Aalto-yliopisto
Aalto-universitetet
Aalto University

Master’s Programme in International Design Business Management

Leveraging blockchain in chemical supply chain trading

Nasim Ali

Master’s thesis
2023

Aalto-yliopisto
Aalto-universitetet
Aalto University

Author Nasim Ali

Title of thesis Leveraging blockchain in chemical supply chain trading

Programme International Design Business Management

Major International Design Business Management

Thesis supervisor Associate Professor Ari Jokilaakso

Thesis advisor(s) D.Sc. (Tech.) Jukka Kortela

Date 31.07.2023 **Number of pages** 86 **Language** English

Abstract

This diploma thesis focuses on the integration of blockchain technology into supply chain trading. Real-world examples are examined to gain insights into the benefits and challenges of implementing blockchain in supply chain operations.
Blockchain is a decentralized technology that utilizes cryptographic techniques and consensus mechanisms to establish a secure and transparent ledger of transactions. Each transaction is grouped into blocks and linked together using unique identifiers. Consensus mechanisms validate and add new blocks to the blockchain. This decentralized approach enhances data security, transparency, and immutability.
The experimental work conducted in this diploma successfully implemented a digital twin and utilized cloud computing in a small-scale manufacturing facility. By integrating the Heroku cloud platform and establishing a digital twin connected to the cloud, the study demonstrated the potential for real-time monitoring, data analysis, and secure data management within the context of blockchain technology.
Measurements were performed on a helical coil heat exchanger to assess its heat transfer efficiency, and a simplified 3D model was created for simulation. The simulation results were compared to the actual measured temperatures, showing a close correspondence with slightly lower temperatures consistently observed. The discussion highlights the practical benefits of digital twin and the potential integration of blockchain in the chemical engineering industry, while addressing the factors contributing to these minor deviations.
These findings underscore the significance of leveraging blockchain, digital twin and cloud technologies to improve efficiency, sustainability, and safety in industrial processes. Further research and development in this area has the potential to drive significant advancements in the field of chemical engineering and manufacturing.

Keywords blockchain, digital twin, industry 4.0, supply chain trading

Aalto-yliopisto
Aalto-universitetet
Aalto University

Tekijä Nasim Ali

Työn nimi Leveraging blockchain in chemical supply chain trading.

Koulutusohjelma International Design Business Management

Pääaine International Design Business Management

Vastuuopettaja/valvoja Associate Professor Ari Jokilaakso

Työn ohjaaja(t) D.Sc. (Tech.) Jukka Kortela

Päivämäärä 31.07.2023 **Sivumäärä** 86 **Kieli** englanti

Tiivistelmä

Diplomityössä tutkittiin lohkoketjuteknologian käyttöönottoa kemianteollisuuden toimitusketjuissa. Lisäksi perehdyttiin lohkoketjuteknologian etuihin, haasteisiin ja sen kasvupotentiaaliin toimitusketjujen hallinnassa.

Lohkoketju oli hajautettu tekniikka, joka käytti salaustekniikoita ja konsensusmekanismeja turvallisen ja läpinäkyvän tapahtumakirjanpidon luomiseksi. Jokainen tapahtuma oli ryhmitelty lohkoihin ja linkitetty toisiinsa yksilöllisten tunnisteiden avulla. Konsensusmekanismit validoivat ja lisäsivät uusia lohkoja lohkoketjuun. Tämä hajautettu lähestymistapa paransi datan tietoturvaa, läpinäkyvyyttä ja sen muuttumattomuutta.

Kokeellisessa työssä toteutettiin lämmönsiirtimen digitaalisen kaksosen onnistunut käyttöönotto. Digitaalinen kaksonen yhdistettiin Heroku-pilvipalvelu alustaan. Kierteisen kelan lämmönsiirtoa arvioitiin suorittamalla lämpötila mittauksia ja kehitettiin yksinkertaistettu 3D-malli simulointia varten. Simulaation tulokset verrattiin todellisiin mitattuihin lämpötiloihin, ja havaittiin läheinen vastaavuus, vaikkakin simuloidut lämpötilat olivat hieman alempia. Tuloksissa käsiteltiin tähän poikkeamaan vaikuttavia tekijöitä. Kokeellinen työ osoitti, että lämmönsiirtimen reaaliaikaisen seuranta, data-analyysi ja turvallinen datahallinta oli mahdollista lohkoketjuteknologian kontekstissa. Tulosten perusteella korostui lohkoketjuihin, digitaaliseen kaksoseen ja pilvipalveluihin perustuvien ratkaisujen merkitys kemianteollisuudessa.

Avainsanat lohkoketjut, toimitusketjut, digitaalinen kaksonen

Table of contents

List of figures:

Preface

During my diploma thesis endeavour, I greatly appreciated the invaluable guidance and unwavering support provided by Doctor Jukka Kortela (thesis advisor). The direction of this thesis has been shaped by his expertise in programming languages, cloud technology, chemical engineering, and insightful feedback.

Furthermore, I extend my appreciation to supervisor professor Ari Jokilaakso for his encouragement, unwavering support and understanding.

Finally, I would like to thank Babak Nasiri and his company. Nasiri Oy who contributed to this research through their participation in providing valuable insights. Your contributions have enriched the findings of this thesis.

Otaniemi, July 31, 2023

Nasim Ali

Abbreviations

ABI	Application Binary Interface
AI	Artificial Intelligence
API	Application Programming Interface
CPS	Cyber Physical System
CSP	Cloud Service Provider
DAC	Distributed Autonomous Corporations
DAM	Digital Asset Management
DeFi	Decentralized Finance
DIDs	Decentralized Identifiers
E2E	End-to-End
ERP	Enterprise Resource Planning
HTTPS	Hyper Text Transfer Protocol Secure
IoS	Internet of Services
IoT	Internet of Things
M2M	Machine-to-Machine
MQTT	Message Queuing Telemetry Transport
NFT	Non-Fungible Tokens
OPC	Object Linking and Embedding for Process Control
OPC DA	OPC Data Access
P2P	Peer-to-Peer
PLC	Programmable Logic Controller
PoI	Proof of Importance
PoS	Proof of Stake

PoW	Proof of Work
SBC	Single-board computer
SCADA	Supervisory Control and Data Acquisition
SCM	Supply Chain Management
VR	Virtual Reality

1 Introduction

Blockchain technology plays an increasingly significant role in enabling and optimizing chemical supply chains in an era of artificial intelligence. Incorporating blockchain technology into Industry 4.0 can unlock a vast array of opportunities and significantly enhance supply chain efficiency (Hopkins, 2021; Sundarakani et al., 2021).

Industry 4.0 combines AI with blockchain and other key components, such as openness, connectivity, and automation, ushering in a new era of production. In today's business environment, topics such as on-demand manufacturing, dematerialization, and disintermediation are gaining more attention. Industry 4.0 can be fully realized with AI and blockchain technology (Lohmer & Lasch, 2020; Zia et al., 2021).

Blockchain technology can enhance supply chain management as well as facilitate financial transactions, secure product identity, and facilitate Industry 4.0. Moreover, it can improve transparency and accessibility to the patent process for small and medium businesses (Ding et al., 2021; Bellini, 2022).

According to Accenture (2018), Block chain can reduce errors and costs, and facilitate compliance with regulatory requirements due to its decentralized nature. Tracking chemicals, materials, and products throughout a supply chain could be secure and verifiable. A smart contract automates contracts as well as the transfer of goods and payments between parties, eliminating the need for intermediaries (Deloitte, 2018).

A study by KPMG (2018) identifies several challenges, such as stakeholder buy-in, implementation costs, and regulatory compliance. A phased approach to adoption, such as starting with small pilot projects and gradually scaling up, may be beneficial as the company gains more experience and confidence in its capabilities.

The complex business environment of today requires companies to invest significant resources in building cross-organizational information systems to improve agility and adaptability. These systems enable companies to respond quickly to market changes by improving coordination between them. Continuous development has resulted in larger scales and more complex organizational structures within the supply chain industry. As companies grow and face their own scale and organizational complexity, supply chain risk becomes more prominent (Zia et al., 2021; Tavana et al., 2023).

1.1 Background

Supply chain operations rely heavily on the flow of information to connect logistics and capital flows. Companies are constantly managing and processing more data due to an increasing number of supply chain partners, increased transaction volumes, and diverse cooperative relationships. Companies must ensure that their information flow is managed effectively to ensure its correctness, efficiency, and security. Logistics and capital flows can only be effectively managed by appropriately managing information flows. Managers can make misleading decisions when information flow is not managed effectively (Zia et al., 2021; Tavana et al., 2023).

Excel sheets are commonly used for updating data in supply chain systems. This conventional approach, however, is insecure, inefficient, and subject to human error. The process can be automated to minimize human intervention. Web-based applications hosted on either a company server or a virtual server have proven more effective at managing supply chains (Asyrofi & Zulfa, 2020; Azangoo et al., 2021).

Understanding the risks associated with information flow in the supply chain to thrive in today's highly competitive environment. Businesses can gain even greater benefits by adapting advanced technologies (Sansana et al., 2021; Zia et al., 2021).

Business operations have become more accurate and efficient because of collaborative robotics and automated monitoring systems. Data-driven production is now possible thanks to the IoT. A company can gain greater insight into its operations by analysing the data collected by different sensors. Additionally, Industry 4.0 technologies enable current workers to take on greater roles in an efficient manner (Busse et al., 2020; Lohmer & Lasch, 2020; Tadessa, 2020).

As globalization transforms the chemical industry, companies are increasingly seeking new markets and expansion opportunities. Among the challenges facing the chemical industry are rising raw material costs and increased regulatory pressure. Developing sustainable solutions will require companies to continue investing in modern technologies and processes, as well as working closely with regulators and other stakeholders. This has led to greater collaboration and partnerships between companies, as well as increased investment in research and development. Investing in sustainable and digital technologies will help the industry meet the demands of a rapidly changing world (Hughes et al., 2019; Hopkins, 2021).

1.2 Research questions and methodology

These research questions aim to investigate the benefits, applications, challenges, and potential of blockchain technology in the context of chemical supply chain trading. They provide a framework for analysing and evaluating the role of blockchain in enhancing chemical supply chain operations and exploring its potential impact on the chemical industry. The research questions are following:

- How can blockchain technology be experimented with in the chemical engineering industry?
- How can real-time sensor data be analysed and utilized to monitor various physical parameters with a digital twin?

The research methods of the diploma thesis can be summarized as follows:
Literature Review: Conduct an extensive review of relevant literature, research articles, and industry reports to gain a comprehensive understanding of blockchain technology and its potential applications in the chemical engineering industry.
Experimental Design: Develop an experimental setup to explore the application of blockchain technology in the chemical engineering industry. This may involve creating a digital twin of a chemical process, integrating real-time sensor data, and implementing blockchain-based solutions for data management and security.
Data Analysis: Collect and analyse real-time sensor data from the experimental setup, focusing on different physical parameters. Utilize data analysis techniques and algorithms to monitor and interpret the data.
Evaluation and Conclusion: Evaluate the effectiveness and feasibility of utilizing blockchain technology in the chemical engineering industry based on the experimental results and analysis. Draw conclusions, discuss the implications of the findings, and propose recommendations for further research and implementation.

1.3 Structure of literature review

The concrete goal of this thesis is to examine the role and implementation of blockchain technology in the context of Industry 4.0, specifically within the supply chain network. The literature review chapters explain the advantages, recent uses, challenges, and future potential of blockchain technology. It will draw insights from scholarly articles, research papers, industry reports, and case studies to present a well-rounded analysis of the topic (Esmaeilian et al., 2020). The structure of literary review is following:

- Advantages of implementing blockchain-based systems: This section will delve into the specific benefits and advantages that organizations can gain by incorporating blockchain in the systems. Supply chain operations will be examined to see how blockchain improves transparency, traceability, security, efficiency, and trust.
- Recent uses of blockchain: Case studies and applications in which blockchain technology has been successfully implemented in the industry will be presented in this section. It will examine real-world examples that address specific challenges or enhance supply chain processes, highlighting the use cases where blockchain has been effectively utilized.
- Primary issues arising from blockchain adoption: Blockchain-enabled supply chains may face several challenges that will be discussed in this section. It will cover areas such as scalability, interoperability, data privacy, regulatory compliance, and the integration of existing systems with blockchain. The review will analyse the risks and obstacles related to blockchain adoption.
- Future growth potential: This section will explore the prospects and growth of blockchain in supply chain. It will examine emerging trends, advancements, and innovations in blockchain that can reshape the supply chain industry. Among the areas discussed in the review are supply chain visibility, automation, smart contracts, and collaborative networks.

2 Supply chain management

Integrating today’s supply chain coordination in distributed manufacturing networks poses several challenges for supply chain management (SCM). These challenges include:

- Centralized Supply Chain: currently, supply chains are centralized, leading to inefficiencies in terms of time, cost, and inadequate features for market analysis (Agarwal et al., 2022; Risso et al., 2023)
- Complexity and Cost: a complex and expensive value network and supply chain results in higher costs for stakeholder. Storing data in a centralized database can also be an expensive process (Agarwal et al., 2022; Tavana et al., 2023).
- Inadequate Transparency and Traceability: the existing structure of the supply chain falls short in providing the necessary degree of transparency and traceability, causing problems in monitoring and tracing products (Agarwal et al., 2022; Risso et al., 2023).
- Coordination and Optimization Challenges: stakeholders and consumers face challenges related to coordination, inventory management, order management, and other aspects of supply chain operations. This leads to suboptimal output and storage due to difficulties in evaluating demand (Agarwal et al., 2022).
- Centralized Approach: traditional SCM is based on a centralized approach, where information is stored in a centralized database. This can lead to data misrepresentation and mistrust between ventures, resulting in higher communication costs (Agarwal et al., 2022; Risso et al., 2023).
- Lack of Pricing Transparency: middlemen in the supply chain hinder pricing transparency, adding inefficiencies to the system (Agarwal et al., 2022; Risso et al., 2023).
- Data Incompatibility and Product Tracing Delays: data manipulation and inconsistencies across supply chain entities delay the product tracing process, making it challenging to track products effectively (Hopkins, 2021; Agarwal et al., 2022).
- Privacy and Security Concerns: today's supply chain lacks an encrypted mechanism to store consumers' confidential information, making it susceptible to cyber-attacks and unauthorized access to sensitive data (Lu, 2019; Agarwal et al., 2022).
- One-Way Flow of Goods: the traditional SCM follows a one-way flow of goods, where customers bear the consequences if a product is faulty. The difficulty of facilitating seamless transactions and exchanges for each individual customer is considerable. (Hopkins, 2021; Agarwal et al., 2022).

- Supply Chain Attacks: suppliers and providers are the targets of supply chain attacks, rather than individual organizations. Supply chain security is significantly impacted by exploiting vulnerabilities in unsecure suppliers to gain access to larger trading partners. (Angrish et al., 2018; Agarwal et al., 2022).

Blockchain technology can provide a tamper-resistant tracking method to address these challenges. Decentralized infrastructure and a foundation of trust provided by blockchain technology transform supply chains. The blockchain acts as an unchangeable and everlasting record system by encrypting information chronologically. Decentralization, traceability, robust cryptography, and tamper resistance are its essential characteristics. (Agarwal et al., 2022; Risso et al., 2023).

The ability to create and execute smart contracts is one of block chains's major advantages, as it enables secure transactions between parties with limited trust. The concept of smart contracts describes digital agreements that can perform tasks automatically in the absence of a third party (Qi &Tao, 2018; Agarwal et al., 2022).

Blockchain technology facilitates stakeholder trust and quality assurance as well as automating payments and improving quality control. A virtual environment enables real-time monitoring, regulation, and data handling. Additionally, block chain enhances supply chain visibility and reduces geographical limitations (Agarwal et al., 2022; Risso et al., 2023). As a result of block chain implementation in supply chains, risk of SCM attacks can also be minimized, ensuring system integrity and security (Lu, 2019).

3 An overview of industry 4.0

Industry 4.0 transforms businesses through cloud computing and storage. However, the cost of cloud storage and operations may be too high for some organizations. Blockchain technology provides a transparent and cost-effective solution to this problem (Ko et al., 2018; Sansana et al., 2021).
The peer-to-peer connection model of blockchain distributes computing and energy demands among multiple IoT devices. The distributed ledger technology of blockchain tracks every aspect of a product's lifecycle. This balance between cost, security, and transparency benefits all stakeholders. Blockchain, artificial intelligence, and big data disrupt traditional business models in the new economy and developing business models based on trends such as Industry 4.0 requires creative thinking (Andoni et al., 2019; Lohmer & Lasch, 2020; Hopkins, 2021).

Blockchain can automate and optimize chemical production processes, reducing energy consumption and waste generation. Additionally, blockchain technology can improve sustainability in the chemical industry by tracking sustainable practices and certifications and automating and streamlining environmental compliance. (Hughes et al., 2019; Ding et al., 2021; Hopkins, 2021).

3.1 Industrial digitalization and chemical processing

The chemical industry has undergone significant changes due to increased automation, digitalization, and sustainability. IoT and AI have enabled chemical companies to optimize their operations and reduce their environmental impact. The chemical industry provides raw materials and products to various industries, including agriculture, construction, and electronics. Sustainable and environmentally friendly practices have become a key trend in the chemical industry, driving growth and innovation. To minimize waste, promote energy efficiency, and reduce environmental impact, innovative technologies and processes have been developed. For example, bioplastics made from plant-based materials are increasingly used as alternatives to petroleum-based plastics. Additionally, many businesses are investing in technologies that reduce greenhouse gas emissions by capturing and storing carbon dioxide (Hughes et al., 2019; Wang et al., 2019; Alfandi et al., 2020).

Data analytics is used to improve efficiency, reduce costs, and optimize production processes. Digital technologies such as IoT and automation are making chemical facilities safer and more secure. The use of IoT-enabled sensors can reduce downtime and increase productivity by monitoring equipment performance and predicting maintenance requirements. AI-powered predictive analytics can also optimize production processes, reduce waste, and increase yields. Digital twin technology can simulate chemical processes virtually, eliminating the need for physical experiments to test different scenarios and optimize production processes (Nasiri, 2017; Deloitte, 2018; Tao et al., 2019; Bapatla et al., 2022).

According to a study published in the Journal of Industrial Engineering and Management, digital technologies can lead to significant cost savings and increased efficiency in the chemical industry. These technologies can reduce energy consumption by up to 20% and increase productivity by up to 30%. As digitalization and advanced technologies become more prevalent in the chemical industry, efficiency, cost, and sustainability are continually improving (Jain et al., 2018; Andoni et al., 2019; Nuttah et al., 2023).

3.2 Industry 4.0 advancements in the chemical sector

Chemical companies benefit from innovative technologies that enable predictive maintenance, production process optimization, and improved supply chain management (Kang et al., 2023). This can be accomplished with digital twins, which allow real-time simulation and optimization of production processes (Zhu et al., 2022). Additionally, blockchain technology enhances the security and transparency of supply chain management in the chemical industry (Wang et al., 2020; Ding et al., 2021).

Integrating production plants into integrated supply chains and enabling access to their data and operations are critical components for Industry 4.0. To leverage Industry 4.0 and share data and processes with customers, suppliers, and other industries, interoperable supply chains are established. This integration of data collection and production processes is necessary for big data analytics, business intelligence, and machine learning. Developing integrated supply chains and data-sharing environments is essential as Industry 4.0 evolves. Big data analytics, business intelligence, and machine learning are key to gaining a competitive edge (Weyer et al., 2016; Hopkins, 2021; Bellini, 2022).

