digital revolution in the seafood sector. Through the facilitation of more intelligent operations, waste reduction, transparency enhancement, and the promotion of sustainable practices, these technologies have the potential to be revolutionary. This chapter introduces the convergence of DTs and cloud computing in Seafood 4.0. It details how cloud infrastructure supports DT implementation in the seafood sector, enabling improved traceability, real-time quality control, and predictive maintenance of processing equipment.

6.2 Digital twins: Concepts and applications

6.2.1 Definition and overview of digital twins

DTs are virtual representations of physical objects, systems, or processes that allow for real-time monitoring, simulation, and optimization. A DT replicates the characteristics and behaviors of its physical counterpart, enabling an interactive and dynamic model that evolves with real-time data inputs. This model can be used to predict outcomes, analyze performance, and test scenarios without directly interacting with the physical object (Raj & Surianarayanan, 2020). The concept of DTs dates back to the early 2000s, initially coined by Dr. Michael Grieves during a presentation on product lifecycle management (Grieves & Vickers, 2016). The idea, however, took root from earlier practices in simulations and virtual prototyping. Over the years, advancements in data analytics, machine learning, and IoT have propelled DTs from theoretical models into practical applications across industries.

DTs have become a cornerstone of Industry 4.0, driving automation, optimization, and the digital transformation of businesses. These advanced systems have evolved from basic static models into sophisticated, dynamic representations that span the entire lifecycle of a product or process—from design and manufacturing to operation and maintenance. Their versatility makes them applicable across diverse sectors, including healthcare, agriculture, the food industry, and military operations, offering unparalleled opportunities for innovation and efficiency (Attaran et al., 2024).

6.2.2 Components of a digital twin system

A fully functional DT system comprises three fundamental components. Physical entity (the actual thing or process), digital counterpart (the software's virtual representation), and data connection, which links the two, allowing for real-time information exchange between them (Boyes & Watson, 2022).

6.2.2.1 Physical entity

The physical entity is the tangible object, system, or process that the DT mirrors. In manufacturing, it might be a piece of machinery or equipment; in healthcare, it could be a human organ or even an entire patient. When representing processes, it may involve operations or workflows in industrial, business, or logistical contexts. For infrastructure, it could encompass buildings, bridges, power grids, or other large-scale physical assets. This entity serves as the foundation for the DT, enabling real-time data collection, analysis, and optimization (Dihan et al., 2024).

6.2.2.2 Digital counterpart

The virtual representation of a physical entity is created by integrating data from diverse sources, including CAD models, IoT sensors, and historical records. This digital counterpart evolves dynamically, reflecting real-time changes and updates as the physical entity undergoes transformations. By maintaining a continuous synchronization with the physical entity, the digital model ensures accuracy and provides a reliable replication of the entity's current status, enabling effective monitoring, analysis, and optimization (Jones et al., 2020).

6.2.2.3 Data connection

The bridge between the physical entity and its digital counterpart is established through sensors, IoT devices, and communication networks. This connection facilitates the continuous flow of real-time data, enabling the DT to provide accurate predictions, simulations, and insights (Attaran et al., 2024). Additional components such AI, machine learning algorithms, and advanced analytics further enhance the capabilities of DTs, allowing them to learn from past data, optimize processes, and provide decision-making support.

6.2.3 Specific use cases in the seafood sector

The seafood sector, traditionally reliant on manual processes, is gradually adopting DTs to enhance efficiency and sustainability.

6.2.3.1 Fish farms

DTs are being implemented in aquaculture to monitor fish health, water quality, and feeding processes. By simulating different environmental conditions, farm managers can optimize feeding schedules, prevent disease outbreaks, and ensure optimal growth conditions, thereby improving yield and reducing costs. Manolin's technology demonstrates the real-world utility of DTs and data intelligence. For example, the software identifies early indicators of fish health concerns, such as subtle changes that may signal the onset of disease. Timely alerts provided to farm managers enable targeted interventions, helping to prevent widespread health issues and ensuring the overall well-being of the stock (Manolin, 2024).

6.2.3.2 Fishing vessels

The marine industry, particularly fishing vessels, leverages DT technology for comprehensive lifecycle management. This includes virtual modeling, smart operations, and efficient error handling, promoting sustainable resource use and safeguarding the environment. On fishing vessels, DTs can monitor equipment, optimize routes, and predict weather patterns. This helps in ensuring safety, reducing fuel consumption, and maximizing catch efficiency. For example, digital twin Marine creates detailed virtual replicas of fishing vessels using cutting-edge 360° cameras, laser scanners, and photogrammetry software. This technology allows users to remotely access and efficiently manage their vessels, enhancing operational control and oversight (Manolin, 2024).

6.2.3.3 Processing plants

In seafood processing, DTs can streamline operations by simulating production workflows, monitoring equipment health, and predicting maintenance needs. This leads to reduced downtime, improved product quality, and higher operational efficiency. In fish processing plants, DTs are utilized to simulate and regulate technological operations, such as monitoring temperature dynamics in drying chambers. Advanced neural networks are integrated to develop precise digital models that align with experimental data, enhancing the efficiency and accuracy of process management (Lv et al., 2023).

6.3 Cloud computing: Enabling technologies for digital twins

6.3.1 Overview of cloud computing

Cloud computing involves providing a range of computing services, including servers, storage, databases, networking, software, analytics, and intelligence, through the internet. This approach enables faster innovation, resource flexibility, and cost-efficiency at scale (Anonymous, 2024). Organizations pay solely for the cloud services they utilize, allowing them to reduce operational expenses and adjust seamlessly to evolving business demands (Attaran & Woods, 2019).