Industry 4.0 relies on communication networks, automation technology, and the digitization of production processes. Building a smart environment requires the integration of IoT, Cyber-Physical Systems (CPSs) and Internet of Services (IoS). Smart industries are controlled and monitored by CPSs, while IoT enables real-time collaboration between them. In contrast, IoS delivers services across an organization's entire value chain.

Figure 1 visually illustrates the technology drivers of Industry 4.0, emphasizing the key role played by CPS, IoT, and IoS (Yu et al., 2020; Alfandi et al., 2020; Abadi & Khalaj, 2022).

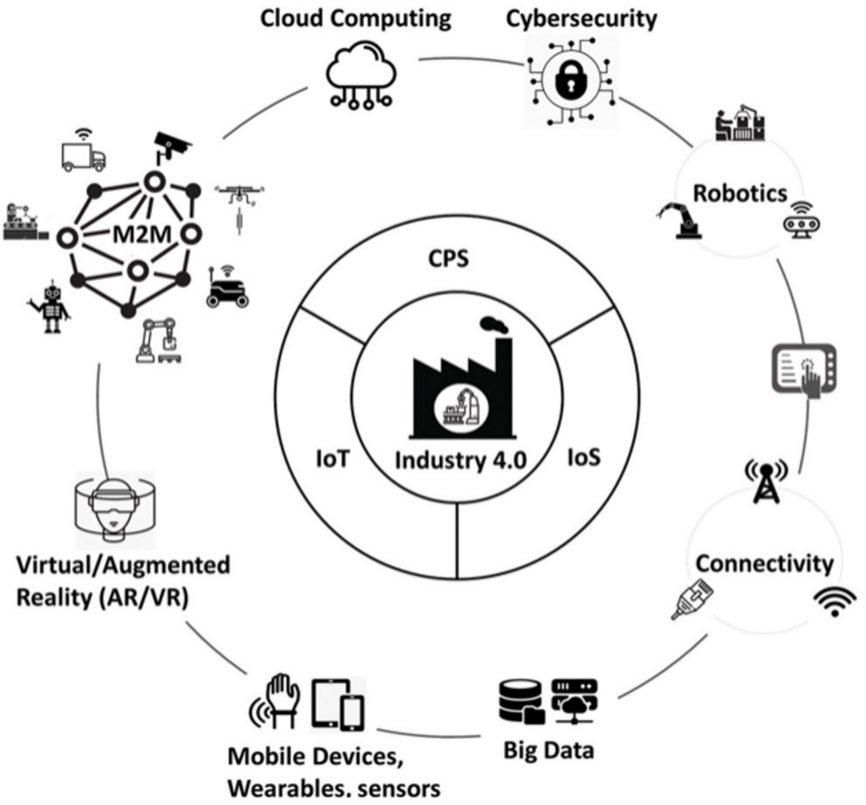


Figure 1. This diagram illustrates how 4.0 is being transformed through digital technologies (Abadi & Khalaj, 2022).

4 An overview of World Wide Web

The internet has undergone significant changes since Web 1.0, Web 2.0, and Web 3.0 emerged. Web 1.0 primarily provided static information through centralized systems, while Web 2.0 introduced interactive content creation and social networks through distributed architectures.
Web 3.0 is now on the horizon, utilizing innovations such as semantic communication, blockchain, and wireless edge computing. Its focus is on decentralizing compute and storage resources, transferring them to wireless edge devices, and empowering users to actively engage in content creation and ownership (Lin et al., 2023).

4.1 Transformation of the World Wide Web

The early World Wide Web served static content using HyperText Markup Language and HyperText Transfer Protocol. Uniform Resource Locators (URLs) were used to identify web pages. These web pages had limited interactivity and relied on a static file system instead of a database. The static nature of Web 1.0 created the groundwork for Web 2.0, a read-write interactive web or social web. Web 2.0 introduced platforms like Facebook, Twitter and YouTube which allowed users to actively participate in content creation without needing technical skills. Using these platforms, millions of users worldwide were able to share videos, pictures, and comments (Jain, 2023).

Despite the success of Web 2.0, it resulted in centralized platforms controlling user data and mining it for commercial purposes. This led to a loss of user control and privacy, leading to the emergence of Web 3.0. The third iteration of the web aims to address the centralization issue and give users control over their data (Jain, 2023).

The design of Web 2.0 entails an inherent reliance on centralized systems. It is noteworthy that these systems, despite being distributed, did not adopt a decentralized architecture. The authority and governance over these systems remained in the hands of individuals or groups, which gave rise to issues related to privacy and data usage. The development of Web 3.0 has maintained decentralization at its foundation. In this regard, data storage and deployment for Web3 applications are expected to adopt a decentralized approach. Thus, understanding the landscape of Web3 necessitates a comprehensive grasp of the concept of decentralization (Jain, 2023).

The concepts of centralization and decentralization refer to the degree of control exercised over a system. Corporations or individuals hold control in centralized systems. In contrast, decentralized systems are characterized by the absence of a single controlling entity and instead feature control that is distributed among several autonomous organizations. The distribution of system components across different physical locations is a key characteristic of distributed systems, which are also known as non-co-located systems. In contrast, non-distributed systems, or co-located systems, have all their components located in the same physical location. It is important to understand the distinction between these types of systems, as it has significant implications for system performance (Angrish et al., 2018; Jain, 2023).

4.2 The dawn of a new internet era: Web 3.0

Blockchain technology and semantic communication are integrated into Web 3.0 to improve user engagement, data security, and information exchange efficiency. Web 3.0 uses decentralized and transparent recording of content, ensuring traceability and security through blockchain ecosystems. This integration ensures transparency and efficiency within the web ecosystem. Web 3.0 services can be accessed through virtual avatars, especially with the rise of new Internet applications such as Metaverse. However, recording content on the blockchain consumes significant computing and storage resources, leading to information overload and limitations in device coverage (Lin et al., 2023).

To address these challenges, semantic communication has gained prominence as a solution within Web 3.0. Instead of analysing raw data, the system can analyse semantics of content to improve service quality. Semantic communication significantly reduces the amount of data required for wireless edge devices, reducing resource consumption by up to 97.5% compared to traditional methods Streamlined information exchange results in a more efficient use of semantic information (Lin et al., 2023).

In summary, Web 3.0 combines blockchain technology and semantic communication to establish a decentralized and efficient web ecosystem. It aims to ensure data security, enhance user participation, and facilitate efficient information exchange. With wireless edge computing, Web 3.0 is more advanced and user-friendly (Lin et al., 2023).

Web 3.0 services have evolved to encompass various blockchain-enabled applications such as DAM, Metaverse, DIDs and DeFi:

- Decentralized Identifiers (DIDs) enable users to take control of their data and privacy. By allowing individuals to store information independently rather than relying on centralized databases, DIDs empower users to maintain sovereignty over their personal information. Furthermore, DIDs serve as the foundation for other Web 3.0

technologies like DAM, the Metaverse and DeFi, facilitating secure and user-centric information exchange.
- Decentralized Finance (DeFi) leverages blockchain technology within Web 3.0 to revolutionize the financial landscape. Using smart contracts, DeFi enables individuals to have greater control over accessing and trading various products and services. Users can interact with DeFi platforms through self-controlled wallets, irrespective of their identity or geographical location.
- Digital Asset Management (DAM) plays a significant role by treating user-generated content and authorities as valuable digital assets. Among the resources offered by DAM are non-fungible tokens (NFTs), digital real estate and cryptocurrencies. DAM allows users to possess, manage, monetize, and even eliminate their digital assets. Additionally, governments can harness DAM within the realm of Web 3.0 to simplify regulatory procedures and minimize transaction expenses (Ko et al., 2018).
- The Metaverse represents the user's perspective of Web 3.0, offering individuals an immersive virtual world experience. Metaverse transforms the online landscape into an interactive and transformative space. Users can engage with the Metaverse, participating in various activities and social interactions.

In conclusion, Web 3.0 services revolve around blockchain-enabled applications like DIDs, DeFi, DAM, and the Metaverse. These technologies empower users to take control of their data, reshape finance, manage digital assets, and immerse themselves in a user-centric virtual world experience.

Web 3.0 presents challenges encompassing security, privacy, management, scalability, interoperability, authentication, and governance. These challenges must be tackled to ensure the effective and secure functioning of Web 3.0 services (Lin et al., 2023).

Security and privacy are key concerns in Web 3.0, particularly evident in incidents of hacks and fraud within decentralized finance (DeFi). Measures such as smart contract code auditing, federated learning, and zero-knowledge proofs can enhance security and protect user privacy (Patil et al., 2018; Lin et al., 2023).

Managing and integrating heterogeneous data specifications is vital for successful Web 3.0 implementation. This involves handling local and shared dats from edge servers and developing mathematical models for semantic information. Communication and computation capacities can be vastly enhanced by integrating emerging technologies like 6G and quantum computing (Lin et al., 2023).

Scalability and interoperability pose significant challenges due to the limited throughput of blockchains and the existence of various heterogeneous blockchain networks. Future Web 3.0 frameworks should focus on efficient consensus algorithms and cross-chain integration to enable seamless service circulation across multiple blockchains (Patil et al., 2018; Esmaeilian et al., 2020; Lin et al., 2023).

In Web 3.0, users are given greater control over content through authentication and governance. Facilitating data exchanges and governance mechanisms is essential to unlock the value of data. However, the decentralized nature of Web 3.0 presents challenges in data authentication and verification. Secure Multi-Party Computation can be employed to ensure data governance within the blockchain and semantic ecosystems (Lin et al., 2023).

5 Blockchain technology

Blockchains have existed since the 1970s, with the development of Merkle trees and consensus algorithms. However, their widespread use did not occur until 2008 with the emergence of Bitcoin cryptocurrency. Since then, there have been several non-monetary applications of blockchain technology, such as transportation, energy management, smart cities, drones, and robotics (Andoni et al., 2019; Restuccia et al., 2019; Yu et al., 2020).

Blockchain has the potential to transform value exchange, contract enforcement, and data sharing processes. To create trust-based ecosystems, rules and regulations have been codified. It has proven to have numerous benefits, including the ability to trace transactions from production to sale to shipping, as well as reducing errors and human errors. The distributed and encrypted nature of blockchain technology provides hope for enhanced security in Industry 4.0. Businesses can conduct secure transactions directly without relying on intermediaries. In addition, smart contracts provide a reliable foundation for an effective technological interface to engage with blockchain transactions. Blockchain technology offers significant benefits such as risk reduction, combating corruption, minimizing errors, fostering trust, and enhancing operational efficiency (Casino et al., 2019; Javaid, 2021).

Smart contracts are automated software programs designed to establish and enforce agreements between multiple parties. For example, if Elsa rents out her property to Anna and requires a monthly rent payment, blockchain technology can easily encode this transaction as a smart contract. To express smart contracts on Ethereum's blockchain, an application binary interface (ABI) specifies the programming language used. With just a few lines of code, the contract can be created and linked to Anna, automating the process of monthly payment at the end of each month. Therefore, smart contracts provide efficient mechanisms for sending and receiving payments, conditional on certain pre-established terms, such as the monthly rent payment deadline (Casino et al., 2019; Restuccia et al., 2019; Alkhader et al., 2020).

Especially when it comes to IoT networks, smart contracts offer numerous advantages. Once contracts are stored in a blockchain, their terms and conditions are immutable and cannot be changed. Since smart contracts have a unique address within the blockchain, they can be accessed from anywhere using the internet. In addition, their simple code structure makes them easy to understand and execute by IoT devices (Casino et al., 2019; Restuccia et al., 2019).

Blockchain smart contracts have been successful in supporting autonomous interactions; they are expected to function similarly in Internet of Things

(IoT) applications to support autonomous interactions. Smart contracts could govern access to device resources in IoT system, generating real-time access permissions. Smart supply chain monitoring is one potential application of smart contracts. In addition to tracking goods' locations and regulating production and shipping fees, smart contracts can keep track of transactions (Restuccia et al., 2019; Hopkins, 2021).

Several industries face challenges in obtaining accurate data and verifying it. A tracker collects data and sends it to a data science facility for analysis. Data integrity and ownership can be preserved through smart contracts and blockchain technology, allowing data scientists to analyse the data directly. Additionally, this can improve the scalability, anonymity, and reliability of the data collection process. As well as tracking and managing connected devices, blockchain software can enable the sharing of data between them, making it possible to share and process data transfers. Through decentralization, single points of failure can be eliminated, and a robust computing environment can be created. Connected devices in an IoT network can cooperate securely with blockchain technology (Smith, 2004; Heinijoki, 2021; Hopkins, 2021; Javaid, 2021).

Using proof-of-work (PoW), the blockchain system establishes a trust network between untrusted parties by adding new blocks. Blockchain nodes may use changeable public keys for identification purposes. The process begins with the PoW algorithm, where participants agree on the validity of transactions. These transactions are then combined into a block, which is appended to the ledger. Each block is uniquely identified by a hash, giving rise to the term "blockchain". Any alteration made to a block, including its transactions, will cause the hash in the following block to become mismatched, thereby preserving the integrity of the ledger. (Restuccia et al., 2019).

Blockchain technology aims to eliminate intermediaries and provide proper rights to legitimate users in capital transfers. Traditionally, banks and governments serve as mediators, verifying user authenticity and validating transfer details. In contrast, blockchain technology replaces these intermediaries by performing similar functions through composite cryptography architecture. Similar to a linked list in computer science, a blockchain stores data in sequential data blocks that are linked by pointers. Each block includes payloads and headers containing information about the activity, its length, content, and SHA256 hash value of the previous block. Blockchains aim to validate and verify transactions after data is recorded in a distributed ledger, using the distributed harmony algorithm to determine the inclusion of transaction sets in blocks. The traditional design of a blockchain is shown Figure 2 (Angrish et al., 2018; Bashir, 2023).

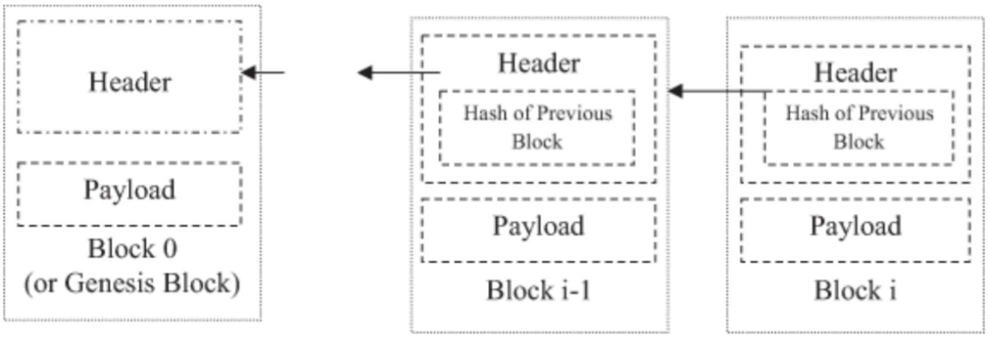


Figure 2. The conventional blockchain architecture (Bashir, 2023).

Most network nodes, i.e., blockchain users, must agree on a new block before it can be added to a blockchain. Each network node has a local replica of the blockchain, and when an additional block is created, the protocol transmits it over the network. Replicating the blockchain in multiple persistent copies increases system reliability and security. The consensus process validates and verifies each transaction before it is recorded on a blockchain. This ensures that each new transaction integrates with existing ones. Failure to reach consensus can result in various attacks (Angrish et al., 2018; Bashir, 2023).

PoW is the primary consensus method used in Bitcoin and most cryptocurrencies. Through the mining process, nodes (miners) solve complex analytical puzzles using increased computing power. These puzzles can be solved by guessing the answer or by taking more time to determine the correct answer. In the former case, the cost is higher because solving puzzles quickly requires faster computing capabilities. The blocks are analysed and created slowly while they are being created, so the puzzle should not be difficult to solve. The blockchain is regularly updated with new blocks, and a consensus must be reached for computational power to be utilized to solve the analytical puzzle. Computing power and energy are needed to complete this process (Bürer, 2019; Bashir, 2023).

Several alternatives to Blockchain exist, including Proof of Stake (PoS) and Proof of Importance (PoI). As shown in Figure 2, the generation of a new hash value depends on the previous one. Each new block generates a new hash value. A consensus algorithm removes unwanted blocks from the blockchain, serving as a security measure against attacks that manipulate or modify blocks. In fact, an attacker with 50% control of the blocks in a blockchain gains full control over the blockchain (Bashir, 2023).

In summary, Blockchain is a distributed ledger technology that operates on a decentralized network. In order to function, it relies on cryptography and consensus mechanisms. Each block consists of transactions that are linked by hashes, which are unique identifiers. As new blocks are added to the blockchain, consensus mechanisms such as PoW or PoS validate them. Blockchain enhances data security, transparency, and immutability by being decentralized. It enables peer-to-peer transactions without intermediaries, fostering trust and efficiency in various industries.

5.1 Advantages of Implementing decentralized blockchain

The traditional centralized approach to supply chain management comes with many challenges, especially in ensuring the integrity and quality of sensitive goods during shipment. A decentralized supply chain system offers a solution to this problem by allowing individual organizations to decide and manage resources without relying on a centralized authority. Decentralized supply chain management also enables organizations to operate in a more flexible and agile manner, as they have a greater degree of autonomy and can respond quickly to changes in the market (Azzi et al., 2019; Lu, 2019).

Decentralized supply chain management offers greater transparency and traceability, as each of the individual organizations can track products and services throughout their supply chains. This allows for greater accountability, as organizations can view and analyse the data to identify areas for improvement. Furthermore, decentralized systems are often more secure than centralized ones, as they are less vulnerable to malicious actors or data breaches (Azzi et al., 2019; Ding et al., 2021).

Overall, a decentralized network offers organizations a more efficient, secure, and reliable way to manage their resources and ensure the smooth flow of goods and services. By leveraging the power of individual organizations within the supply chain, organizations can ensure that sensitive products maintain their quality and integrity throughout the entire shipment process (Angrish et al., 2018; Azzi et al., 2019).

Transparency and immutability are two of the advantages of blockchain transactions. Once recorded on the blockchain, transactions cannot be altered, and transaction details are available to all participants. Transactions are timestamped, bundled into blocks, and identified with a cryptographic hash. Each transaction includes the receiver's address, data payload, and value (Hopkins, 2021).

Blockchain technology offers several benefits to the process industry. For instance, it provides a clear and detailed record of all transactions and activities, which helps identify bottlenecks, verify authenticity, and ensure compliance with quality standards. Furthermore, it streamlines and automates supply chain processes, eliminating manual paperwork, reducing administrative overhead, and minimizing the need for intermediaries. This results in faster transaction settlements, fewer errors, and improved efficiency (Hopkins, 2021; Bashir, 2023).

Blockchain also enhance data security and integrity by using cryptographic techniques, making it difficult for malicious actors to tamper with or manipulate data. This is particularly important in industries where data security and intellectual property protection are crucial efficiency (Hopkins, 2021; Bashir, 2023).

In addition, blockchain promotes collaboration and interoperability between stakeholders, enabling seamless communication and collaboration between suppliers, manufacturers, distributors, and other participants through a shared infrastructure for data exchange. This makes the industry ecosystem more efficient, reduces redundancy, and improves overall coordination efficiency (Hopkins, 2021; Bashir, 2023).