The origins of cloud computing can be traced back to utility computing and grid computing, concepts that emerged in the 1960s and 1990s, respectively. However, the modern form of cloud computing began to develop in the mid-2000s with the introduction of platforms like Amazon Web Services (AWS). Over the years, it has evolved into a foundational component of contemporary information technology (IT) infrastructure, driving rapid advancements across various industries (Foote, 2021).

6.3.2 Key features and benefits

Cloud computing offers several key features including scalability, flexibility, cost-efficiency, and accessibility that make it an indispensable technology for businesses.

6.3.2.1 Scalability

Cloud computing offers virtually unlimited scalability, enabling businesses to adjust their IT resources seamlessly based on demand. This flexibility is particularly beneficial for organizations with variable workloads, ensuring optimal resource utilization and cost efficiency (Awesome, 2023).

6.3.2.2 Flexibility

The flexibility of cloud computing enables businesses to choose from a range of services and solutions tailored to their specific needs. Whether it is infrastructure, platforms, or software, the cloud offers customizable options that can be quickly deployed and modified (Awesome, 2023).

6.3.2.3 Cost-efficiency

By leveraging cloud computing, businesses can reduce capital expenditure on IT infrastructure. Instead of investing in expensive hardware and software, they can access these resources on a "pay-as-you-go" basis, thereby optimizing costs (Awesome, 2023).

6.3.2.4 Accessibility

Cloud services are accessible from anywhere with an internet connection, enabling remote work and global collaboration. This has become increasingly important in today's distributed work environments. The cloud is crucial for data storage, processing, and analytics, providing the computational power needed to handle vast amounts of data generated by DTS and other IoT devices (Awesome, 2023).

6.3.3 Types of cloud services

Cloud computing services are often classified into three primary categories and one supplementary category.

6.3.3.1 Infrastructure as a service (IaaS)

This is the most basic service of cloud computing. IaaS provides virtualized computing resources over the internet, including virtual machines, storage, and networks. In IaaS, the cloud service provider offers a "pay-as-you-go" model, enabling users to access a range of features such as network servers, computing applications, and storage solutions through the internet (Nazir et al., 2020). Companies use IaaS to build and manage their IT infrastructure, gaining flexibility and control without the need to invest in physical hardware. Examples include AWS EC2 and Microsoft Azure (Le et al., 2024).

6.3.3.2 Platform as a service (PaaS)

Platform as a service (PaaS) provides developers with a comprehensive platform to build, deploy, and manage applications without the need to handle the underlying infrastructure (Susnjara & Smalley, 2024). This streamlines the development process and minimizes the challenges of managing servers and databases. As an intermediate layer in cloud services, PaaS grants control over system management aspects such as the operating system and runtime environment (Özdemir et al., 2019). PaaS offers several advantages, including faster application development and deployment, reducing time-to-market. It provides cost-effective access to a wide range of resources, enabling developers to experiment freely with minimal risk. Additionally, PaaS enhances security, ensuring robust protection for applications and data (Susnjara & Smalley, 2024). Examples include Google App Engine and Heroku, and IBM (Le et al., 2024).

6.3.3.3 Software as a service (SaaS)

Software as a service (SaaS) provides software applications to users over the internet on a subscription basis. These applications are accessible directly through a web browser, removing the need for local installation (without the cost of establishing the necessary infrastructure to operate it) or maintenance (Susnjara & Smalley, 2024). Popular examples of SaaS include Salesforce, Microsoft Office 365, and Google Workspace, offering convenience and flexibility to users (Le et al., 2024).

6.3.3.4 Serverless computing

Serverless computing, closely related to PaaS, emphasizes developing application functionality without the need to manage underlying servers and infrastructure. The cloud provider takes care of tasks such as setup, capacity planning, and server maintenance. This architecture is event-driven and highly scalable, utilizing resources only when triggered by specific events or functions (Anonymous, 2024).

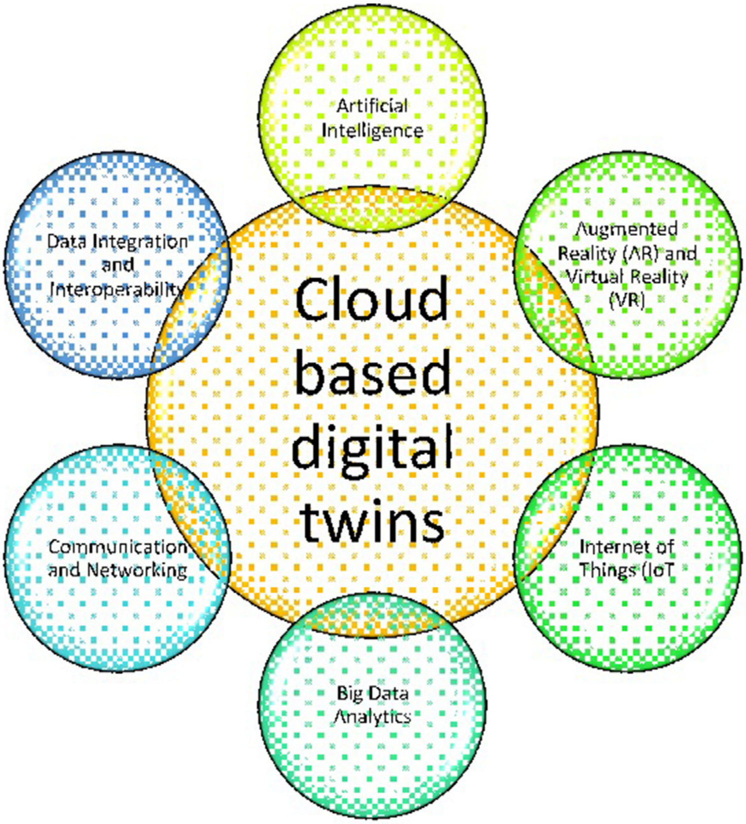

Figure 6.1 Components of the cloud-based digital twin.