Blockchain could also enhance trust and compliance in the process industry by providing an auditable record of transactions, which makes it easier to demonstrate compliance with industry regulations and standards. This is particularly important in industries with complex regulatory frameworks efficiency. Blockchain offers innovative business models and tokenization by representing assets, services, or rights using tokens or cryptocurrencies. Process industries can take advantage of this by developing innovative business models and tokenizing assets. For instance, tokenizing energy credits or carbon emissions can facilitate sustainable practices and create new trading avenues efficiency (Hopkins, 2021; Bashir, 2023).

In summary, blockchain technology can revolutionize supply chain management, streamline processes, and drive innovation in the process industry by increasing transparency, efficiency, security, and trust, while also creating new opportunities for collaboration and value creation (Hopkins, 2021; Bashir, 2023).

This can improve the efficiency and scalability of IoT systems, enabling the translation and storage of IoT data, and increasing their interoperability. IoT data can be processed, extracted, compressed, and stored in blockchains to protect the system's privacy and security (Hopkins, 2021).

The ability of a person to manage their personal data without having to rely on third parties is called data empowerment. Maintaining information integrity is crucial to ensuring access and storage reliability by IoT devices. Protocol integrity guarantees the execution of user transactions according to specified protocol requirements. To ensure data integrity, blockchain technology can be a valuable tool when appropriate measures are implemented. In a blockchain system, each block is valid based on its hash value. This depends on the previous block's hash value. This results in an integrity check being applied to both new blocks and previously created blocks. Similarly, blockchain-based IoT systems follow a similar process (Hopkins, 2021; Bashir, 2023).

Integrating IoT systems with blockchain methodologies allows IoT devices to upgrade their firmware and correct insecure functions, further enhancing their security. The blockchain system stores data from IoT systems within blockchain transactions, which are secured using cryptographic public keys. This improves the security of IoT systems (Hopkins, 2021; Bashir, 2023).

IoT data reliability and traceability can be safeguarded to prevent security breaches. The blockchain system allows for data identification and validation from any location at any time. Furthermore, all historical transactions stored in blockchains can be tracked, making it easier to trace the source of data breaches (Abdelgalil et al., 2021; Bashir, 2023).

Blockchains are immutable, making it impossible to modify or falsify transactions. Various security mechanisms, including public key encryption, private key encryption, authentication, consensus, and fault tolerance, have been extensively researched and tested in blockchain. IoT systems using blockchain are thus considered secure and reliable (Abdelgalil et al., 2021; Bashir, 2023).

Blockchain technology facilitates autonomous interactions among IoT systems. The deployment of smart contracts allows for the creation of Distributed Autonomous Corporations (DAC) that can operate independently without human involvement, leading to reduced operational expenses (Bashir, 2023).

5.2 Blockchain and internet of things

Assuring the security and anonymity for billions of Internets of Things transactions and devices daily remains a major challenge to IoT success, despite considerable research efforts in recent years. Although blockchain holds promise for addressing IoT security concerns, extensive research will still need to adapt computation-intensive blockchain algorithms to meet today's strict energy and processing limitations (Casino et al., 2019; Restuccia et al., 2019).

As part of IoT development, blockchain offers several benefits, including maintaining anonymity, enabling a decentralized system that eliminates the need for centralized validation, and addressing performance bottlenecks using consensus algorithms. Furthermore, blockchain provides a non-repudiation policy, ensuring the integrity of data (Restuccia et al., 2019; Hopkins, 2021).

Industrial applications of IoT have gained widespread acceptance, particularly in areas such as automation, diagnostics, and managing industrial automation and supply chain processes. Due to their battery-powered nature, IoT devices have some limitations, such as limited processing power, memory capacity, and data transmission bandwidth. In response to these constraints, new communication protocols have been developed for IoT devices. The majority of IoT protocols utilize multiple data access points based on publish-subscribe models. There are also machines capable of direct communication with one another, which is called machine-to-machine communication. IoT devices face interoperability and security challenges due to their heterogeneous nature and resource constraints. Insufficient updates can leave IoT devices vulnerable to security breaches. Interoperability, privacy, and security are being improved through the implementation of blockchain in IoT applications (Ferreira et al., 2020; Hopkins, 2021; Bashir, 2023).

The blockchain can secure and store IoT device data by converting, processing, extracting, encrypting, and digitally signing data generated by IoT devices. A smart contract or blockchain-based technology enhances the functionality and security of machine-to-machine (M2M) communication by automating tasks and payments between devices without the presence of humans while ensuring complete information traceability and reliability. Blockchain data can be identified and always verified and locations, resulting in a secure and unalterable record of transactions. Blockchain provides the capability of developing auditable and traceable IoT applications since it can be used to store transactions that cannot be altered or forged. An example of this concept in practice can be found in an IoT retail system that uses blockchain technology to ensure product traceability while maintaining quality and authenticity. Due to the immutable nature of the embedded information, product inspection and verification can be conducted at any time without risk of fraud (Haughton et al., 2017; Kshetri, 2018; Ferreira et al., 2020).

As part of the Industrial IoT, IoT devices are connected to industrial machines to improve efficiency. A novel approach to this is the Blockchain Platform of IoT (BPI IoT), which combines industrial IoT with blockchain technology in a peer-to-peer network. Manufacturers can negotiate service terms using smart contracts with customers. IoT devices, such as Arduinos and Raspberry PIs, facilitate the integration of older gadgets with cloud and blockchain networks, allowing machines to transmit data to the cloud and interact with smart contracts via the blockchain network (Li et al., 2020; Asyrofi & Zulfa, 2020).

The integration of Arduinos and Raspberry PIs allows for the control of sensors and actuators, as well as the transmission of data to the SBC (Single-board computer) through the digital and analog inputs and outputs. SBCs contain control drivers for sensors and actuators, and users can monitor device status and configure the SBC through a web interface. The SBC can connect to the blockchain network through its blockchain service, maintaining a blockchain network account and a blockchain wallet. There are three aspects of IoT based on blockchain that can be elaborated. Firstly, an open manufacturing model is if links customers and companies across the entire manufacturing ecosystem. Secondly, a knowledge model is proposed that describes the material and processes of manufacturing, as well as the exchange of information and services. Finally, a manufacturing platform and process based on edge computing and blockchain is suggested (Angrish et al., 2018; Bashir, 2023).

Several new applications related to Industry 4.0 utilize M2M communication, aiming to eliminate repetitive and potentially hazardous tasks that are critical to business operations.
Industry 4.0 integrates disruptive technologies and standards, enabling decentralized control through interconnected intelligent devices in manufacturing and logistics. In the same way that the Internet has had a significant impact on modern society, this foundation of connectivity among machines, systems, and assets will affect the industrial sector as well (Haughton et al., 2017; Ferreira et al., 2020).

IoT industrial activities can be visualized using blockchain technology to promote intelligent production models. Manufacturing companies can automate product migration, safeguard their IP rights, and store data and documents related to IoT systems using this technology. Across a network, blockchains replicate and duplicate digital transactions. Automobile manufacturers, for example, are constructing fully autonomous vehicles using IoT-enabled sensors with the digitization of every enterprise. IoT-enabled blockchain technology will be used by the automotive industry to facilitate the efficient exchange of information. Blockchain technology can be used in IoT applications such as autonomous vehicles, smart parking lots, and traffic control systems (Ferreira et al., 2020; Reddy et al., 2021; Nuttah et al., 2023).

IoT data cannot be shared using the traditional centralized approach because it lacks security requirements. For example, smart home systems can be made more secure by removing centralized network restrictions and ensuring that data extracted from smart devices cannot be altered by centralized systems. Multinational companies operating in several countries often use different payment methods and issue multiple invoices. The task of gathering data can typically take hours or days, but can take weeks or months without a single, user-friendly data collection system. Blockchain technology offers an effective solution to this challenge. It is inevitable that human error, shortages, and additional expenses will disrupt supply chains, which is a driving force behind blockchain's accountability initiative. All trades, agreements, and tracking processes are managed by blockchain, from self-executing procurement contracts to cold chain autonomy (Lu, 2019; Ferreira et al., 2020; Reddy et al., 2021).

Digital twins will be reduced in cost, but blockchain will also be used in a broader range of industries. Blockchains combined with digital twins create a secure, affordable, scalable solution that combines tracking data and digital identification. As a result, organizations would be able to maintain complete privacy while processing massive amounts of data on their own servers (Javaid, 2021; Nuttah et al., 2023).

5.3 Implementation of smart contracts

Incorporating blockchain technology and smart contracts allows for development of decentralized M2M industrial applications. Smart contracts allow machines to communicate autonomously with other machines by establishing pre-agreed-upon contracts. Services like 3D printing are available for on-demand manufacturing (Haughton et al., 2017; Abdelgalil et al., 2021).

Improving machine diagnostic and maintenance capabilities, smart contracts can also enable autonomous state monitoring and self-service, leading to proactive solutions to operational issues, such as maintenance from service providers (Ferreira et al., 2020; Abdelgalil et al., 2021).

Smart contracts facilitate the traceability of machine-to-machine interactions, allowing the tracking of processes and assets as well as providing a complete record of production. The history of M2M interactions can be used to identify defective products through the traceability of the entire production chain. Supply chain managers can, for example, determine the ownership and delivery dates of assets (Haughton et al., 2017; Biswas & Gupta, 2019).

Blockchain-based smart contracts can store information such as the manufacturer, specifications, date of manufacture, expiration date, and maintenance date, reducing or eliminating the need for physical certificates. Authenticity verification enhances security and dependability, and it can reduce the likelihood of forgery during manufacturing processes and in machine interactions (Ferreira et al., 2020).

An example application of smart contracts is subscription services, where consumers can purchase services from multiple manufacturers or machines. Smart contracts allow machines to communicate with each other to carry out manufacturing or service tasks. The use of smart contracts facilitates the evaluation of vendors based on publicly available data such as delivery times and customer ratings. They enable computers to process orders and negotiate automatically. Smart contracts allow machines to access these details, coordinating audits and inventory control activities. Smart contracts can be invoked by IoT-to-machine applications that integrate business rules and sensing with blockchain (Alkhader et al., 2020; Lobachev et al., 2022).

A client Application Programming Interface (API) library provides front-end applications with access to the blockchain. The IoT and blockchain can interact in several ways. Devices and applications can conduct blockchain transactions independently when they possess the key. In the second scenario, an IoT device does not have a blockchain account; it acts as a passive sniffer. It verifies blockchain-generated events created by smart contracts. Another scenario is an IoT device lacks a blockchain wallet; it acts as a passive sniffer. It verifies blockchain-generated events created by smart contracts. The sensor can execute actions, such as turning on a relay, or view transactions on the blockchain, such as checking blockchain addresses. IoT devices and clients must have certain capabilities to enable communication and these front-end approaches (Alkhader et al., 2020; Lobachev et al., 2022).

Web3.js is a JavaScript library developed by the Ethereum Foundation to provide an API for interacting with the Ethereum blockchain. It serves as a crucial tool for developers looking to incorporate Ethereum functionality into their applications. This open-source project is actively maintained and receives contributions from a dedicated community of developers (Ferreira et al., 2020).

To obtain web3.js, developers can conveniently download it from the npm package manager, which is the central repository for JavaScript libraries and frameworks. By executing the npm install command, web3.js can be easily added as a dependency to projects. The official website of the Ethereum Foundation offers comprehensive documentation, guides, and examples for leveraging web3.js, making it an invaluable resource for developers seeking to integrate Ethereum capabilities into their applications (Ferreira et al., 2020).

The web3.js library includes functions for interacting with smart contracts, such as deploy (), call (), and estimateGas(). It is possible to place a smart contract on the blockchain by using deploy (), while a smart contract that has already been deployed can be invoked with call (). Using the estimateGas() function, you can estimate the amount of gas required for a specific transaction. It is also important to note that web3.js has the getTransactionReceipt() function, which enables retrieving the receipt for transactions (Ferreira et al., 2020).

Additionally, the web3.js library contains functions that retrieve information about specific blocks from the blockchain network, as well as functions that retrieve Ethereum account balances from getBalance(). The web3.js library facilitates developers' interaction with the Ethereum blockchain network through a comprehensive set of tools. Developers can use these tools to perform a wide range of operations, including signing transactions, deploying smart contracts, and retrieving blockchain information (Ferreira et al., 2020; Lobachev et al., 2022).

The blockchain can facilitate M2M connectivity. Although most academic literature has emphasized blockchain-based smart contracts to improve communication and address identity challenges. Combining the two enables decentralized machine-to-machine communication (Ferreira et al., 2020; Puthilibai et al., 2022).

5.4 Supply chain management and blockchain

Today's global economy relies heavily on supply chain management (SCM). SCM encompasses the entire goods movement process, from inventory supply to final delivery to consumer. It involves multiple stakeholders, including producers, distributors, and retailers, working collaboratively to ensure the smooth flow of products (Zia et al., 2021; Magogaran et al., 2022).

Traditionally, the SMC system relied on established processes and intermediaries to manage each stage of SC. However, blockchain technology and smart contracts present opportunities to revolutionize this conventional system. Blockchain, due to its decentralized nature, offers a solution to enhance transparency, traceability, and security of supply chains (Zia et al., 2021).

As a result of blockchain technology, self-executing agreements are possible based on predefined conditions. They can help managers track origins and ensure product integrity. By automating processes and providing real-time visibility, smart contracts can streamline operations and reduce manual interventions, leading to increased efficiency and cost savings (Zia et al., 2021).

Recognizing blockchain and smart contracts' potential, researchers have explored their application in supply chain management to address existing challenges. Through discussions and analysis, they have proposed solutions to leverage these technologies effectively and overcome issues related to transparency, traceability, and security (Zia et al., 2021).

By integrating both technologies into the SCM system, organizations can create a framework that enhances trust between stakeholders and enables seamless product tracking (Zia et al., 2021; Magogaran et al., 2022).

6 Blockchain technology: applications across industries

Manufacturing industry benefits from blockchain data security through encryption, preventing unauthorized access to data transferred over public networks. In the realm of intellectual property and Industry 4.0, blockchain can establish copyright and track distribution rights.
Sensors can detect physical parameters such as acceleration, temperature, pressure, moisture, and vibration. Combining, processing, and analysing real-time sensor data generates statistically significant data sets. Sensors are inexpensive and can be easily integrated into existing capital equipment without disrupting operations. However, integrating these devices into existing networks requires careful consideration of the costs of storing and processing the acquired data (Helo et al., 2014; Kurpjuweit et al., 2021). A plant's cyber-physical infrastructure, parts suppliers, and enterprise resource planning (ERP) systems can integrate with blockchain technology to allow machines to order replacement components safely and autonomously (Javaid, 2021).

6.1 Recent Use Cases: Trustchain and Cloudity

TrustChain explores how blockchain can solve accountability and reliability challenges in complex supply chains. Blockchain technology enhances reliability and transparency by enabling tamper-proof auditing of supply chain activity and data. Existing reputation systems that allow users to evaluate each other and build trust cannot be used with blockchain-based supply chains. It’s granularity, automation, and scalability are limited (Jayashri et al., 2023).

TrustChain system addresses these limitations on three levels. TrustChain tracks supply chain actors' interactions via IoT and blockchain. These connections are analyses to determine trust and reputation scores. By distinguishing supply chain actors from goods, TrustChain can assign product-specific reputations to the same parties (Jayashri et al., 2023).

TrustChain is comprised of the following components:

- Based on multiple observations from the supply chain, a reputation model is built that assesses commodities' performance and trustworthiness.
- There are smart contracts that facilitate transparent, impactful, secure, and automated reputation rating calculations.

- A reputation score that differentiates between supply chain members and services, allowing a more holistic view of supply chain reputation.

TrustChain integrates these components to provide a robust and scalable reputation management solution. TrustChain contributes to the advancement of blockchain technology by addressing the challenge of information reliability. TrustChain will provide insights on how reputation systems can be implemented in blockchain-based supply chains. As well as practical solutions for increasing trust and accountability (Jayashri et al., 2023).

The TrustChain system is organized into three layers (see Figure 3):
A database layer, a blockchain layer, and a software layer. Figure 1 shows a system architecture The database layer collects supply chain data from business-to-business transactions, sensor networks, and regulatory forms. Information is stored here, and transactions are transmitted to the Blockchain layer. The application layer can also maintain a dataset of the gathered information (Jayashri et al., 2023).

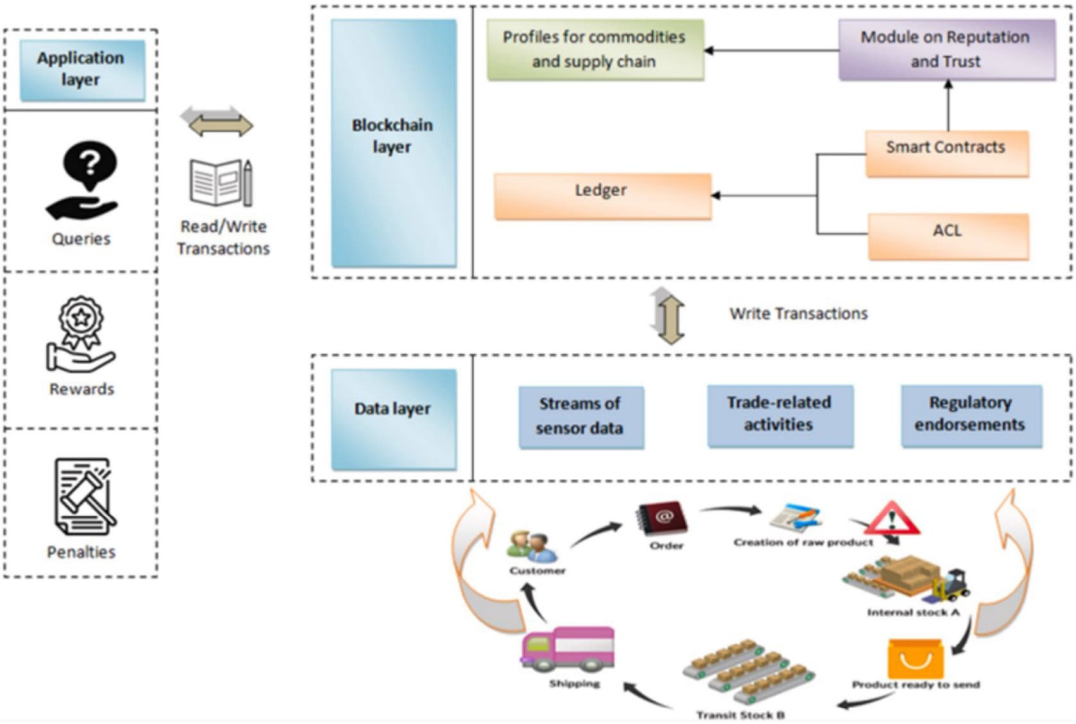


Figure 3. Illustration of Trustchain system architecture (Jayashri et al., 2023).

The Blockchain layer facilitates the recording of transactions in the general ledger, which are governed by an Access Control List. Permissions are determined by access policies for reading and writing ledger data. Transactions leverage reputation and trust mechanisms to provide reputation scores, trust levels, and product quality assessments. Smart contracts can warn under specific conditions. Within the Blockchain layer, the digital identities of stakeholders in the supply chain are stored, including their reputation and trust values. The application layer interacts with the blockchain layer to access this information. Authorities and regulators can retrieve reliability and quality ratings for various products and services. End users can also access product quality based on aggregated scores. These scores can inform reward programs for high performing organizations or penalize low-scoring entities (Jayashri et al., 2023).

Blockchain-as-a-service platforms oversee organizations and blockchain networks. Business Network Managers design business networks and control the blockchain layer. TrustChain opted for Hyperledger Fabric as its deployment platform due to its exceptional capabilities in handling business applications. Additionally, Hyperledger Fabric offers utility tools for deployment, maintenance, querying, smart contract creation, and collaboration (Jayashri et al., 2023).