6.3.4 Integration of cloud computing with digital twins

Cloud computing plays a pivotal role in the development and deployment of DTS by providing the necessary infrastructure for data storage, processing, and real-time analytics. The components of the cloud based DTs are illustrated in Fig. 6.1. The integration of cloud computing with DTs offers several advantages such as data management and accessibility.

6.3.4.1 Data management

Cloud platforms provide highly scalable storage solutions designed to manage the extensive data produced by DTs. These platforms enable real-time storage, processing, and analysis of data, ensuring that DT models remain dynamically updated. By leveraging cloud-based DTs, organizations can monitor systems and analyze data as it is generated, facilitating faster decision-making. This real-time capability is crucial for preventing costly failures and optimizing overall system performance (Neumann, 2024).

6.3.4.2 Collaboration and accessibility

The cloud enables stakeholders from various locations to access and engage with DTs, fostering collaboration and enabling informed decision-making. This capability is especially advantageous in industries such as seafood, where global supply chains involve multiple participants. Cloud-based DTs allow real-time monitoring and analysis of data, accelerating decision-making and helping prevent costly failures or enhance system efficiency. Additionally, the cloud's accessibility bridges geographic divides, allowing teams to interact with DTs from anywhere, significantly improving the immediacy and effectiveness of collaboration (Zhang et al., 2022).

6.4 Digital twins in the seafood supply chain

The seafood supply chain is a complex and dynamic system involving numerous interconnected processes, from harvesting or farming to final delivery at the consumer's table (Ahamed et al., 2020; Al-Busaidi et al., 2016; Denham et al., 2015). Managing this intricate network presents challenges such as ensuring food safety, maintaining product quality, optimizing resource use, and adhering to regulatory requirements. These challenges are further amplified by the highly perishable nature of seafood, environmental variability, and the need for sustainability. In this context DTs offer a transformative solution (Jiang et al., 2021). By leveraging technologies such as IoT sensors, big data analytics, machine learning, and blockchain, DTs provide unprecedented visibility and control across the seafood supply chain. They allow stakeholders to monitor operations in real time, predict potential risks, and make informed decisions to enhance efficiency and minimize waste (Mihai et al., 2022; Sharma et al., 2022).

The adoption of DTs in the seafood industry has been growing steadily, with applications spanning aquaculture, fishing, processing, transportation, and retail (Føre et al., 2024; Purcell et al., 2023; Pylianidis et al., 2021; Teixeira et al., 2022). These technologies are helping to address key issues, such as traceability, quality assurance, and equipment reliability.

6.4.1 Traceability and transparency

Ensuring traceability throughout the seafood supply chain is critical for food safety, regulatory compliance, and consumer confidence. DTs facilitate traceability by providing real-time visibility into each step of the supply chain, from harvest to retail (Dyck et al., 2023; Liu et al. 2021; Zhuang et al., 2021). DT systems integrate data from IoT devices, sensors, and blockchain technology to create a cohesive, real-time digital representation of seafood products (Hasan et al., 2020; Suhail et al., 2022; Yaqoob et al., 2020). For example, sensors installed on fishing vessels can monitor and log data on the catch's origin, species, handling practices, and environmental conditions. These data points are transferred to the DT, creating a unique digital record for each batch of seafood. As products move through the supply chain, the DT can be updated with transportation conditions, storage temperatures, and handling practices, ensuring that every step is documented. This comprehensive traceability system not only satisfies regulatory requirements but also enhances operational efficiency and minimizes the risk of contamination or fraud (Verna et al., 2025).

One notable example of improved transparency is the application of DTs by "Thai Union Group," a seafood supplier (Anonymous, 2020). The company implemented a blockchain-enabled DT system to track tuna from the point of capture to the consumer. This system allowed customers to scan a QR code on the product packaging to access information about the fishing vessel, location, and sustainability practices. Such initiatives have bolstered consumer trust by demonstrating a commitment to ethical and sustainable practices. In another case, Norwegian aquaculture firms employed DTs to track the lifecycle of farmed salmon and quality of the water. By integrating data on feeding practices, water quality, and fish health, these systems ensured transparency and enabled companies to address consumer concerns about the environmental impact of aquaculture operations (Føre et al., 2024).

6.4.2 Quality control and assurance

Seafood is highly perishable, necessitating stringent quality control measures throughout the supply chain. DTs enable proactive quality monitoring by capturing real-time data on factors such as temperature, humidity, and handling conditions. For instance, cold-chain logistics can be optimized using DTs that simulate temperature fluctuations during transportation (Ashok & Pillai, 2024; Suhail et al., 2022; Defraeye et al., 2019; Wu et al., 2023; Hu et al., 2023). Alerts can be triggered if conditions deviate from optimal ranges, allowing for immediate corrective actions. This capability not only preserves product quality but also reduces waste and ensures compliance with safety standards. DTs can also facilitate predictive quality control by analyzing historical data to identify potential quality risks (Rodríguez et al., 2023; Zhu & Ji, 2022). By correlating parameters such as water quality during aquaculture or handling times post-harvest with product degradation, companies can take preventive measures to maintain freshness and safety.

A significant example is the deployment of DT technology by "Marine Harvest" (Insights, 2022). The company used real-time DTs to monitor the quality of salmon during processing and transportation. Sensors embedded in packaging provided data on temperature and gas composition, which was relayed to the DT for continuous quality assessment.

Similarly, an Indonesian seafood distributor employed DTs to track the quality of tuna (Putra,2020). By integrating IoT sensors and machine learning algorithms, the system predicted spoilage risks, enabling the distributor to take pre-emptive actions, such as rerouting shipments to closer markets or adjusting storage conditions (Føre et al., 2024).

6.4.3 Predictive maintenance and equipment monitoring

Seafood processing facilities rely heavily on specialized machinery, such as filleting machines, freezing systems, and conveyor belts. Unexpected equipment failures can lead to costly downtime and product losses. DTs address this challenge by enabling predictive maintenance (Aivaliotis et al., 2019; Van Dinter et al., 2022). By collecting and analyzing data from sensors embedded in processing equipment, DTs can detect anomalies indicative of wear or malfunction (You et al., 2022). Machine learning algorithms can then predict when components are likely to fail, allowing for timely maintenance before a breakdown occurs (Liu et al., 2018). This approach minimizes unplanned downtime, reduces repair costs, and ensures uninterrupted operations.

In a prominent case, a seafood processing plant in Iceland implemented DT technology to monitor its freezing and packaging equipment. By leveraging data from vibration sensors, temperature gauges, and motor current monitors, the DT identified early signs of compressor wear. This allowed the plant to schedule maintenance during a low-production period, avoiding costly disruptions (Nyirenda, 2020; Sougioultzogloua & Cookb, 2023).

Another example is the use of DTs in a shrimp processing facility in Bangladesh. By integrating sensor data with advanced analytics, the system provided insights into equipment performance and energy usage. This not only improved reliability but also reduced energy consumption, contributing to the facility's sustainability goals (Kabir et al., 2023; Hassoun et al., 2024).

6.4.4 Case studies in aquaculture and fishing

DTs have found significant applications in aquaculture and fishing, driving advancements in productivity, sustainability, and profitability. In aquaculture, DTs are used to simulate and optimize farm conditions. For example, a Norwegian salmon farming company developed DTs of its sea cages to monitor parameters such as oxygen levels, water currents, and fish behavior. This allowed the company to adjust feeding schedules, reduce stress on fish, and improve growth rates (Føre et al., 2018).

In a research for aquaculture net damage detection, the authors explored a DT-based system for real-time damage detection in aquaculture fishing nets (Zhao et al. 2022). By integrating artificial neural networks (ANNs) with sensor data, the researchers created a robust model capable of identifying damage under varying conditions. Numerical simulations and physical experiments provided training data for the ANN, with inputs such as wave height, tension signals, and net states. The model achieved high accuracy ($\geq$93%) across diverse scenarios, including different damage locations and wave-current angles. The findings demonstrate the potential of DT technology for enhancing aquaculture operations, offering a scalable solution for maintaining structural integrity in dynamic marine environments.

In another study, DT-based system leveraging artificial intelligence Internet of Things (AIoT) was used for precision aquaculture (Ubina et al., 2023). The system integrates sensors, cloud computing, and AI to monitor and manage fish farms. Key services include automated feeding, fish health assessment, and water quality monitoring. Advanced AI models like YOLOv4 and Mask-RCNN enable fish detection, size estimation, and vitality analysis. Real-time data from sensors guide farm decisions through intuitive interfaces. Tested in offshore environments, the framework enhances productivity by optimizing feeding, predicting growth, and preventing diseases. This innovation demonstrates the potential of digital transformation for sustainable aquaculture practices.

The integration of DTs into the seafood supply chain represents a paradigm shift, addressing critical challenges in traceability, quality control, and operational efficiency. By enabling real-time monitoring, predictive analytics, and data-driven decision-making, DTs enhance transparency, sustainability, and profitability across the supply chain. As illustrated by the case studies discussed, these technologies are not merely theoretical constructs but practical solutions that are reshaping the seafood sector. Their continued adoption promises a future of safer, more sustainable, and more efficient seafood supply chains.

6.5 Integration of digital twin and cloud computing

The seafood sector, characterized by its complexity and reliance on efficient processing and supply chain operations, is increasingly adopting advanced technologies to meet modern challenges. Among these, the integration of DTs and cloud computing is emerging as a transformative solution. The DT technology and cloud computing are increasingly integrated to enhance the capabilities and applications of DTs across various industries. Cloud computing provides the necessary infrastructure and resources to support the data-intensive and computationally demanding nature of DTs (Chandhana et al., 2023; Wang et al., 2022). The integration of cloud computing with DTs offers several advantages. It enables seamless data storage, processing, and analysis, allowing for real-time monitoring and simulation of physical systems (Wang, 2023). Cloud-based DTs can leverage big data analytics, AI, and machine learning (ML) algorithms to provide predictive insights and optimize performance (Wani et al., 2023). Furthermore, cloud integration facilitates better scalability, accessibility, and collaboration among stakeholders (Kasiviswanathan et al., 2024). This integration allows for more efficient resource allocation, improved decision-making, and enhanced sustainability in urban environments (Hu et al., 2023; Wang et al., 2022). The combination of DTs and cloud computing also presents opportunities in industrial applications. Cloud-based DT platforms can support intelligent scheduling, real-time monitoring, and predictive maintenance in production environments (Yu et al., 2021). This integration enhances operational efficiency, reduces downtime, and enables more agile and responsive manufacturing processes (Prarthana et al., 2021). However, challenges such as data privacy, connectivity issues, and the need for scalable solutions must be addressed to fully realize the benefits of this integration (Jayasanker, 2024).