Manufacturers and consumers are expected to have IoT sensors to monitor factors like temperature, location, and moisture throughout the supply chain. These sensors provide valuable data to assess the quality and safety of food products. This is particularly important when they are stored within the required temperature ranges. To illustrate, the researchers examined temperature readings. This highlights the significance of maintaining appropriate temperatures from production to retail. The TrustChain framework incorporates a reputation system that evaluates both assets and participants to increase the efficiency of the system. This system assigns different reputations to individuals involved in different products. Smart contracts enable digitalization and optimization, further streamlining processes. Furthermore, the researchers conducted a qualitative security assessment to identify potential vulnerabilities in the reputation management system when combined with IoT technology (Jayashri et al., 2023).

The research team found TrustChain's overhead costs to be negligible during a proof-of-concept application. The overall system efficiency is not significantly affected by TrustChain implementation (Jayashri et al., 2023).

CLOUDITY system offers a cloud-based solution for supply chain management by incorporating the SELAT architecture and Blockchain system. The aim is to enhance the security and efficiency of information exchange between companies and manufacturers in the supply chain network. Traditional approaches using Excel sheets are prone to errors and lack automation, necessitating a more reliable and automated solution (Asyrofi & Zulfa, 2020).

Hosting applications on local or company servers may not be ideal due to technical constraints, scalability issues, and vendor lock-in. To overcome these challenges, cloud service providers (CSP) offer preconfigured services, but this approach can be costly and resource fragmentation may pose challenges. The CLOUDITY system (Figure 4) addresses these issues by utilizing the SELAT system as a broker between users and CSPs, selecting the most suitable providers based on user requirements (Asyrofi & Zulfa, 2020).

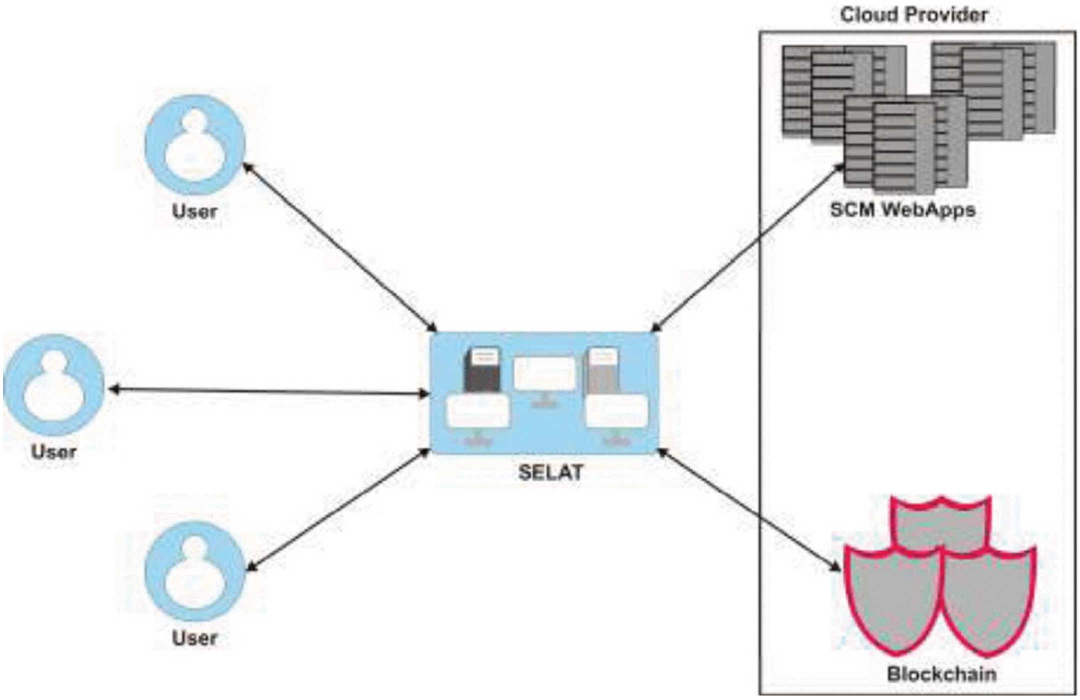


Figure 4. The CLOUDITY system architecture is designed to provide a secure and efficient solution for supply chain management.

The existing SCM system relies on centralized databases, which have limitations in terms of failure tolerance, vulnerability to unauthorized modifications, and scalability. In contrast, the CLOUDITY system employs Blockchain technology to enhance data security and integrity. By leveraging decentralized data verification and a peer-to-peer network, CLOUDITY ensures transactional integrity and secure information exchange. The system also addresses various aspects such as resource provisioning, service selection, authentication, security, and access control, enhancing efficiency and security (Asyrofi & Zulfa, 2020).

As shown in the diagram, CLOUDITY contains four main elements: the SCM system, the SELAT system, the Blockchain system, and multiple CSPs. The SELAT system acts as an intermediary, connecting users with CSPs and recommending suitable providers based on user requirements. The Blockchain system verifies data on each server before presenting it to the user, significantly enhancing data security and protection against unauthorized modifications (Asyrofi & Zulfa, 2020).

While the Blockchain system enhances security, it may introduce processing time delays due to the verification process. Research could be conducted on the application of Blockchain in other web applications, considering the trade-off between security and performance. Optimization efforts can focus on balancing data integrity and system efficiency, particularly in retrieving stored data from the server (Asyrofi & Zulfa, 2020).

Overall, the CLOUDITY system presents a promising solution for secure and efficient supply chain management, leveraging cloud-based technologies and blockchain principles to enhance data security and automate processes (Asyrofi & Zulfa, 2020).

6.2 Preserving and collecting data through blockchain

In the field of robotics, ensuring the integrity and security of collected information is crucial, and this is where data protection comes in. Aerial drones, for instance, use sensors and cameras to gather data on soil moisture and composition. To preserve the data and prevent the drone's battery from draining, the collected information is transmitted to a blockchain network. Each piece of data stored in the blockchain is assigned a unique identification number, and an electronic receipt is generated for record-keeping purposes. In addition, a hash value is generated by the command system to identify the source of data that has already been collected on the blockchain (Yu et al., 2020; Bashir, 2023).

Transactions on the blockchain network involve adding a new record to a block, and all operations must be recorded to identify any vulnerabilities. Each node in the network is aware of the other blocks, ensuring data protection for all information. The drone-chain system's architecture comprises four key components: the drone, cloud database, blockchain network, and cloud server. Figure 5 provides an illustration of this architecture (Asyrofi & Zulfa, 2020; Bashir, 2023).

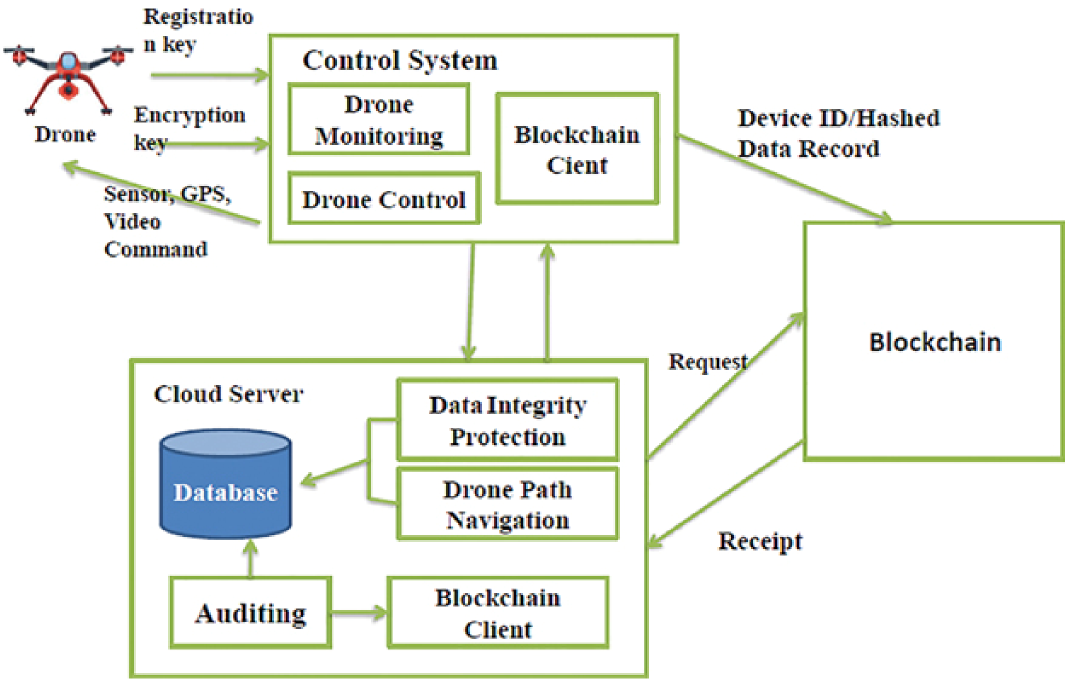


Figure 5. The integration of a drone system and blockchain (Bashir, 2023).

Cloud databases are used to store data collected from drones and instructions from control systems, as well as access information. Access control mechanisms, such as fingerprints, are often implemented to ensure data confidentiality. In addition, the cloud server performs a similar function to the blockchain network in terms of data protection (Li et al., 2018; Bashir, 2023).

Blockchain technology can facilitate data storage and transfer from sensors to analysis devices, minimizing the risk of data breaches. A decentralized network protects the data integrity of the transferred data. However, using a private network still presents a slight risk when it comes to data transfer. Alternative approaches include using cloud computing, which is cost-effective and offers a variety of payment options. Although, since data is shared on a network, cloud storage can also pose a vulnerability. The most effective way to mitigate this risk is to implement a robust and secure data storage and sharing system (Smith, 2004; Asyrofi & Zulfa, 2020; Javaid, 2021).

Blockchain technology can help resolve quality issues by allowing the identification and quantification of products and assemblies. An integrated blockchain platform can provide detailed information about a product's subassemblies, components, and delivery instructions. In current systems, reminders can cause significant disruptions and costs, so this technology can collect data at each stage. Assembling items and managing inventory is an efficient method. Therefore, the blockchain could impact on various industries (Bapatla et al., 2022; Lobachev et al., 2022).

Financial services are a major application of in the sector. Financial assets can be managed using blockchains. Blockchain technology can also resolve issues related to foreign currency and regulate supply transactions. Blockchain technology is currently gaining traction in various industries, led by the banking and payments industry (Biswas & Gupta, 2019; Yang, 2021).

The growth of artificial intelligence and blockchain technology is based on data-driven connections. With this connection, banks and insurance companies are moving away from traditional methods. One or more blockchain blocks could streamline transactions, enhance security and transparency, and optimize data management for these organizations. However, as these technologies are still in their developmental stages, their deployment at a critical level has not yet been explored due to their nascent state (Javaid, 2021; Yang, 2021).

As we enter the second phase of the fourth industrial revolution, AI and blockchain will benefit each other even more. For example, using machine learning and algorithms can provide faster and better customer service (Casino et al., 2019; Javaid, 2021).

6.3 Enhancing chemical monitoring with blockchain technology - Nasiri Ltd.

Nasiri Ltd. is a versatile service provider offering comprehensive solutions to the oil and gas, marine and shipbuilding, and energy industries. With a focus on procurement, process design, and automation, the company delivers innovative services tailored to the specific needs of each sector. From supporting exploration and extraction in the oil and gas sector to providing functional design for marine and shipbuilding projects, Nasiri Ltd. is dedicated to delivering efficient solutions. The company also specializes in utilizing chemical fuels and power boilers for sustainable energy generation. With industry-specific expertise, Nasiri Ltd. aims to exceed client expectations and contribute to the growth and success of these vital industries.

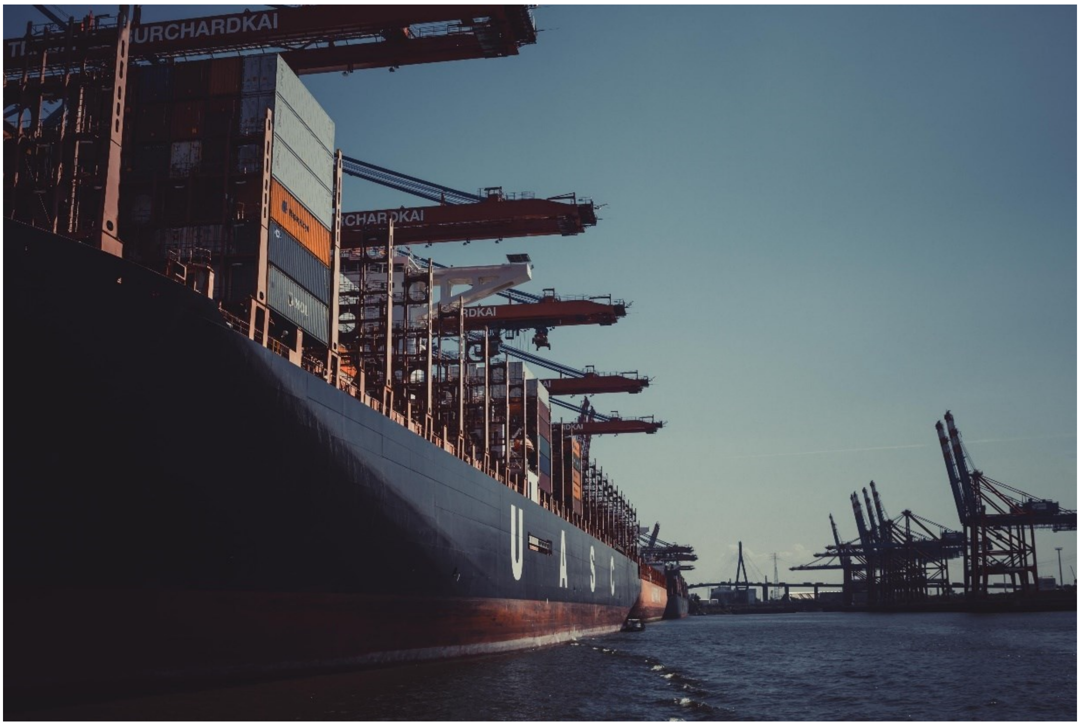


Figure 6. A cargo ship rests in the bustling harbour.

In an interview, Babak Nasiri 's response highlights the potential applications and benefits of integrating blockchain technology into chemical monitoring processes: “The use of blockchain offers a transformative solution, ensuring accurate and reliable reporting of chemical components. By leveraging blockchain's immutability, decentralization, and transparency, it addresses challenges related to monitoring and reporting by-products. Chemical monitoring systems can benefit from Blockchain due to its data integrity, traceability, and accountability capabilities.

Blockchain enables effective management of chemical monitoring processes, particularly in scenarios like fuel switching on cargo ships based on location. Fuel types, quantities, and emissions can be securely recorded on a blockchain, allowing regulation compliance to be verified and data manipulation to be avoided. Smart contracts enable the collection and validation of real-time data, ensuring transparency and identifying noncompliance issues in a timely manner.

Blockchain technology revolutionizes chemical monitoring, providing a secure and transparent platform for recording and verifying data accurately. It provides officials and monitoring organizations with the tools to manage processes effectively, ensuring compliance and environmental sustainability. The Blockchain effectively addresses challenges related to data manipulation and trustworthiness in chemical monitoring, establishing a robust and accountable system. As a result, chemical monitoring can achieve increased accuracy, transparency, and collaboration among stakeholders, enhancing environmental sustainability and regulatory compliance."

7 The challenges of blockchain technology

Blockchain technology is still a relatively new and evolving technology. Therefore, it is important to examine the current challenges in the chemical process industry. There are several challenges to consider, including scalability, energy consumption, data privacy, regulatory and compliance complications, integration challenges, lack of standardization, and cost implications. Organizations in the process industry can maximize the value of blockchain technology by evaluating its drawbacks alongside its potential benefits (Bürer, 2019, Restuccia et al., 2019).

Blockchain networks face challenges with scalability in the process industry due to high transaction volumes that can cause delays and slow processing times. Energy consumption is also high, which can interfere with efforts to reduce energy use and environmental impact. While blockchain technology offers benefits, its energy-intensive nature must be balanced against them. Privacy concerns may arise due to blockchain's immutability and transparency, requiring innovative approaches to balance the need for privacy and transparency (Bürer, 2019, Restuccia et al., 2019).

Integrating blockchain technology into the process industry's complex regulatory framework poses additional challenges. Organizations must navigate these complexities while adhering to industry-specific regulations and data protection laws. The industry's heavy reliance on legacy systems may also make it challenging and time-consuming to integrate blockchain technology into existing processes and systems, requiring significant investments and efforts to achieve seamless integration (Bürer, 2019, Restuccia et al., 2019).
The lack of standard protocols and frameworks across different blockchain platforms hinders efficient interaction and collaboration among stakeholders in the process industry. Organizations must address this challenge to foster effective communication and data exchange (Bürer, 2019, Restuccia et al., 2019).
Implementing blockchain networks can be expensive due to the costs of developing and maintaining infrastructure, which may be more than any potential benefits for some industries. It's important to do a thorough cost-benefit analysis to make sure the advantages of blockchain outweigh the financial burdens of implementing it (Bürer, 2019, Restuccia et al., 2019).

Integrated blockchains in supply chains face a variety of challenges before they can be considered successful. The following are some of these challenges:

- Blockchain Selection: Choosing the most suitable blockchain for the supply chain ecosystem requires considering factors such as throughput, latency, capacity, and scalability. It is important to evaluate different blockchain implementations and select the one that aligns with the specific requirements of the supply chain.
- Dual Storage Architecture: Handling large volumes of data in a blockchain-based supply chain requires an efficient storage architecture. Implementing a dual storage approach, where an additional private blockchain or off-chain storage is used, can help manage and optimize data storage without affecting the performance of the blockchain.
- Tracking Device Selection: Selecting appropriate tracking devices is crucial for accurate data collection and monitoring within the supply chain. The choice of tracking devices should align with the specific product criteria that need to be tracked, ensuring compatibility and reliability.
- Communication Protocol: The communication protocol used within the supply chain ecosystem should meet the required speed, data rate, communication range, power consumption, and cost considerations. It is essential to select a protocol that enables seamless and secure data transfer between the blockchain and tracking devices.
- Security Considerations: Maintaining the security of the supply chain system is paramount. Addressing security vulnerabilities in the communication protocol is essential to establish a secure and reliable traceability system. This includes implementing authentication mechanisms for tracking devices and employing encryption and digital signatures to protect data integrity.

By addressing these challenges, organizations can successfully integrate blockchain into their supply chain operations, leveraging its benefits while ensuring the reliability, transparency, and security (Azzi et al., 2019; Casino et al., 2019).

8 Future growth of blockchain

Blockchain facilitates seamless data exchange between supply chain participants. By harnessing these advantages, businesses can elevate their operations to unprecedented levels of success (Esmaeilian et al., 2020; Bellini, 2022).
The complexity of the supply chain industry makes risk management increasingly important. The smooth flow of information is crucial in connecting logistics and capital flows within supply chain operations. With a growing number of supply chain partners, increasing transaction volumes, and diverse cooperative relationships, companies are faced with an ever-expanding volume of data to manage and process. Effective information flow management is imperative to ensure accuracy, efficiency, and security in the supply chain. Failure to manage information flow effectively can result in misleading decisions by managers (Zhao & Li, 2022).