6.5.1 Synergistic benefits

The integration of DTs and cloud computing provides the seafood industry with unparalleled capabilities to enhance processing efficiency, quality control, and traceability. DTs, virtual replicas of physical systems, enable real-time monitoring, and simulation of seafood processing operations. When combined with the scalable and analytical power of cloud computing, these virtual models become dynamic tools for operational optimization. This synergy enhances processing in multiple ways. DTs simulate equipment such as graders, filleting machines, freezers, and transport systems, identifying inefficiencies and predicting maintenance needs. Cloud computing collects and processes data from sensors and IoT devices in real time, enabling centralized analysis and actionable insights. For instance, a seafood freezing plant using DTs integrated with cloud analytics can monitor variables such as temperature, humidity, and energy consumption to ensure optimal freezing while minimizing resource usage (Rashed et al., 2025). Practical applications highlight the transformative potential of this combination. For instance, DTs of packaging lines combined with cloud platforms optimize throughput by analyzing bottlenecks and automating adjustments in real time. Similarly, quality control is enhanced through cloud-powered predictive models that analyze data on seafood texture, color, and freshness, ensuring compliance with stringent standards. The combined capabilities of these technologies also improve traceability, a critical factor in the seafood industry, by providing end-to-end visibility into processing and logistics.

6.5.2 Technical architecture and frameworks

DT technology can be effectively integrated with cloud computing to create powerful, scalable, and flexible systems for various applications. The integration of cloud computing and DT technology typically involves a multi-layered architecture that leverages the strengths of both technologies (Ouahabi et al., 2021; Kasiviswanathan et al., 2024). A common framework for this integration includes a physical layer, a transmission layer, and a virtual layer. The physical layer consists of the actual objects or systems being monitored, equipped with sensors and IoT devices. The transmission layer handles data collection and communication between the physical and virtual layers, often utilizing edge computing for real-time processing. The virtual layer, hosted in the cloud, contains the DT models, data storage, and advanced analytics capabilities (Ding & Fan, 2022; Chandhana et al., 2023).

The architecture for a DT system in fish processing integrates physical, digital, and cloud-based elements. Table 6.1 summarizes the major components, their functionalities, and key enabling technologies.

6.5.3 Data security and privacy considerations

Data security and privacy are paramount when integrating DTs and cloud computing in seafood processing, as these systems handle sensitive operational and product information. Breaches or unauthorized access could disrupt operations, compromise quality, and erode consumer trust (Roumeliotis et al., 2024). Security measures must be implemented at multiple levels. IoT

Table 6.1 The components, functionalities, and key technologies of various layers in digital twin technology.

Section	Components	Functionalities	Key Technologies
Physical Space	Physical Fish Processing System, Sensors, Actuators	Monitors real-world parameters, collects data, and implements DT-driven actions.	IoT, actuators, and sensor technologies (temperature, humidity, water quality, etc.).
Data Collection and Preprocessing	Sensor Data, Edge Processing	Gathers and processes raw data to ensure quality and usability for DT models.	IoT-enabled devices, edge computing, data filtering, and normalization.
Cloud and Digital Space	Cloud Computing Infrastructure, Digital Twin Model (Simulation, Optimization, Data Analytics, Action Recommendations)	Stores, processes, and analyzes data; predicts, simulates, and optimizes operations; and provides actionable insights.	AI, ML, DL, cloud platforms, simulation software, and predictive analytics tools.
Communication Technologies	Network Communication (LPWAN, 4G/5G, Wi-Fi, LoRa, NB-IoT)	Facilitates real-time data exchange between physical systems and DTs, ensuring synchronization and control.	LPWAN, LoRa, NB-IoT, wireless protocols, and internet-based connectivity.
User Interaction and Visualization	Decision Support System (DSS), Visualization Tools	Enables stakeholders to monitor, visualize, and interact with DT insights for informed decision-making.	Dashboards, AR/VR platforms, immersive visualization tools, and DSS interfaces.
Feedback and Optimization	Monitoring Systems, Feedback Loop	Synchronizes physical and digital twins through continuous updates and optimizes processes.	Feedback algorithms, monitoring systems, and AI-driven recommendations.

devices and sensors require secure firmware and encrypted communication protocols to prevent unauthorized manipulation. Cloud platforms must utilize advanced encryption standards, such as AES-256, to protect data during transmission and storage. Multi-factor authentication and role-based access control limit access to sensitive systems, ensuring that only authorized personnel can make critical adjustments (Hassan et al., 2023). Privacy concerns are particularly significant when integrating traceability systems that store data about suppliers, customers, and transportation. Compliance with regulations such as General Data Protection and Regulation (GDPR) and California Consumer Privacy Act (CCPA) is essential to ensure ethical data handling. Anonymization and tokenization techniques protect sensitive information while enabling analysis. Best practices include performing regular security audits, adopting intrusion detection systems, and ensuring real-time monitoring of cloud environments. Leading cloud providers, such as Amazon Web Services (AWS) and Microsoft Azure, offer built-in security features like identity management and threat detection to support secure integrations. In addition, blockchain technology is increasingly being explored to ensure the integrity and transparency of traceability systems (Roumeliotis et al., 2024; Huang et al., 2024).

6.5.4 Best practices for integration

Leveraging cloud platforms for scalability and accessibility is crucial. Cloud-based DTs can handle large amounts of data and complex simulations more efficiently than traditional systems (Kasiviswanathan et al., 2024). The use of cloud computing features in DT solutions provides benefits such as cross-platform compatibility, easy deployment of lightweight applications, and simplified update and maintenance processes (Kasiviswanathan et al., 2024). Implementing a service-oriented architecture (SOA) approach can enhance the reliability and flexibility of DT systems. The cloud computing platform (CS-DT) strategy, which combines SOA and cloud computing, has shown promising results in practical applications, demonstrating its potential for widespread adoption across different industries (Kasiviswanathan et al., 2024). Utilizing cloud services for data storage, modeling, learning, simulation, and prediction is essential. For instance, the mobility digital twin (MDT) framework leverages AWS to implement digital functionalities for various mobility entities (Wang, 2023). This approach allows for efficient management of complex systems and enables real-time monitoring and analysis. Integrating IoT sensors, historical databases, and external application programming interfaces (APIs) is crucial for comprehensive data collection and analysis. The combination of connected vehicle technology and cloud computing in the MDT framework demonstrates the potential for creating holistic DT systems (Wang 2023). Employing hybrid modeling strategies with data fusion algorithms can lead to more interpretable and accurate predictive DT platforms. Filter methods with dimensionality reduction algorithms can help minimize computational resource demands in real-time operating algorithms (Kandemir et al., 2024). Implementing high-bandwidth communication networks is vital for efficient data transmission between physical assets and DTs, reducing latency and improving overall system performance (Kandemir et al., 2024). Successful integration of DTs and cloud computing in the seafood industry requires a phased approach, encompassing several key steps

Phase 1: Defining Objectives and Scope

The initial step involves clearly defining the specific objectives and scope of the DT implementation (Singh et al., 2021). This includes identifying the key aspects of the value chain to be modeled, the types of data to be collected, and the desired outcomes of the DT implementation. For instance, a seafood company might prioritize improving the traceability of its products, optimizing its production processes, or reducing its environmental impact. This clear definition of objectives will guide subsequent steps in the integration process (Barricelli et al., 2019).

Phase 2: Data Acquisition and Management

The next step involves establishing a robust data acquisition and management system (Rayhana et al., 2024). This includes identifying the relevant data sources, selecting appropriate sensors and data collection methods, and developing a strategy for data storage, processing, and analysis. The choice of sensors and data collection methods will depend on the specific objectives of the DT implementation and the nature of the data being collected (Huang & Khabusi, 2025). Data management strategies should consider data security, privacy, and compliance requirements (Carroll et al., 2011). The use of cloud computing platforms is crucial for managing the large volumes of data generated by DT (Qi et al., 2023).

Phase 3: Digital Twin Development and Validation

Once the data acquisition system is in place, the next step involves developing the DT model itself (Barbie & Hasselbring, 2024). This involves creating a virtual representation of the physical system, incorporating relevant data sources, and developing algorithms for simulating and predicting system behavior. The DT model should be validated against real-world data to ensure its accuracy and reliability (Minerva et al., 2020). This validation process may involve comparing the DT predictions with actual observations, adjusting the model as needed to improve its accuracy (Brönner et al., 2023).

Phase 4: Cloud Integration and Deployment

The developed DT model needs to be integrated with a cloud computing platform (Rayhana et al., 2024). This involves selecting an appropriate cloud provider, designing the cloud infrastructure, and deploying the DT model to the cloud environment. The choice of cloud provider will depend on factors such as cost, scalability, security, and compliance requirements (Saini et al., 2019). The cloud infrastructure needs to be designed to handle the large volumes of data generated by the DT and to support the computational requirements of the DT algorithms (Rawat & Bhandari, 2023).

Phase 5: System Monitoring and Evaluation

After deployment, ongoing monitoring and evaluation are essential (Amthiou et al., 2023). This involves tracking the DT performance, identifying any issues or errors, and making adjustments to the model or infrastructure as needed. Regular performance evaluations help to ensure the DT's accuracy and effectiveness over time (Dahlberg et al., 2017). Feedback mechanisms should be in place to allow users to provide input on the DT performance and identify areas for improvement.

6.6 Challenges and solutions in adopting digital twins and cloud computing in the seafood sector

The adoption of DTs and cloud computing in the seafood sector is faced with a variety of challenges. These issues range from technological and economic challenges to cybersecurity threats and data integration problems. However, with careful planning and targeted solutions, these challenges can be effectively addressed to ensure successful integration. This section examines key challenges and offers potential solutions to facilitate the implementation of these advanced technologies in the seafood sector.

6.6.1 Technological barriers

One of the primary challenges in adopting DTs and cloud computing is the lack of adequate digital infrastructure, particularly in developing regions (Broo & Schooling, 2023). Many seafood facilities are located in remote or rural areas where robust internet connectivity, continuous power supply, and advanced hardware and software are unavailable (Anand et al., 2024). Without these essential components, implementing Industry 4.0 technologies becomes a huge challenge. Additionally, the deeply rooted traditional practices within the seafood sector often leads to resistance among stakeholders (Kochanska, 2020). This resistance may stem from a lack of understanding, fears of job loss, or doubts regarding the tangible benefits of these technologies (Rodríguez-Espíndola et al., 2022).

Integration of new systems with existing frameworks further complicates the adoption process. Legacy systems, often outdated and incompatible with modern real-time data processing capabilities, can make integration costly and technically challenging (Subash et al., 2024). Moreover, a significant skills gap exists within the industry, as many supply chain partners lack the technical expertise to operate and maintain these advanced systems. Even when there is a willingness to adopt these technologies, the rapid pace of innovation often outstrips the industry's ability to adapt (Bhatt et al., 2016; Yang et al., 2024).

To overcome these barriers, substantial investment in digital infrastructure is necessary. Public-private partnerships can play a critical role in developing reliable internet connectivity, power grids, and data storage facilities in remote areas where most seafood facilities are based (Lewis & Boyle, 2017). User-friendly interfaces for DT and cloud platforms should also be prioritized to make these systems accessible to non-technical users (Alcaraz et al., 2025). A phased approach to implementation, starting with simpler technologies like traceability systems and gradually progressing to more advanced solutions, can help mitigate resistance and ease the transition (Kochanska, 2020). Comprehensive training programs, including workshops, courses, and live demonstrations, are essential to upskill the workforce and build confidence in these innovations (Fernandes Borges Pena Seixas et al., 2012). Furthermore, collaborative pilot projects involving governments, academia, technology providers, and seafood industry stakeholders can showcase the effectiveness of these technologies on a larger scale (Nisar et al., 2024).