To fully realize the potential of blockchain technology, manufacturers must adopt a progressive mindset and develop versatile strategies. The immutability and security of blockchains can create a secure and reliable workflow, and smart contracts can simplify transactions and reduce costs. Manufacturers should also consider how blockchain technology can increase efficiency and accuracy in scenarios involving a variety of transactions. By embracing these innovative approaches, manufacturers can stay ahead of their competitors in the blockchain era (Zhao & Li, 2022).

Blockchain technology is being explored by the public sector for the purpose of creating a registry of citizens' buildings, homes, and vehicles. Besides reducing fraud, blockchain technology can improve back-end operations such as purchasing. Blockchain technology has the potential to revolutionize corporate transactions, data management, and decision-making. In industrial settings, where parts and systems must be monitored, it is crucial to trace the activities and operations of any business. By combining commercial logic with IoT sensor data, blockchain can optimize end-to-end supply chain and minimize fraud risks (Bellini, 2022).

Blockchain technology can improve supply chain security and transparency. By mapping and tracing the origin and authenticity of products, companies can facilitate recalls and speed up the movement of goods. This data becomes valuable for modern industrial process management since it facilitates coordination between factories and provides tracking and traceability mechanisms. All stakeholders benefit from this consensus-based system, as external certifying agents are not required, and customers can trust each other (Zhao & Li, 202).

Blockchain technology can help organizations strengthen their digital infrastructure and protect their data through Industry 4.0. This can be achieved by using data-safety hash algorithms and encryption schemes, along with a reliable supply chain foundation. Additionally, blockchain can be used for M2M and human-to-machine authentication, device lifecycle management, and access control protocols. Blockchain technology can also facilitate accurate recalls of products and services, implement new methods of loyalty management, and improve supply chain efficiency and transparency (Fu & Zhu, 2019; Lim et al., 2021; Kang et al., 2023).

In addition to facilitating secure collaboration between partners, blockchain eliminates repetitive tasks and optimizes processes across various industries. It also enables the verification of asset ownership, diminishes counterfeiting, and permits free market contracting. Blockchain networks can enhance supply chain management by allowing components to be tracked comprehensively and facilitating payments. By codifying market agreements between supply chain members, it can also augment automation, reducing human involvement. A globally competitive market demands organizations adopt an agile strategy and consider integrating AI for a range of scenarios, including predictive maintenance and assembly line optimization (Kumar & Tripathi, 2019; Javaid, 2021; Lim et al, 2021).

Using blockchain technology to create a level playing field can enable smaller companies to compete with larger ones. Its transformation may also foster autonomy and inclusivity. Blockchain technology is fundamentally characterized by its ability to spread immutable, verifiable information within a decentralized network. However, developers must address data storage and privacy issues as technology advances and its applications extend beyond cryptocurrencies. Additionally, integrating blockchain technology with legacy systems, particularly within complex supply chain networks, may pose challenges (Javaid, 2021; Fu & Zhu, 2019).

One of the key characteristics of Industry 4.0 is the advancement of intelligent ecosystems, which give rise to smart products, smart machines, and augmented operators. Smart machines enable autonomous and self-optimized processes, fostering the development of self-organizing production systems. Likewise, smart products exhibit self-awareness and the ability to interact individually with other entities within the system. The concept of augmented operators, also known as Operator 4.0, is introduced to address the growing diversity of systems and their unique requirements, which in turn leads to new forms of human-machine collaboration and alters the industrial workforce. By adapting to these changes, smart environments can automatically identify risks or exceptions and continually adjust supply chain parameters (Abadi & Khalaj, 2022; Tavana et al., 2023).

Industry 4.0 enables rapid and adaptable responses to supply chain changes. This integration is achieved through Cyber-Physical Systems (CPS), which promote transparency and interoperability across different system levels. CPS integration can occur horizontally, vertically, and end-to-end (E2E). Vertical integration involves incorporating diverse technologies throughout an organization, from equipment to enterprise planning. Horizontal integration encompasses the integration of the entire value chain, including resources, processes, and information exchange, enabling autonomous CPSs to trigger actions. Across the value chain, E2E integration aims to reduce operational costs and bridge the gap between product design and customer delivery (Yu et al., 2020; Abadi & Khalaj, 2022).

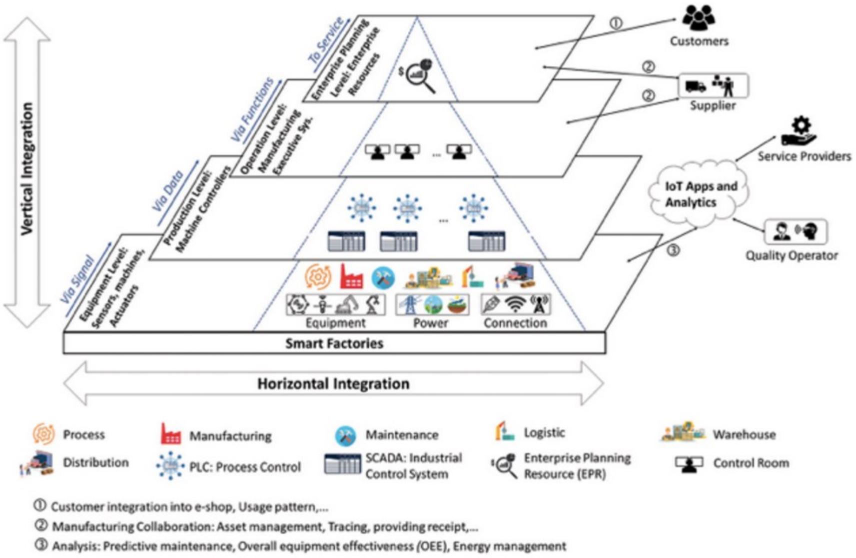


Figure 7. The integration of the entire value chain of a smart factory (Abadi & Khalaj, 2022).

Industry 4.0 is fuelled by integrated technologies, smart equipment, and autonomous robots, all of which increase supply chain efficiency. The collaboration of various digital technologies adds value to the supply chain, as no single technology can comprehensively impact it. Visual computing technologies play a crucial role in improving efficiency by providing cohesion between different technologies. Network configurations are continuously monitored to ensure alignment with business requirements (Zhang et al, 2019).

In addition to improving product quality throughout the entire value chain, Industry 4.0 facilitates stakeholder collaboration, and introduces advanced operations that enhance supply chain efficiency (Abadi & Khalaj, 2022; Fu and Zhu, 2019).

Blockchain technology offers valuable applications in risk management for large-scale production enterprises. In addition to exploring the structure of a blockchain supply chain system, the study will examine the operation of smart contracts under consensus authentication, conduct case studies, and design mechanisms for data storage and access. Efficiencies and data privacy are enhanced by the data storage mechanism, while supply chain data management and application efficiency are improved by the data access mechanism. By leveraging blockchain technology in these areas, enterprises can enhance their supply chain operations and mitigate risks effectively. A blockchain network includes retailers, customers, upstream suppliers and downstream distributors. This integration ensures that traditional supply chains are less fragmented and disjointed, ensuring their integrity and agility. The supply network chain relies on an industrial private network or the Internet for construction, with only relevant business entities authorized to join the blockchain network to prevent interference from unrelated users and minimize the risk of fraudulent supply chain information. Regulatory mechanisms and competitive environments drive each business entity's incentive for accurate information and active monitoring of network. (Fu & Zhu, 2019; Zhang et al, 2019).

Fu and Zhu (2019) study authors propose a blockchain-based solution to address these risks. By considering principles and previous research on blockchain in academia and industry, this paper focuses on large production enterprises. It presents a system structure, a mechanism for operating smart contracts, a case analysis, a mechanism for storing data, and a mechanism for accessing data related to managing endogenous risks through blockchain technology.

The analysis demonstrates the practicality and feasibility of implementing blockchain technology to manage endogenous risks within these supply chains. Besides contributing to the ongoing development and application of blockchain, this research provides practical solutions for mitigating supply chain risks without disrupting existing operational methods (Fu and Zhu, 2019).

In a blockchain-based supply chain, each business's data forms a block, and blocks containing the same type of business data are stored by corresponding business subjects. Data authenticity and integrity are ensured by the subsequent blocks in the blockchain, which include all previous blocks' hash function values. In blockchain storage, supply chains run parallel from different production enterprises and are correlated by hash function pointers to form a cohesive whole. Figure 8 provides valuable guidance for storing business data in complex supply chains despite being a simplified illustration. Supply chain structures of different production enterprises will vary over time, as will the capacity of blockchain data. Supply chain data storage is illustrated in Figure 8 (Fu and Zhu, 2019).

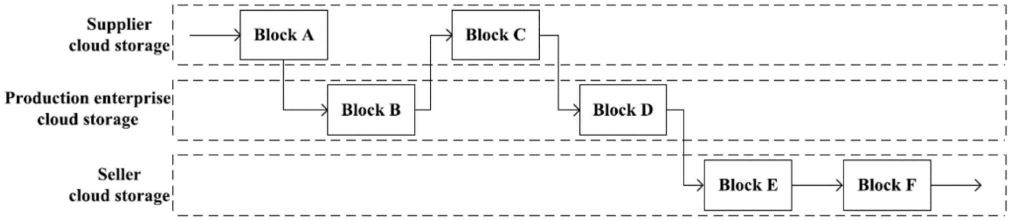


Figure 8. This diagram represents how the blockchain organizes and stores the business data within the supply chain (Fu & Zhu, 2019).

A blockchain system allows for data interaction among various supply chain business subjects through hash function pointers, creating a cohesive whole. There is no correlation between the supply chains of different production organizations in traditional information systems (Fu & Zhu, 2019).

With blockchain's proof mechanism, supply chain information "incompleteness" can be effectively addressed. To resolve this issue, relevant business data must be obtained from other parties. Accessing this data depends, however, on how efficiently it can be retrieved from the blockchain. To improve access efficiency, the researchers propose giving supply chain authentication subjects full control over blockchain data. The blockchain system requires permission for general users to access data within the authorized scope. Access can be restricted to specific blocks or keywords. Through hash function pointers, blockchain enables authorized users to traverse blocks quickly.

For each block in the blockchain, an information content structure can be constructed to improve access efficiency. Business categories and substances are used to organize block information content. As new blocks are added, their information content is copied and appended to the previous block. Access users can establish virtual connections based on retrieval requirements starting from the most recent block. Through these virtual connections, access users can retrieve information efficiently and accurately. The order of virtual connections contradicts the chronological order of the production of blockchains (Fu & Zhu, 2019).

A blockchain-based supply chain for large production enterprises, which aims to maintain overall supply chain efficiency, is illustrated in Figure 9. A supply chain authentication centre (CA) verifies the authenticity of supply chain data from suppliers, large production enterprises, and sellers (distributors and retailers). Since customers are more random and unstable, they are not considered authentication centres in this study. However, blockchain still enables customers to access and share all business data.

All business entities can access and share supply chain data through blockchain, reducing risks associated with information asymmetry and incompleteness. This enhances the resilience of supply chain information and improves operational efficiency and responsiveness (Fu & Zhu, 2019).

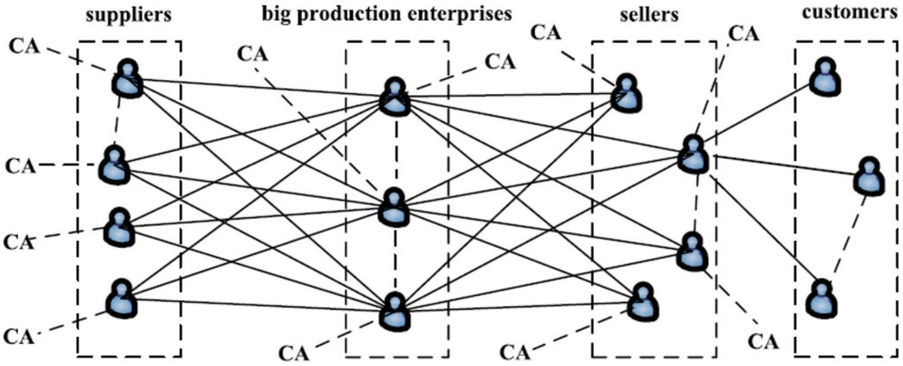


Figure 9. Supply chain data is verified by an authentication centre (CA) Fu & Zhu, 2019).

The demand subject broadcasts the business section's information across the blockchain, and authentication subjects verify its authenticity after receiving it. Respond and re-authenticate until the authentication subject confirms the authenticity of the information. Authentication subjects analyze demand information according to the requirements and characteristics of each supply chain section, and formulate an analysis procedure, shared within the network. Therefore, the authentication subjects perform distributed accounting for the analysis (Fu & Zhu, 2019).

The authentication subjects then vote by ballot according to the analysis results. An analysis result with a low support rate is vetoed, and an analysis result with a high support rate is voted on in the next round. The process continues until the most supported analysis result is obtained. Supply chain ensures rationality of demand information by averaging the voting results and vetoing the results with low support rates. This smart contract operation mechanism enhances trust and reliability in the supply chain by including multiple authentication subjects in the analysis and decision-making process (Fu & Zhu, 2019).

The smart contract operation mechanism for consensus authentication follows a specific process. First, the authentication subjects authenticate and analyse the demand information. Then, a voting process determines the optimal analysis result and optimal responder.

During this process, demand information is broadcast across the network and authenticated by authentication subjects. Each authentication subject proposes a method and result, which is then broadcast across the network. The demand information is stored and accounted for by the authentication subjects. The information responders provide the requested information, and the authentication subjects authenticate their authenticity as usual (Lee et al, 2021).

The optimal responder for supply chain authentication is determined by ballot. First, low support rate respondents are vetoed, and then high support rate respondents are voted on. This voting process continues until the optimal responder is identified. Once identified, they cooperate with the demand information producer and broadcast their cooperation. The cooperation information is distributed accounted for and stored by the authentication subjects. This process, consensus authentication, rationality analysis, and optimal cooperation are ensured in the supply chain using blockchain technology (Lee et al, 2021).

9 Discussion

As industries transform their operations and businesses with blockchain. The benefits of this technology become more apparent. Smart tools and innovative solutions, including the IoT, robotics, AI, cybersecurity, 3D printing, cloud databases, augmented reality and virtual reality. The immutability and security of blockchains can create a secure and reliable workflow, and smart contracts can simplify transactions and reduce costs.

One of the main challenges is scalability. Additionally, integrating blockchain technology with legacy systems, particularly within complex supply chain networks, may pose challenges (Lohmer & Lasch, 2020; Javaid, 2021).

Despite these challenges, businesses that adopt a progressive mindset and develop and implement versatile strategies can stay ahead of their competitors by leveraging blockchain technology. By embracing these innovative approaches, manufacturers can optimize end-to-end supply chain management, improve back-end operations, and enhance overall supply chain efficiency and transparency (Bellini, 2022).

In conclusion, blockchain technology has already proven to be a crucial innovation for the advancement of secure and dependable IoT systems. Its ability to create an immutable ledger of all transactions, facilitate secure and efficient data sharing, and provide a reliable source of transactional data are just a few of the many advantages that make it an ideal technology for Industry 4.0. Incorporating blockchain technology, industries can achieve new heights, stay ahead of their competitors, and transform how they operate and do business.

10 Experiment

The experimental part of this Diploma thesis focuses on conducting a pilot study in the laboratory of Aalto University to explore the creation of a digital twin for a heat exchanger process (Figure 10) and its connection to the cloud. During the experimental phase, a specific testing method is followed. This study examines how blockchain could be applied to the chemical industry. In the context of process digitization and digital twin projects, these experimental results can provide valuable insights for research and practice.

Figure 10. Heat exchanger system (Kortela, 2019a).

The use of blockchain technology has many applications across many industries. Through blockchain, businesses can track products, manage inventory more efficiently, ensure secure information transfers, establish copyright protection, manage contracts, and improve overall efficiency. The integration of real-time sensor data and digital twin technology further enhances the monitoring and optimization of physical parameters, contributing to improved manufacturing processes and product quality.

A digital twin of a heat exchanger process is created in a laboratory setting to explore these possibilities. Real-time process data will be collected by connecting the heat exchanger to the cloud. By comparing the data collected from the physical heat exchanger with its digital twin, valuable insights can be gained into the effectiveness and accuracy of the digital twin model. Furthermore, this research presents an opportunity to test the functionality of blockchain technology in managing and securing the data generated by the digital twin. Conducting experiments will allow for a comprehensive assessment of how blockchain can effectively handle and protect the data associated with the digital twin. This aspect, which was not explored in the current study, holds potential for further investigation and can contribute valuable insights to the field.

10.1 Objective

This experiment is designed to develop a digital twin of a heat exchanger and connect it to a cloud platform. The digital twin model will be compared to the physical exchanger in real time. Additionally, the experiment will estimate the functionality of blockchain in securing the data generated by the digital twin.

The research questions guiding this experimental study are twofold: Firstly, how can blockchain technology be experimented within the chemical engineering industry, specifically in the context of digital twins? And secondly, how can real-time sensor data be analysed to effectively monitor different physical parameters through the utilization of a digital twin?

This experimental investigation holds great significance, as it aims to bridge the gap between theoretical understanding and practical implementation. The insights gained from this study will advance the understanding of digital twins and blockchain applications in the chemical industry. Furthermore, the experimental findings may provide valuable inputs for organizations looking to advance their digitalization efforts and embrace the concept of digital twins within their industrial processes.

10.2 Experimental Design

In this diploma thesis, blockchain was explored in the chemical industry by creating a digital twin of a heat exchanger. For the pilot study to be successful, various components and methodologies must be incorporated.

> Experiment Components:
> The experiment comprises several key components, including a digital twin, a heat exchanger, 3D modelling of the helical coil, and predictive process control in the cloud. Each component has a role in investigating the potential of technologies in the experimental phase. The following outlines the details of each component.
>
> Digital Twin:
> Virtual replicas or simulations serve as digital twins of physical heat exchangers. It mimics the behaviour, characteristics, and performance of the actual process. The digital twin is created by integrating various technologies such as sensor data, mathematical models, and simulation algorithms. It enables real-time monitoring, analysis, and optimization of the heat exchanger process.
>
> Heat Exchanger:
> The heat exchanger is a physical apparatus used in the experiment. It is designed to facilitate the exchange of heat between two fluids or substances. Data from the physical heat exchanger is used to validate and compare the digital twin's behaviour and predictions.
>
> 3D Modelling of the Helical Coil:
> The helical coil is an essential component within the heat exchanger system. It is responsible for facilitating efficient heat transfer between the fluids. In the experiment, 3D modelling techniques are employed to create a detailed representation of the helical coil structure. The 3D model provides valuable insights into the geometric properties and flow characteristics of the coil, aiding in the analysis and optimization of the heat exchanger process.
>
> Predictive Process Control in the Cloud:
> The experiment involves implementing predictive process control techniques in the cloud environment. Predictive process control utilizes historical and real-time data to predict future process behaviour and optimize system performance. By leveraging cloud computing resources, advanced algorithms, and machine learning techniques, predictive process control can enhance operational efficiency, energy utilization, and overall process optimization.

> Integration and Interactions:
> The components of the experiment are interconnected to form a comprehensive system. The physical heat exchanger generates data, which is then used to validate and refine the digital twin. Helical coil 3D models provide insights into geometric properties and flow dynamics, contributing to the accuracy of the digital twin. Predictive process control algorithms in the cloud analyse the data from the physical heat exchanger and its digital twin, providing real-time predictions and optimization recommendations.

Overall, the experiment's objective is to explore the capabilities and potential benefits of digital twin technology, 3D modelling of the helical coil, and predictive process control in the cloud environment. By integrating these components, the experiment aims to advance the understanding of these technologies and their applicability in optimizing heat exchanger processes and related industrial applications.