6.6.2 Data integration and interoperability

Data integration is a critical challenge in aquaculture operations due to the diversity of sources generating information. Devices such as sensors, GPS units, RFID tags, and DTs produce data in various formats, making it difficult to consolidate and analyze effectively (Zhang & Gui, 2023). Additionally, data silos persist as different stakeholders in the seafood supply chain often rely on isolated systems, impeding real-time collaboration and data sharing (Mustapha et al., 2021; Mahroof et al., 2022).

To address these challenges, standardizing data formats—such as adopting Extensible Markup Language (XML) and JavaScript object notation (JSON)—and using communication protocols like message queuing telemetry transport (MQTT) and constrained application protocol (CoAP) can simplify integration across platforms. Centralized cloud-based systems offer a practical solution by providing synchronized access to data and enabling real-time processing across the supply chain. APIs and middleware can bridge disparate systems, ensuring seamless data exchange and interoperability (Hammerseth, 2024). Additionally, blockchain technology can be employed to enhance transparency and security in the seafood supply chain, facilitating traceability and reducing risks of data manipulation (Khan et al., 2022). DTs can further aid in data integration by creating virtual replicas of physical systems, offering visualization and analysis tools that streamline decision-making processes. Together, these approaches improve the efficiency and reliability of data management in fisheries, aquaculture, and the seafood industry.

6.6.3 Cybersecurity threats

As cloud-based systems become integral to the seafood supply chain, they are increasingly vulnerable to cybersecurity threats (Ismail et al., 2023). Data breaches pose significant risks by exposing sensitive information to unauthorized parties, potentially undermining traceability systems and damaging stakeholder trust (Duan et al., 2024). Phishing and social engineering attacks exploit human errors to infiltrate secure networks. Furthermore, distributed denial of service attacks can overwhelm systems with traffic, causing operational downtime. Malware and ransomware attacks jeopardize system integrity, often demanding substantial payments to regain access (Aslam et al., 2025). Insider threats—whether deliberate or accidental—also pose unique risks due to the privileged access held by employees and stakeholders (Aslam et al., 2025).

Mitigating these threats requires a multi-faceted approach. Implementing robust encryption and access controls, such as multi-factor authentication, ensures that sensitive data remains secure from unauthorized access (Fakhouri et al., 2024). Regular security audits can identify vulnerabilities and strengthen system defences. Educating employees on recognizing phishing attempts and adhering to security protocols is crucial in addressing human-related risks (Golkarnarenji & Ali, 2013). Backup and recovery plans should be established to safeguard critical data and maintain business continuity in the event of an attack. Network segmentation can limit the spread of potential intrusions by isolating critical systems (Manninen, 2018). Leveraging blockchain technology also enhances security by creating immutable records that ensure data integrity and transparency (Rani et al., 2024). These strategies collectively provide a robust defence against evolving cybersecurity threats.

6.6.4 Economic and regulatory challenges

The adoption of DTs and cloud computing in aquaculture entails significant economic and regulatory challenges. High initial investments are required for hardware, software, and infrastructure, making it difficult for small and medium enterprises (SMEs) to participate (Bhagwat & Sharma, 2007). Ongoing operational costs—including cloud subscriptions, data storage, maintenance, and cybersecurity—further strain limited budgets (Johnson et al., 2024). Demonstrating a clear return on investment can be particularly challenging when the benefits of these technologies are long-term or indirect.

On the regulatory front, aquaculture businesses must navigate a complex landscape of international standards and compliance requirements (Yang et al., 2024). Regulations such as the EU General Data Protection Regulation (GDPR) and food safety standards demand robust governance frameworks. Traceability requirements in major markets like the EU, USA, and Japan necessitate comprehensive documentation and advanced technology systems to ensure compliance. Environmental regulations also compel businesses to adopt sustainable practices, adding another layer of complexity to the adoption process (Charlebois et al., 2014).

To alleviate economic challenges, governments can provide subsidies, grants, and tax incentives to reduce the financial burden on SMEs (Waiho et al., 2020). Conducting thorough cost-benefit analyses can help stakeholders understand the long-term economic advantages of adopting advanced technologies (Borit & Olsen, 2020). Early engagement with regulatory bodies during the planning phase can ensure that systems are designed to meet compliance requirements (Bhatt et al., 2017). Acquiring sustainability certifications can not only support adherence to environmental regulations but also enhance market access and consumer trust (Roheim et al., 2018).

Public-private partnerships involving governments, research institutions, and industry players can foster innovation, streamline compliance processes, and support widespread adoption of these technologies (Tzankova, 2021).

The adoption of DTs and cloud computing in the seafood sector is not without its challenges. From technological barriers and data integration issues to cybersecurity risks and economic constraints, the road to implementation is complex. However, by addressing these obstacles through strategic investments, collaborative efforts, and innovative solutions, the seafood industry can harness the transformative potential of these technologies. Ultimately, the integration of DTs and cloud computing promises to enhance efficiency, sustainability, and transparency across the seafood supply chain, paving the way for a smarter and more resilient sector.

6.7 Future trends and innovations in the seafood industry

The seafood sector is currently undergoing a significant technological transformation, spurred by advancements in AI, IoT, blockchain, DTs, and cloud computing. These emerging technologies are driving the shift toward Seafood 4.0, an era defined by smart, efficient, and sustainable seafood production and distribution (Hassoun et al., 2024).

The convergence of AI, IoT, and blockchain is enhancing DTs and cloud computing, creating an interconnected ecosystem that supports efficiency, transparency, and sustainability. AI offers advanced analytics that automate critical tasks such as fish health monitoring, disease detection, and feeding optimization. AI-driven systems provide predictive insights into fish growth and water quality, enabling proactive decision-making. Meanwhile, IoT devices like sensors continuously monitor key parameters, including temperature, oxygen levels, and fish behavior. These real-time data streams feed into DT models and cloud platforms, allowing accurate simulations of aquaculture operations and supporting precise decision-making (Kochanska, 2020).