10.3 Experimental setup

The experimental setup will consist of the following components:
a. Heat Exchanger: A physical heat exchanger system will be used as the basis for the digital twin creation.
b. Model Predictive Control Architecture: The experiment will employ a model predictive control architecture, comprising a process plant, an edge device, and a cloud platform. This architecture will facilitate data collection, communication, and visualization.
c. Edge Device: An edge device will be utilized to interface between the physical heat exchanger and the cloud platform. It will gather data from the heat exchanger and transmit it to the cloud for further analysis.
d. Cloud Platform: Cloud platforms store, process, and analyse data. Real-time monitoring of the heat exchanger will be possible through the platform, along with comparing the physical process to its digital counterpart.
e. Blockchain Integration: As part of the experiment, blockchain technology will be examined with the digital twin and evaluated for its potential benefits in data management and security.

The experimental setup will consist of a model predictive control architecture, comprising a heat exchanger process plant, an edge device, and a cloud platform. The cloud system will employ a Java application to read water level measurements and control pumps, utilizing NodeJS and the JSON protocol for communication. The user interface will be displayed in a web browser, providing continuous updates on pump and water level values. Using ABB Control Builder, a PM856A PLC and its cards will be employed, with relevant variables connected and uploaded to the PLC. The existing three-tank system will be replaced with a model specifically designed for this experiment.

MPC Architecture Setup:
The process plant is configured to include the necessary hardware components for the MPC architecture (Figure 11). The ABB PM856A PLC is integrated into the system, and the appropriate cards defined in ABB Control Builder are connected to the relevant variables. The cloud system, implemented with a Java application, is set up to communicate with the edge device and receive water level measurements and control signals.

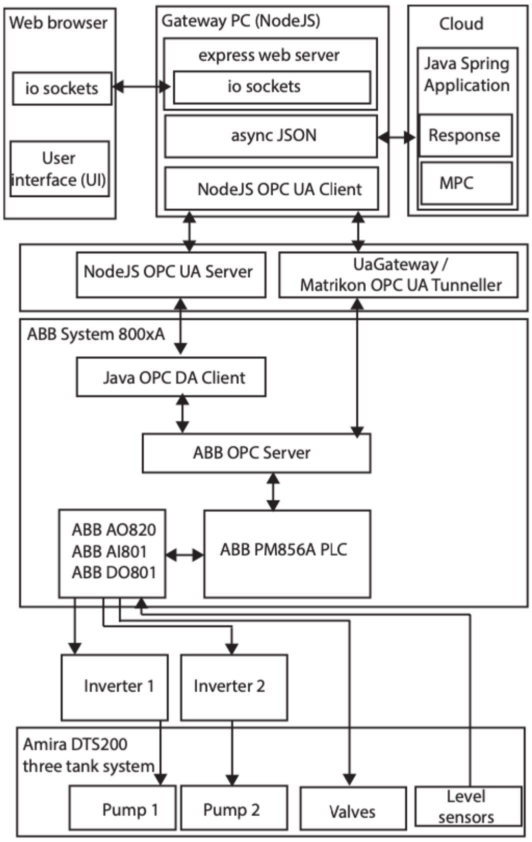
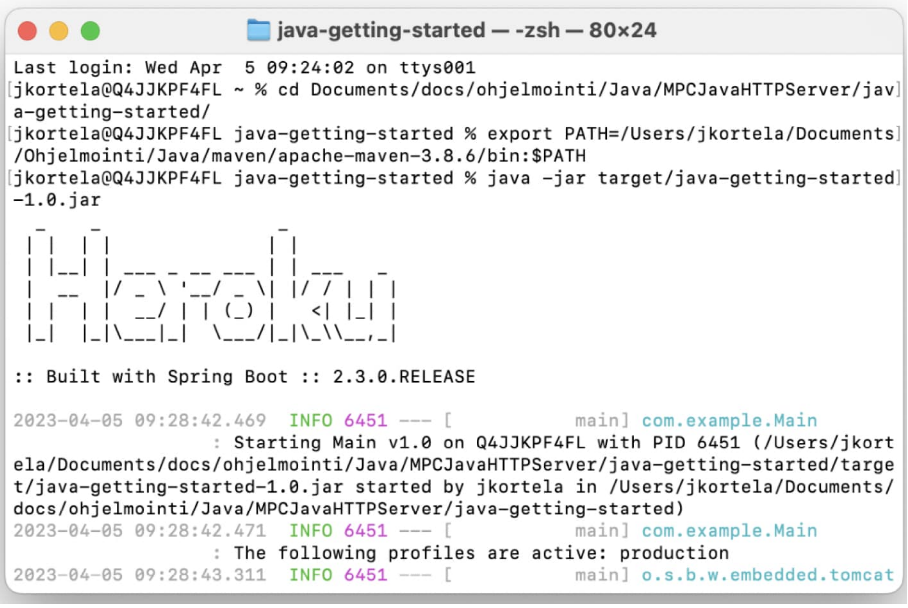


Figure 11. The architecture of the model predictive control in the cloud (Kortela & Tadesse, 2022c).

Heat exchanger system was controlled by ABB's 800xA DCS system, which comprised an OPC server, controller (AC 800M), and I/O modules. The input signals for the system were the pump flow rates from GA-101 and GA-102, while the output variables were the liquid levels in tanks FA-100 and FA-200. A control user interface was created using ABB's Graphics Builder, which included graphical elements representing pumps, tanks, valves, and connecting pipes. Interactive elements such as PID controllers, level indicators, and pushbuttons were incorporated to facilitate the control of the process.

Data Acquisition and Communication:
The edge device, connected to sensors measuring water levels in the process plant, acquires real-time data. The acquired data is transmitted from the edge device to the cloud platform using NodeJS and a JSON protocol. Communication protocols and data formats are defined to ensure seamless data transmission and reception between the edge device and the cloud (see Figure 12).



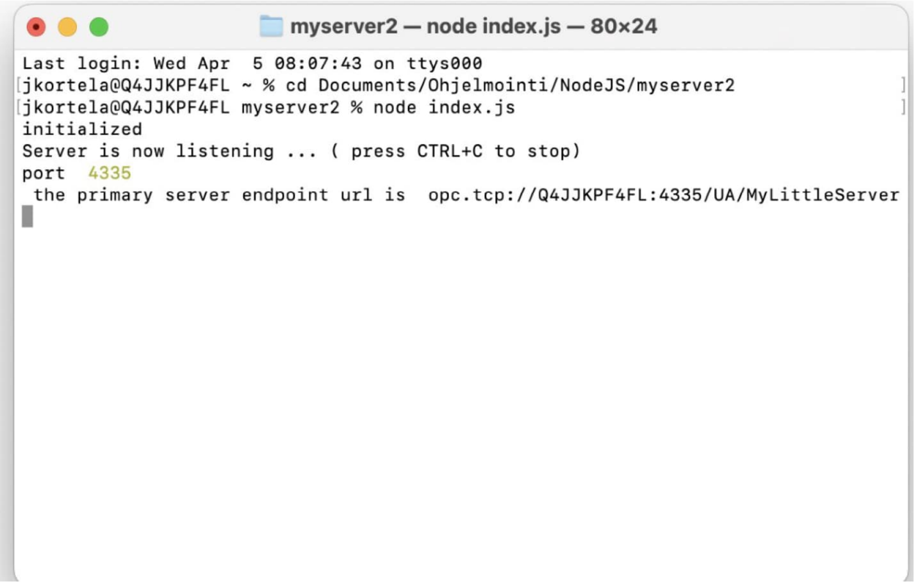
```
Last login: Wed Apr  5 09:24:02 on ttys001
[jkortela@Q4JJKPF4FL ~ % cd Documents/docs/ohjelmointi/Java/MPCJavaHTTPServer/jav]
a-getting-started/
[jkortela@Q4JJKPF4FL java-getting-started % export PATH=/Users/jkortela/Documents]
/Ohjelmointi/Java/maven/apache-maven-3.8.6/bin:$PATH
[jkortela@Q4JJKPF4FL java-getting-started % java -jar target/java-getting-started]
-1.0.jar
  _   _                 _
 | | | |               | |
 | |__| | ___ _ __ ___ | | ___   _
 |  __  |/ _ \ '__/ _ \| |/ / | | |
 | |  | |  __/ | | (_) |   <| |_| |
 |_|  |_|\___|_|  \___/|_|\_\\__,_|

:: Built with Spring Boot :: 2.3.0.RELEASE

2023-04-05 09:28:42.469  INFO 6451 --- [           main] com.example.Main
                  : Starting Main v1.0 on Q4JJKPF4FL with PID 6451 (/Users/jkort
ela/Documents/docs/ohjelmointi/Java/MPCJavaHTTPServer/java-getting-started/targe
t/java-getting-started-1.0.jar started by jkortela in /Users/jkortela/Documents/
docs/ohjelmointi/Java/MPCJavaHTTPServer/java-getting-started)
2023-04-05 09:28:42.471  INFO 6451 --- [           main] com.example.Main
                  : The following profiles are active: production
2023-04-05 09:28:43.311  INFO 6451 --- [           main] o.s.b.w.embedded.tomcat
```

Figure 12. Heroku cloud service.

Cloud-Based MPC Control:
Heroku cloud system employs model predictive control algorithms to generate optimal control signals based on the received data. The edge device is equipped with a dedicated database hosted on the Heroku platform, which serves the specific purpose of storing data (see Figure 13). The Java application in the cloud platform processes the acquired data and calculates the control signals for the pumps. The control signals are sent back to the edge device, which adjusts the pump settings accordingly.

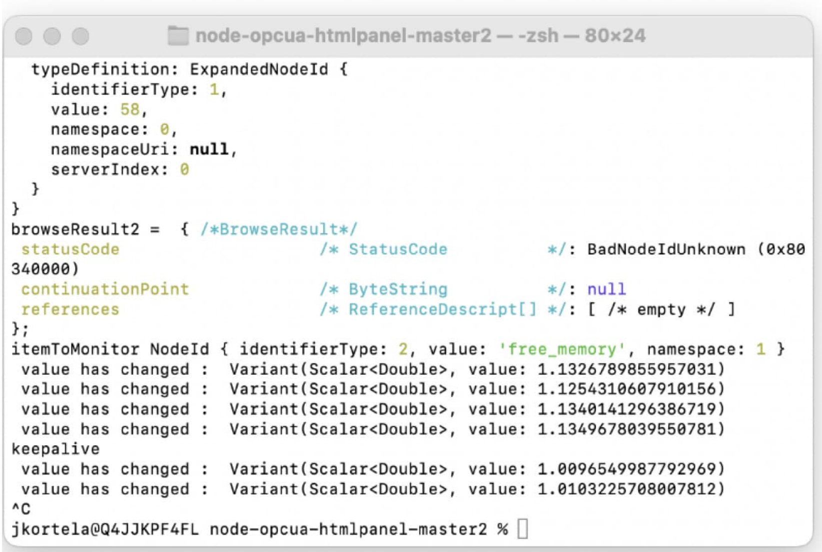


```
Last login: Wed Apr  5 08:07:43 on ttys000
jkortela@Q4JJKPF4FL ~ % cd Documents/Ohjelmointi/NodeJS/myserver2
jkortela@Q4JJKPF4FL myserver2 % node index.js
initialized
Server is now listening ... ( press CTRL+C to stop)
port  4335
 the primary server endpoint url is  opc.tcp://Q4JJKPF4FL:4335/UA/MyLittleServer
```

Figure 13. The edge side of data storage.

User Interface and Visualization:

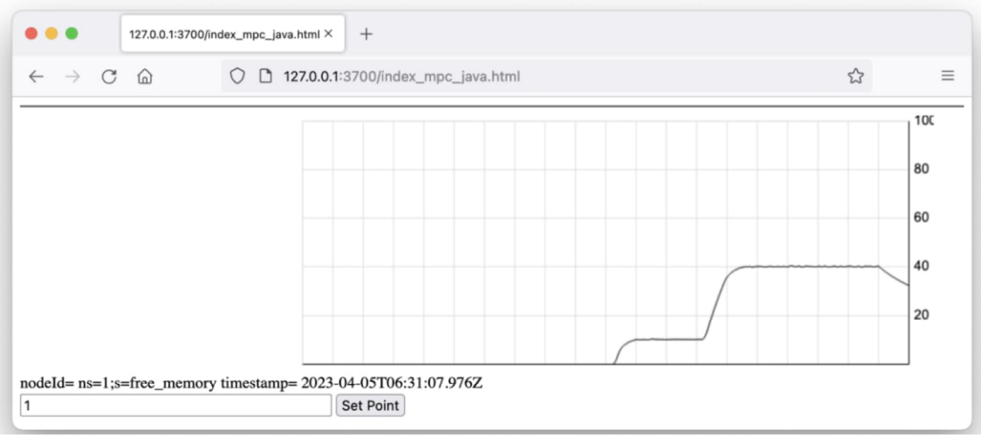
The web browser-based user interface is developed to display real-time pump and water level values. The user interface is regularly updated with the latest values received from the edge device via the cloud system (see Figure 14). Visualization tools and techniques are implemented to provide a clear representation of the system's behaviour and control actions.



```
  typeDefinition: ExpandedNodeId {
    identifierType: 1,
    value: 58,
    namespace: 0,
    namespaceUri: null,
    serverIndex: 0
  }
}
browseResult2 =  { /*BrowseResult*/
 statusCode                  /* StatusCode          */: BadNodeIdUnknown (0x80
340000)
 continuationPoint           /* ByteString          */: null
 references                  /* ReferenceDescript[] */: [ /* empty */ ]
};
itemToMonitor NodeId { identifierType: 2, value: 'free_memory', namespace: 1 }
 value has changed :  Variant(Scalar<Double>, value: 1.1326789855957031)
 value has changed :  Variant(Scalar<Double>, value: 1.1254310607910156)
 value has changed :  Variant(Scalar<Double>, value: 1.1340141296386719)
 value has changed :  Variant(Scalar<Double>, value: 1.1349678039550781)
keepalive
 value has changed :  Variant(Scalar<Double>, value: 1.0096549987792969)
 value has changed :  Variant(Scalar<Double>, value: 1.0103225708007812)
^C
jkortela@Q4JJKPF4FL node-opcua-htmlpanel-master2 % 
```

Figure 14. The illustration of the communication between the edge device, the browser, the cloud, and the local computer.

In the current architecture, there is a cloud service operating in the cloud, while an edge device runs a dedicated data storage server. A gateway is facilitating the communication between the browser and the cloud service. On the edge, the OPC UA server enables data storage. Figure 15 presents an example of a three-tank process controlled by MPC (Model Predictive Control). The image depicts a remote-control chart of the process in the browser, which is also located on the edge device. In this instance, the three-tank process is governed by MPC, initially set to 10 cm and later adjusted to 40 cm. This example highlights the implementation of MPC within a cloud service. The architecture serves digital twin testing purposes, but MPC is not utilized in this specific experiment. Instead, the digital twin model resides in the cloud.



nodeId= ns=1;s=free_memory timestamp= 2023-04-05T06:31:07.976Z

Figure 15. Simulated process control.

Experimental Execution:

The experimental setup is executed, with the model predictive control architecture actively controlling the pumps based on the acquired data and calculated control signals.

Data from the experiment, including pump settings, water level measurements, and control performance metrics, is collected and recorded for analysis.

Overall, the experimental part of the Diploma thesis involves setting up a model predictive control architecture consisting of a process plant, an edge device, and a cloud platform. The system utilizes a Java application in the cloud, NodeJS for communication, and a web browser-based user interface for visualization. The experiment replaces the three-tank system with a model that accurately represents the behaviour of the original system. Data acquisition, communication, cloud-based control, and visualization components are implemented, and the experiment is executed to collect relevant data for analysis and evaluation.

10.4 Data collection

Data collection will be a crucial aspect of the experiment. Various sensors will be deployed to measure the relevant physical parameters of the heat exchanger (Figure 16), such as temperature, pressure, and flow rates. A continuous monitoring and analysis will be ensured by real-time data transmission from the edge device to the cloud platform.

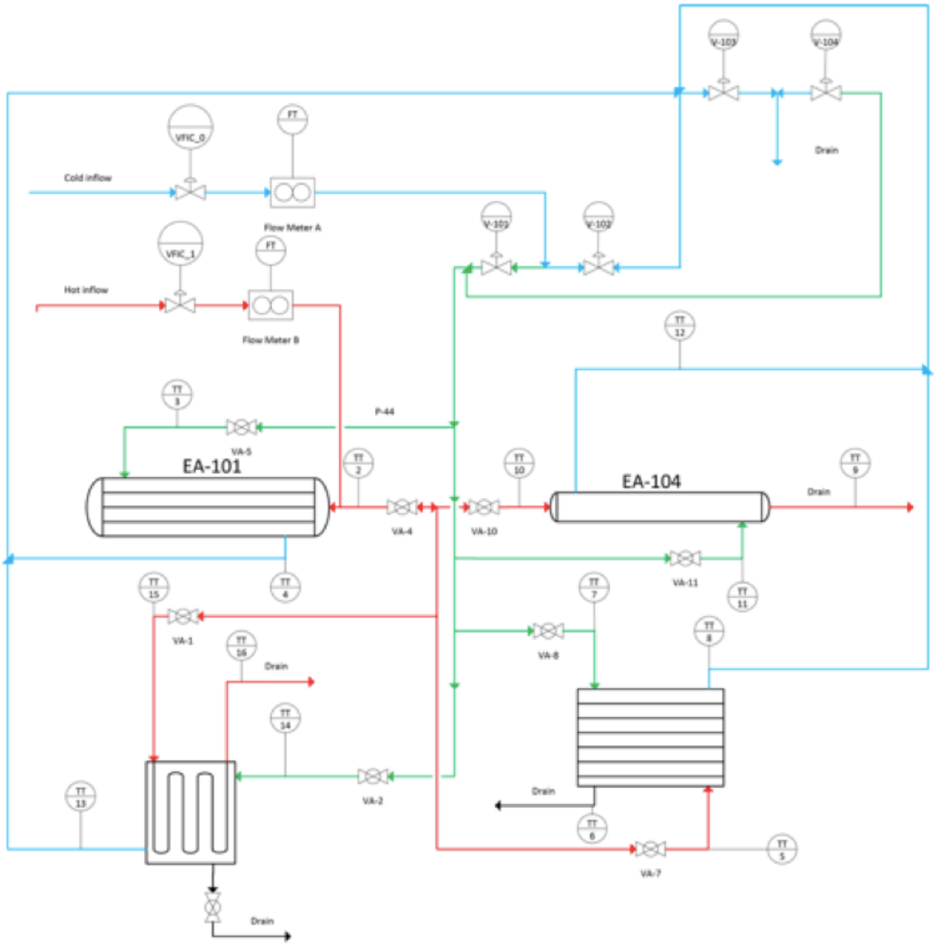


Figure 16. A physical heat exchanger system (Kortela et al., 2019b).

Data collection plays a central role in the experimental phase of this Diploma thesis. The following outlines the data collection procedures and methods employed in this experiment:

> Selection of Relevant Parameters: Before commencing data collection, it is essential to identify the relevant parameters that characterize the heat exchanger process. These parameters may include temperature, pressure differentials, flow rates, and other variables specific to the heat exchanger's operation. The selection of these parameters will depend on the objectives of the study and the desired details for the digital twin model.

Installation of Sensors
Sensors will be strategically placed within the physical heat exchanger system to capture real-time data for the identified parameters. These sensors may include temperature sensors, pressure transducers, flow meters, or any other appropriate sensors required for measuring the desired variables. The sensors will be calibrated and validated to ensure accurate and reliable data acquisition.

Data Acquisition System
Data from the sensors will be recorded using a data acquisition system will be employed. This system may involve hardware components such as data loggers or programmable logic controllers (PLCs) capable of interfacing with the sensors and collecting data at specified intervals. The data acquisition system will ensure synchronized and accurate data collection from multiple sensors.

Real-time Data Transmission
Data collected by the acquisition system will be transmitted in real-time to the edge device and then to the cloud platform. This real-time transmission enables continuous monitoring and facilitates the comparison of the physical process with its digital twin. Communication protocols such as MQTT, AMQP, or HTTPS may be utilized to ensure efficient and secure data transfer.

Data Validation and Quality Control
The collected data will undergo validation and quality control procedures to ensure its integrity and reliability. This involves checking for any inconsistencies, outliers, or potential errors in the data. Data validation techniques such as range checks, statistical analysis, and data visualization may be employed to identify and rectify any anomalies or discrepancies.

Data Storage and Management
Data will be stored within a suitable format and database on the cloud platform. This storage ensures data accessibility and provides a centralized repository for further analysis. The data management system will ensure proper organization, labelling, and indexing of the collected data to facilitate easy retrieval and retrieval for subsequent processing.

Data Security and Privacy
To safeguard the collected data, appropriate security measures will be implemented. This may involve encryption techniques, access controls, and user authentication protocols to protect integrity of the data. Compliance with relevant data protection regulations and ethical considerations will be ensured throughout the data collection process.

As a result of effectively collecting and managing the data from the physical heat exchanger, this experimental phase enables the development of a robust and accurate digital twin model. Analysing and comparing the collected data provides insights into the performance and optimization of the digital twin in the chemical industry.

10.5 Digital twin development

The architecture presented in Section 10.3 is being utilized in digital twin development. Digital twins are created by modelling the physical heat exchanger's behaviour and characteristics. The digital twin model will be designed to receive real-time data from the edge device and synchronize its operation with the physical process. This synchronization will enable accurate comparison and analysis of the data collected from both the physical heat exchanger and its digital twin. The heat exchanger data was used to build a digital twin, which was connected to the cloud platform.

The digital twin enabled real-time monitoring of the heat exchanger, facilitating the identification of potential issues and the optimization of the manufacturing process. To enhance data management and security, blockchain technology was integrated with the digital twin, providing a secure and transparent means of handling data. This integration aimed to improve sustainability of the manufacturing process by leveraging the benefits of blockchain technology.

Blockchain technology could be integrated with the digital twin to explore its potential applications in the chemical industry. The experiment will focus on leveraging blockchain for secure data management, ensuring data integrity, and enhancing transparency in the manufacturing process. The integration could be implemented using appropriate protocols and frameworks, ensuring the compatibility and functionality of the blockchain solution.
In Figure 17, a simplified helical coil model is presented, specifically designed for simulation purposes.

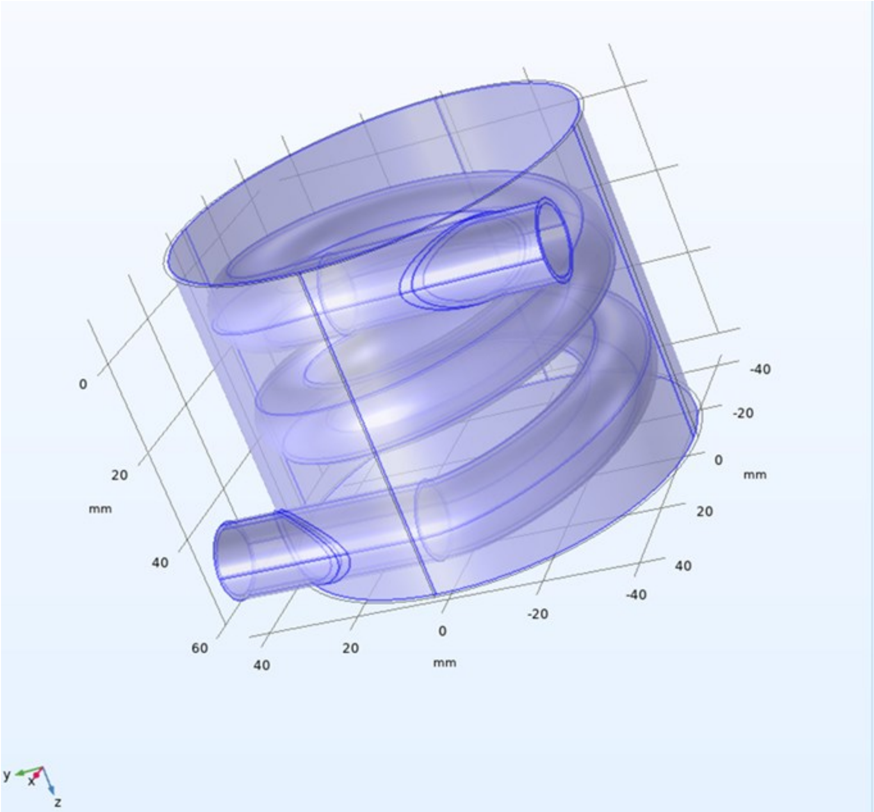


Figure 17. A simplified helical coil model has been created using COMSOL.

10.6 Data analysis and comparison

The collected data from the physical heat exchanger and its digital twin will be analysed and compared. Analysis will determine how digital twins can be implemented and how blockchain technology can be incorporated into chemical processes.

In the experimental part of the Diploma thesis, additional data related to the helical coil system was collected, specifically focusing on flow rate measurements using a flowmeter and temperature measurements. These measurements were essential in understanding the behaviour and performance of the helical coil system.

A flowmeter was installed in the helical coil system to measure the flow rate of the fluid passing through the coils. The flowmeter provided accurate and real-time readings, allowing for the analysis of flow dynamics and variations in flow rates during different operating conditions. The data obtained from the flowmeter was recorded and used to assess the performance and efficiency of the helical coil system.

The modelling of the helical coil heat exchanger was performed using the simulation software COMSOL Multiphysics. Through simulations, the behaviour of the helical coil heat exchanger was analysed, providing both graphical and numerical results. These simulation results were compared with corresponding tests conducted on pilot equipment, yielding numerical data that closely matched the actual experimental outcomes. The results of COMSOL model and experiment (Figure 18), indicate a temperature difference of nine degrees. Despite the significant difference, simulations can still be conducted using this model. Figure 18 shows experimental and modelled temperatures over time.

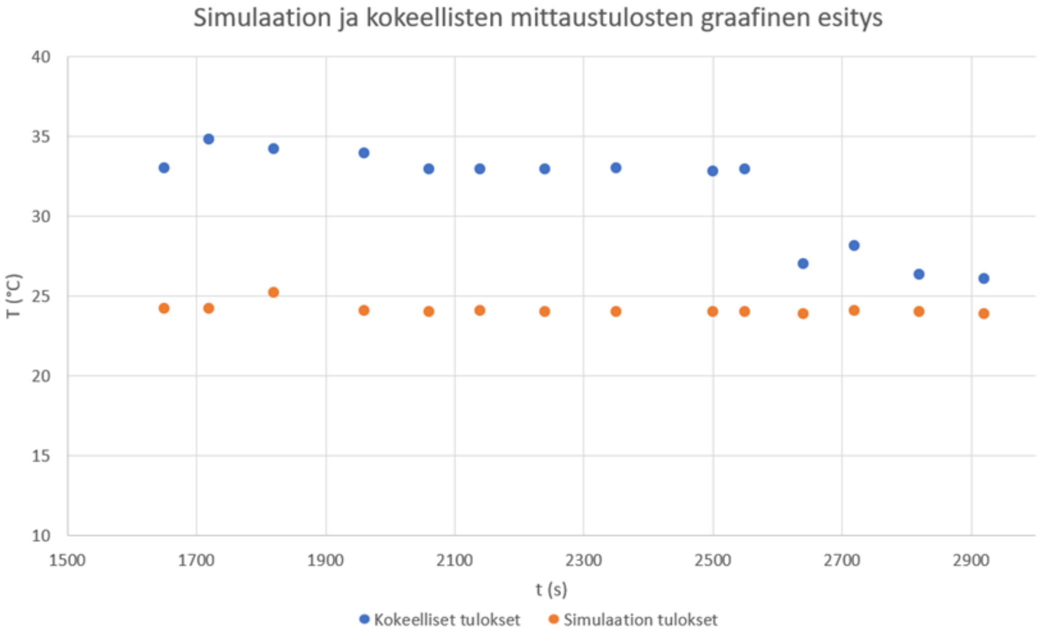


Figure 18. The experimental (blue) and modelled (orange) temperatures over time.

Temperature sensors were strategically placed at various points within the helical coil system to monitor temperature changes throughout the process. These measurements provided valuable insights into heat transfer characteristics, thermal gradients, and overall system performance. Using the temperature data, any potential issues or deviations from desired operating conditions were identified and the efficiency of the heat transfer process was evaluated.

The integration of flowmeter measurements and temperature data enhanced the understanding of the helical coil system's behaviour. These additional measurements provided valuable information regarding flow dynamics, heat transfer efficiency, and overall system performance. The collected data served as a basis for analysis, allowing for the evaluation of key parameters and the optimization of the helical coil system.

In Figure 19, there is a temperature gradient across the helical coil. Due to the significant computational requirements, only two loops have been utilized instead of the intended total 36 loops. However, in the future, with the utilization of a high-performance computer, we can significantly improve this model by incorporating all 36 loops. This will result in a more accurate digital twin. The temperature gradient in Figure 19 accurately represents the physical conditions, showcasing the potential of this model for conducting simulations. The temperature rises from 10 degrees to 30 degrees, indicating a clear heat transfer. A computer's capability and computational time determine the accuracy of the results, however. In this study, further development and refinement have not been pursued.

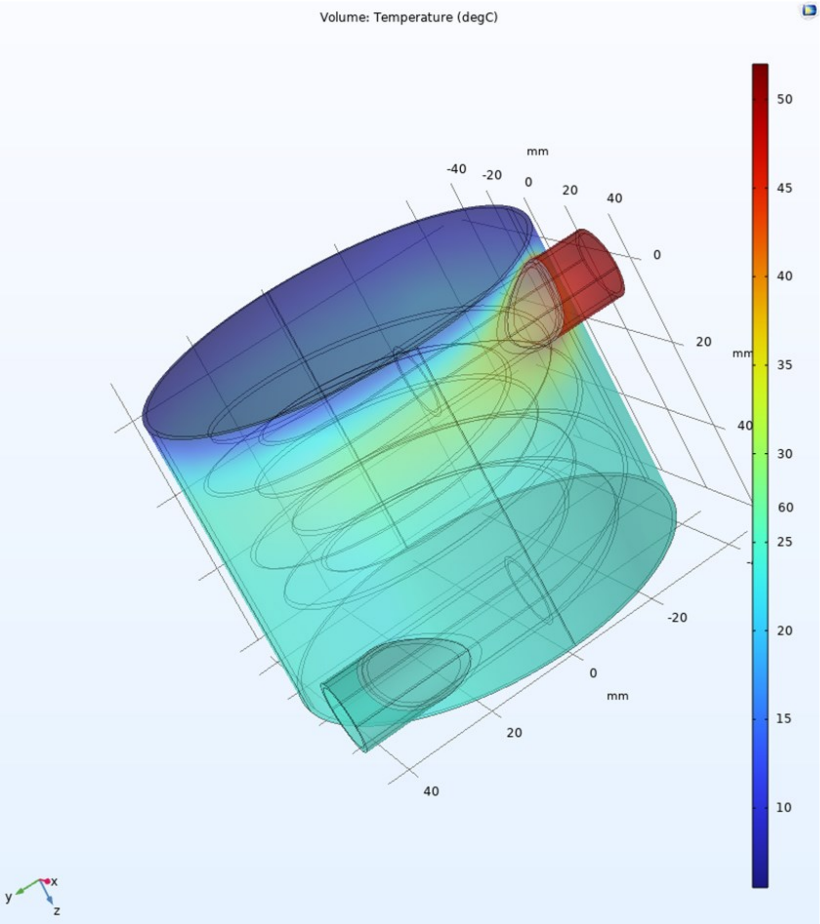


Figure 19. Two loops of the helical coil temperature gradient in Celsius degrees are shown.

11 Comparison of the Results

11.1 Experimental Results

In the initial phase of the measurement, the heat exchanger system was operated for approximately 30 minutes to ensure proper water filling and the attainment of a steady-state temperature for the components. The heat exchanger shell was supplied with water at a temperature of approximately 5°C, while the pipeline received water at around 52°C. The flow rates, as measured by the flow meters, are presented in Data 1 and Data 2, as depicted in Figure 20. After approximately 1600 seconds, the volumetric flow rate of the hot water supply in the pipeline stabilized. The volumetric flow rate of the cold water supplied to the shell started at approximately 1400 litres per minute and gradually increased to around 2500 litres per minute.
Figure 20 provides a visual representation of how the temperature of the heat exchanger decreases as the volumetric flow rate of the supply water in the shell increases. Similarly, the temperature of the outlet water from the pipeline begins to decline at approximately 1600 seconds, as shown in Figure 20.

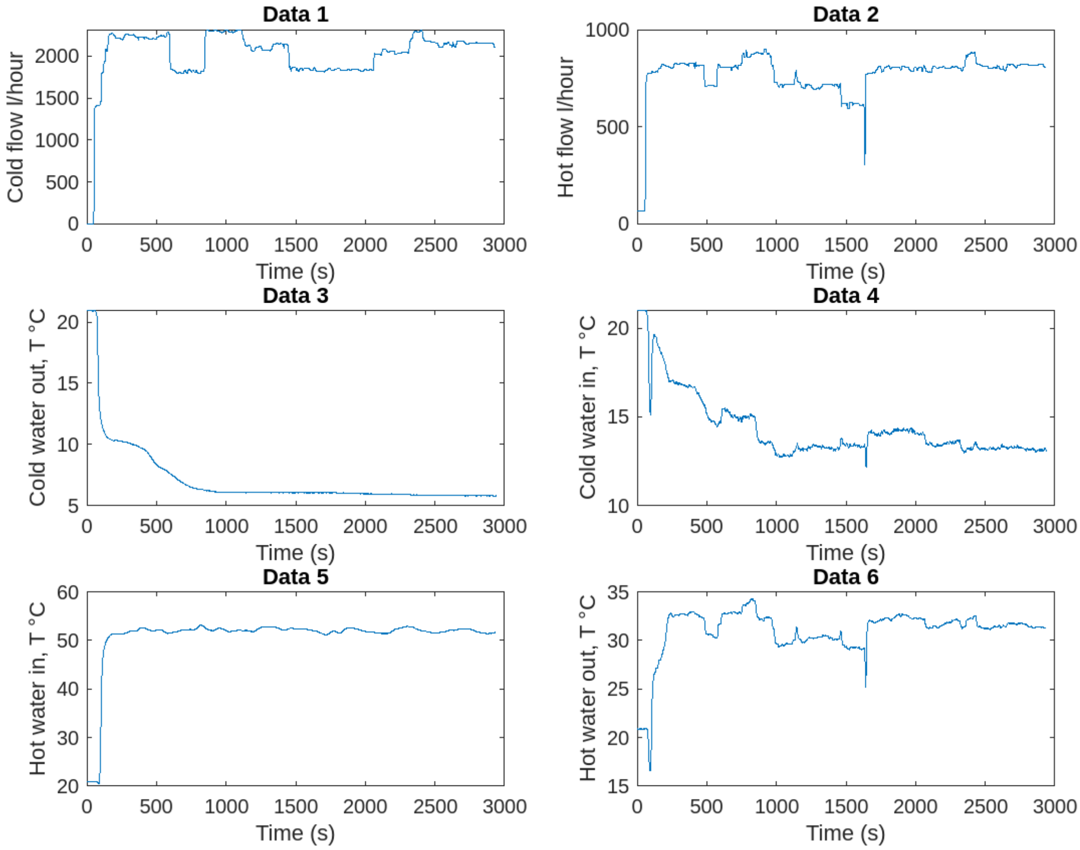


Figure 20. Depicts the volumetric flow rates in data sets 1-2 and the temperature variations of the inlet and outlet in data sets 3-6.

Figure 20 presents the data for the volumetric flow rate of the inlet and outlet water (in litres per hour) in a helical coil over time (in seconds), referred to as Data 1 and Data 2. Additionally, the temperature (in degrees Celsius) of the inlet and outlet water in the heat exchanger piping system is represented by Data sets 3-6, also as a function of time (in seconds).

11.2 Simulation Results

Upon, comparing the results, it becomes apparent that certain parameters significantly influence the accurate modelling and simulation of the helical coil heat exchanger. While some parameters introduce systematic errors, others have a more substantial impact on the overall outcomes. Notably, the simulation closely aligns with the measured data, particularly up to the 2600-second mark. However, during this period, the modelled temperatures consistently register approximately 9°C lower than the corresponding measured temperatures.
The presence of a systematic error within the simulation environment becomes evident. From a modelling perspective, this outcome is considered positive, as it indicates that the model effectively responds to changes in simulation input values and emulates the behaviour of the actual pilot equipment.

11.3 A linear and non-linear ARX model Results

The experimental phase of the Diploma thesis focused on data collection, model development, and analysis. Model identification involves extracting the parameters and structures of a mathematical model from test data. It involves estimating the model's parameters, adjusting it to fit observed data, and using validation techniques to assess its reliability. Identification tests involve comparing the model's predictions to real-world observations to evaluate its ability to explain a specific phenomenon or behaviour. This study developed cloud-based linear and non-linear ARX (AutoRegressive with eXogenous inputs) models using collected data (Figure 21 and 22). These models demonstrated the capability to learn patterns and make accurate predictions. The ARX models were specifically designed to capture the dynamic behavior of the system for control purposes. Performance metrics were evaluated to assess the effectiveness of the models.

In this case, a more accurate linear ARX model was developed for deployment in a cloud service instead of COMSOL. Due to the computational complexity of the COMSOL model, it could not be utilized in the cloud environment. Figure 21 illustrates the use of multiple parameters, resulting in a satisfactory model fit with an accuracy of 85% and 92%. The comparison of the simulated response amplitudes provides good validation for the model's performance.