Blockchain technology ensures data integrity, security, and traceability by maintaining an immutable record of transactions. This capability is crucial for building trust among stakeholders, meeting regulatory standards, and preventing fraudulent activities. By integrating these technologies, cloud computing serves as a central hub for storing and processing vast quantities of data, making it readily accessible to all stakeholders. Together, AI, IoT, and blockchain drive smarter operations, reduce waste, and support sustainable and compliant practices within the seafood supply chain (Kochanska, 2020).

DT technology is revolutionizing the seafood sector by creating virtual replicas of aquaculture systems. These models integrate sensor data, AI, and cloud computing to offer real-time insights into fish health, growth, and behavior under various conditions. For example, DTs of Atlantic salmon farms enable precision aquaculture by combining biological data with environmental and operational parameters. This approach helps reduce fish mortality, optimize feeding strategies, and improve overall fish welfare (Le et al., 2024).

DTs also allow operators to conduct "what-if" scenarios, reducing the need for live experiments and aligning with ethical and sustainable farming principles. Future developments in DT technology aim to enhance model accuracy and incorporate more sophisticated AI algorithms. This will improve predictive behavior modelling, such as anticipating fish responses to environmental changes or disease outbreaks. Further integration with IoT and AIoT (AI combined with IoT) will enable more responsive and autonomous systems, enhancing real-time decision-making capabilities. Additionally, sustainability modelling through DTs can help assess the environmental impact of aquaculture operations, guiding the adoption of eco-friendly practices (Le et al., 2024).

Cloud computing plays a crucial role in supporting smart technologies within the seafood sector by facilitating the storage, processing, and analysis of large data volumes generated by IoT, DTs, and AI systems. Modern cloud platforms provide essential features such as scalability, cost efficiency, and real-time data accessibility, which are vital for managing complex aquaculture and supply chain operations.

Recent innovations in cloud computing include edge computing, which processes data closer to its source—for instance, directly on fish farms—thereby reducing latency and improving real-time decision-making. Big data analytics powered by cloud platforms enables advanced predictive modelling and operational optimization, boosting productivity and promoting sustainability. Enhanced cybersecurity measures safeguard data integrity and protect against cyber threats, helping maintain trust in digital systems. These cloud advancements support seamless integration of IoT, AI, and DT technologies, ensuring robust and reliable aquaculture systems.

In seafood supply chains, cloud computing also supports blockchain-driven traceability. This ensures transparent, real-time tracking of seafood products from their origin to the consumer, improving food safety, operational efficiency, and regulatory compliance.

The integration of AI, IoT, blockchain, and DTs is set to significantly reshape traditional seafood industry practices. These technologies offer numerous long-term benefits, such as (Hassoun et al., 2023): Firstly, it helps with enhanced traceability. For instance, blockchain ensures end-to-end transparency by providing verifiable records of product origin and handling, reducing fraud improving food safety and food authenticity. AI and DTs play an important role in precision aquaculture. It allows control of farming environments, optimizing fish health, improving productivity and enhancing sustainability. Finally, these technologies support sustainability, by monitoring real-time environmental conditions through IoT and cloud computing. Overall, it helps in minimizing sector's ecological footprint.

Seafood 4.0 represents the future of the seafood sector, driven by the adoption of digital technologies to achieve greater efficiency, sustainability, and transparency. This vision includes automated smart farms powered by IoT and AI systems (Rowan, 2023). It helps in efficient management of fish health, feeding times, and environmental conditions, thereby reducing the need for human interference and optimizing seafood operations. Blockchain can improve transparency of seafood supply chain. It ensures the authenticity and ethical sourcing of seafood products, thereby improving consumer trust and complying with regulatory processes. Data-driven decisions based on cloud-based analytics and DTs can provide stakeholders with actionable insights, thereby improving decision-making process and improving operation efficiency.

The seafood sector is on the cusp of a digital revolution, driven by innovations in AI, IoT, blockchain, DTs, and cloud computing. These technologies offer transformative potential by enabling smarter operations, reducing waste, enhancing transparency, and supporting sustainable practices. As the industry embraces Seafood 4.0, the integration of these digital solutions will lead to a more efficient, resilient, and environmentally responsible future for seafood production and distribution (Rowan, 2023).

6.8 Conclusion

The combination of DTs and cloud computing in the seafood sector has created an improved efficiency, sustainability, and transparency. They have enabled real-time visibility, predictive analytics, and data-driven decision-making process, thereby optimizing overall seafood supply chains. A DT, which offers a dynamic and virtual representation of actual seafood operations and activities, allows stakeholders to simulate various scenarios, reduce risks, and improve resource allocations. Meanwhile, cloud computing complements it by providing scalable data storage, processing power, and remote accessibility, thereby improving collaboration across whole seafood supply chain. However, despite its numerous benefits, there are challenges such as cybersecurity risks, costly implementation costs, and regulatory intricacies that exist. Addressing these challenges needs a multi-faceted approach, which includes strong security measures, strategic investments, and government support in the form of incentives and subsidies. Additionally, the implementation of blockchain technology improves traceability and regulatory compliance, increasing consumer trust in seafood products. As the sector embraces the era of "Seafood 4.0," the continued integration of AI, IoT, and blockchain with DTs and cloud computing will enhance innovation and resilience. Furthermore, collaboration among industry stakeholders, policymakers, and researchers will be important in ensuring the extensive and sustainable implementation of these technologies, eventually promoting a more intelligent and environmentally responsible seafood sector.

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