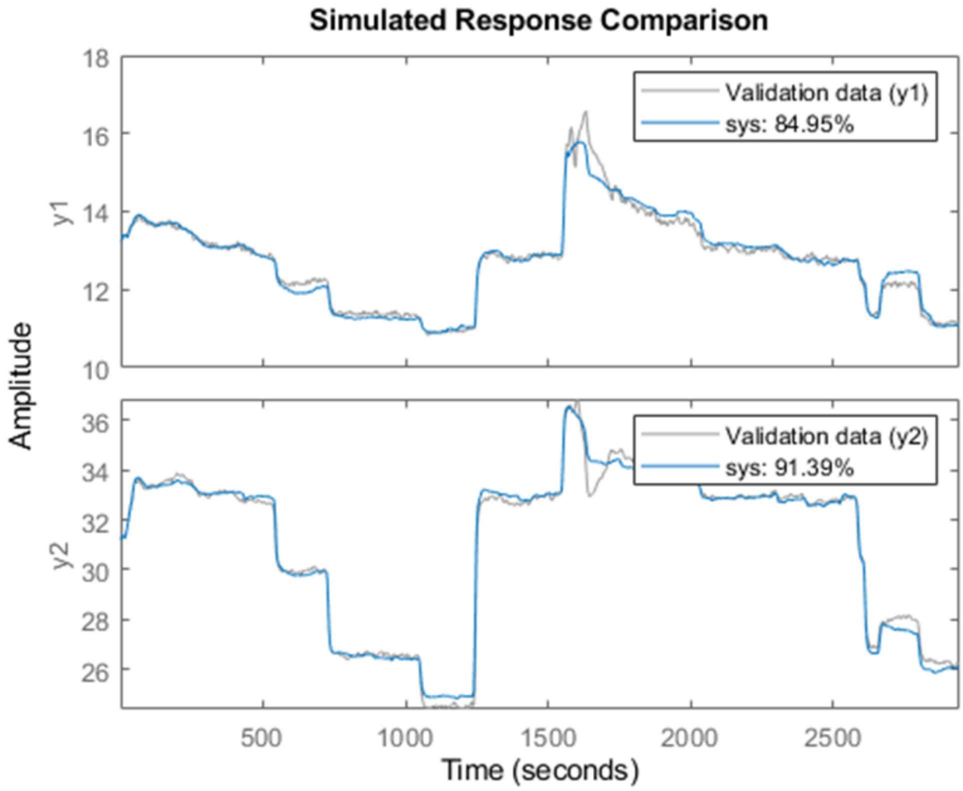


Figure 21. A linear ARX model's simulated response comparison. Two variables: y1 representing hot water flow and y2 representing cold water flow.

In Figure 22, a simulated response comparison of a nonlinear ARX model is presented. Although the model identification process does not significantly outperform the linear model, the nonlinear ARX model shows improved performance when deployed in a cloud environment.

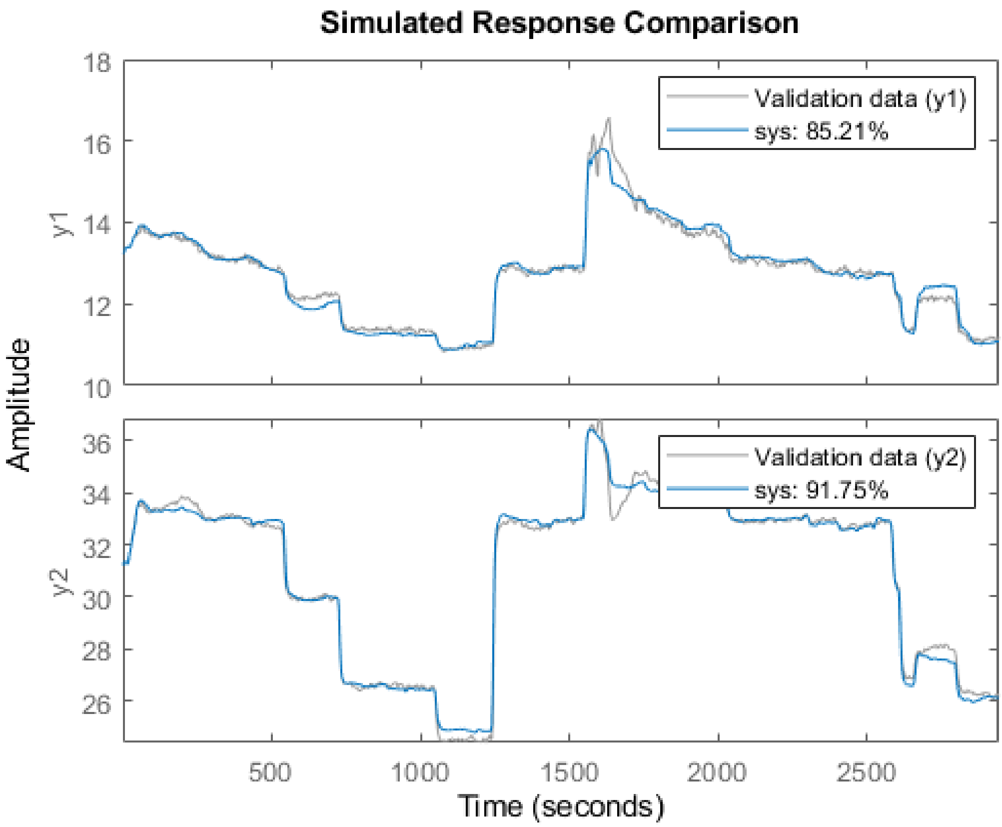


Figure 22. A non-linear ARX model's simulated response comparison. Two variables: y1 representing hot water flow and y2 representing cold water flow.

Validation 1: offline model validations with collected data

Next, the ARX model will be validated using the collected data to determine if the model performs linearly and nonlinearly in the cloud environment. Validation 1 refers to offline validation, while Validation 2 refers to online validation. First offline linear validation will be shown in Figure 23.

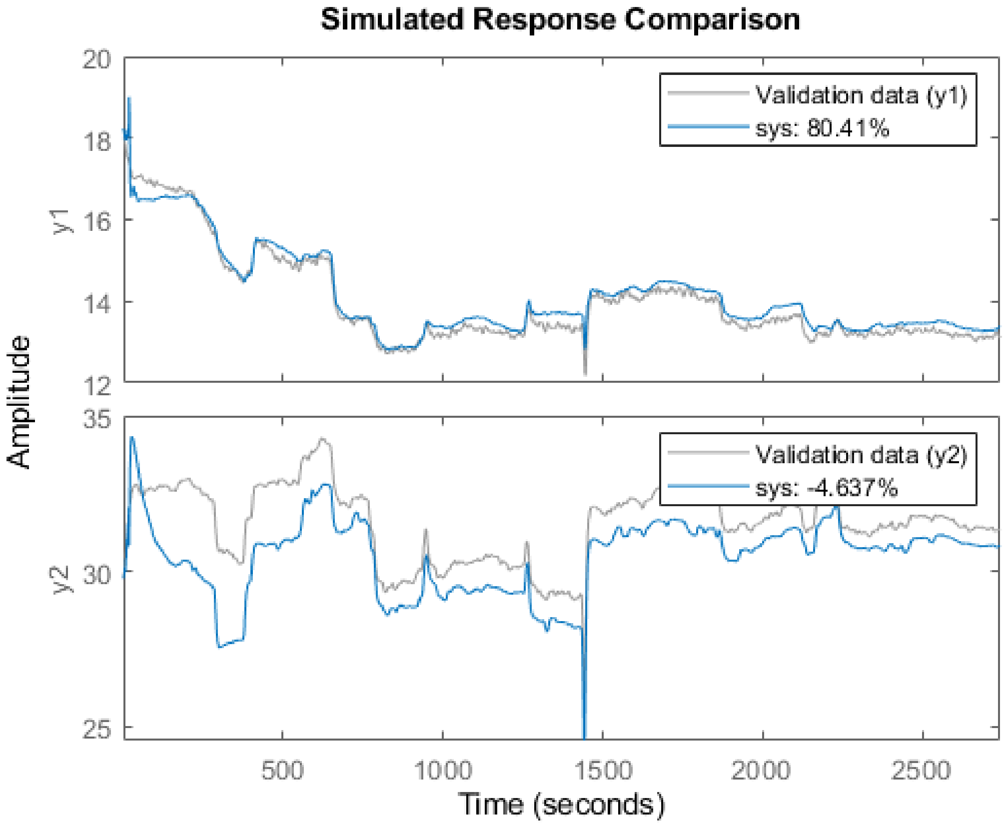


Figure 23. Offline linear ARX model's simulated response comparison. Two variables: y1 representing hot water flow and y2 representing cold water flow.

During the offline validation of the linear helical model (Figure 23) in the cloud, there is some improvement compared to previous results. However, there are still deviations, especially in the hot temperature range. This could be attributed to inaccuracies in the calibration of the hot temperature and limited visibility of hot water inside the metal helical coil. It is challenging to determine if there is sufficient water and if the heat transfer is occurring correctly. Additionally, the possible presence of air bubbles within half of the coil can contribute to these deviations, despite the known flow rate. On the other hand, the nonlinear model performs exceptionally well during offline validation, showing minimal deviations. In this offline scenario, the nonlinear model outperforms the linear mode (Figure 24).

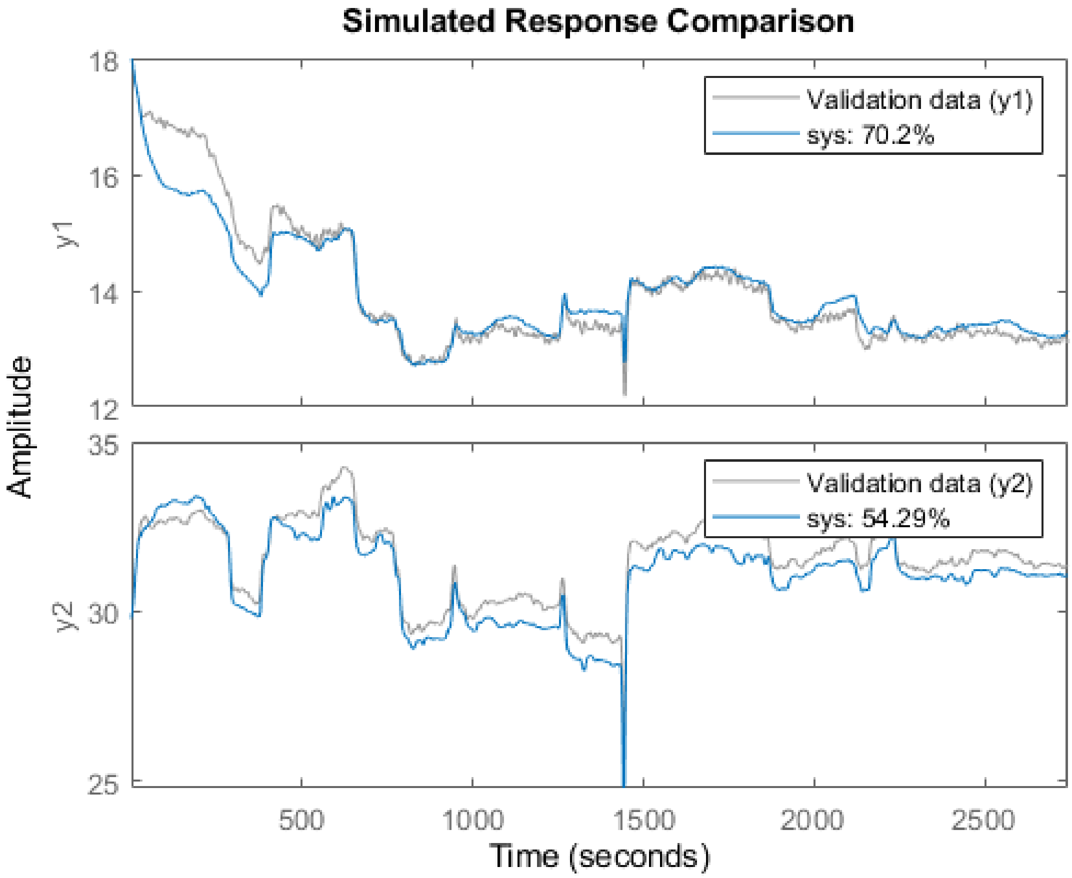


Figure 24. Offline non-linear ARX model's simulated response comparison. Two variables: y1 representing hot water flow and y2 representing cold water flow.

Validation 2: online model validations with collected data

The online linear ARX model performs slightly worse, as shown in Figure 25. It indicates that the cold-water response is good, while the hot water response deviates to some extent. The same reasons as in validation 1 could contribute to these discrepancies, although they may not fully explain the differences. The deviation in hot water could be due to poorly calibrated water flow or inadequate water supply, resulting in different heat transfer characteristics.

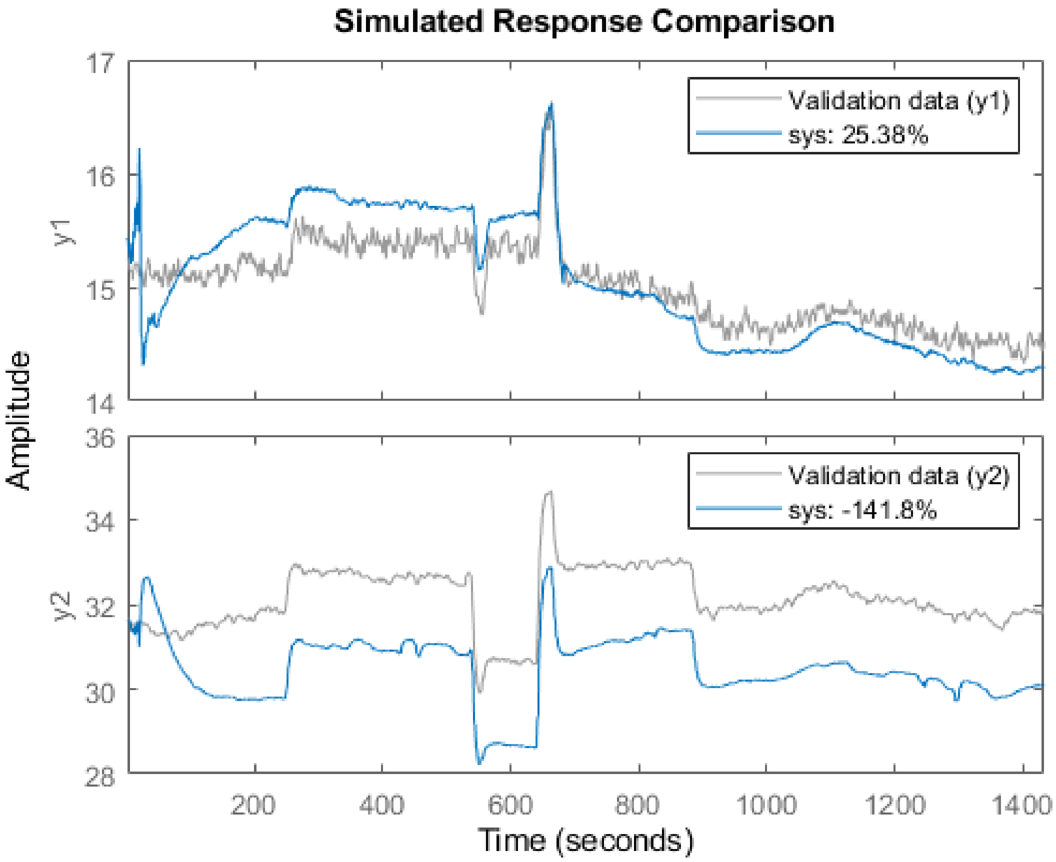


Figure 25. Online linear ARX model's simulated response comparison. Two variables: y1 representing hot water flow and y2 representing cold water flow.

On the other hand, the online nonlinear model outperforms the linear model once again. In this case, the cold-water response with the online nonlinear model exhibits a different behaviour, as depicted in Figure 26. The hot water response is good, but there are deviations in the cold-water response. The reasons for these deviations are not known, but there is a downward trend observed. Overall, the online nonlinear model proves to be more effective than the linear model in capturing the system dynamics.

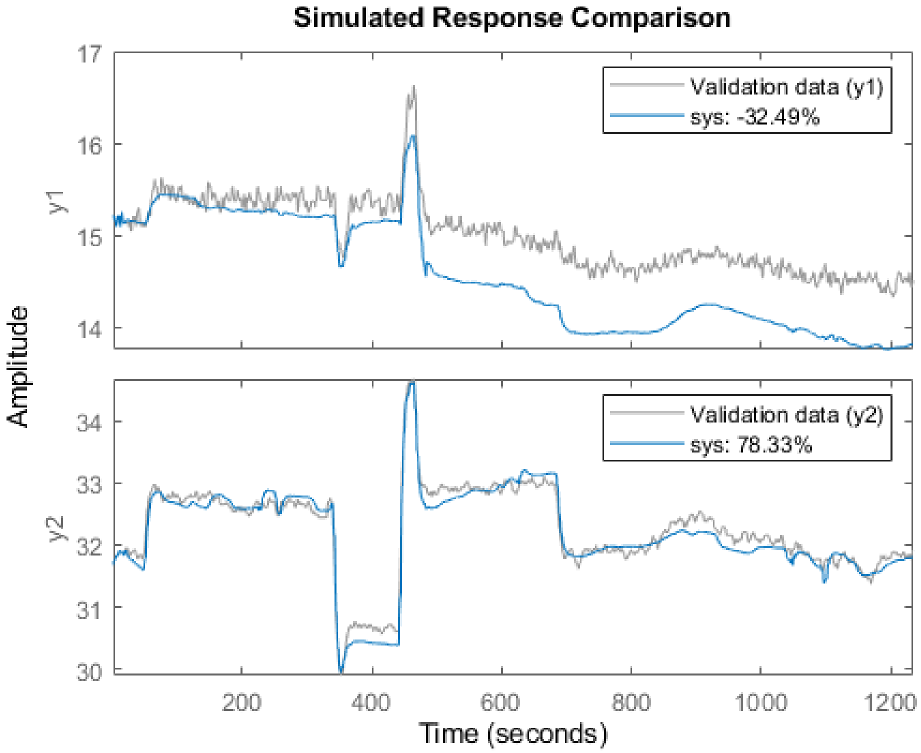


Figure 26. Online non-linear ARX model's simulated response comparison. Two variables: y1 representing hot water flow and y2 representing cold water flow.

The experiment begins with model creation, specifically developing linear and nonlinear ARX models. These models are lightweight and can be run on both cloud services and local computers. In the future, when COMSOL is ready, it will be able to capture more detailed aspects that ARX models cannot account for. ARX models are data-driven, meaning they rely on collected data to make predictions. For example, the nonlinear ARX model attempts to capture nonlinearities, such as exponential growth, but it may not be able to capture all complexities.

In conclusion, the models show promising results, but further simulation on a high-performance computer is needed to validate their performance over a longer period. Additionally, it is recommended to continue refining and improving the models to capture additional complexities. It is worth noting that while the ARX models demonstrate effectiveness, they may not encompass all factors and considerations in the system.

11.4 Analysis of measurement discrepancies and optimization

The measurement results revealed a consistent difference between the simulated and actual data. To enhance computational efficiency, certain compromises were necessary. Each data point required approximately 7 minutes to model using the current settings. However, for this simplified model with only two loops, the calculation process on a passive computer alone took over one and a half hours. It is important to consider that the pilot equipment consists of a total of 36 loops, further impacting the computational demands.

Another significant factor affecting the optimization process was the modelling of laminar flows instead of accurately capturing the turbulent nature of the flow. Turbulent flow exhibits chaotic characteristics that differ significantly from the modelled flow within the heat exchanger shell. This disparity contributes to the discrepancies observed between the simulation and actual results.

Despite diligent efforts to create an accurate model of the heat exchanger, compromises had to be made in terms of the geometry. The cross-section of the coil pipes deviates from a perfect round shape and takes on a rectangular form. Additionally, the outlet pipe is positioned within the circumference of the coil, further influencing the flow dynamics.

These factors highlight the challenges encountered during the optimization process and underscore the importance of considering computational efficiency, flow characteristics, and geometric limitations when modelling a helical coil heat exchanger.

11.5 Conclusion

The experimental work conducted in this study showcased the successful implementation of a digital twin tool and the utilization of cloud computing in a small-scale process plant. This study demonstrated the potential for real-time monitoring and data analysis using Heroku cloud platforms. These findings emphasize the importance of leveraging digital twin and cloud technologies to enhance efficiency, sustainability, and safety in industrial processes. Chemical engineering and manufacturing can benefit from further research.

A cloud-based model replaced the previous 3-tank model in the architecture, providing an accurate representation of the original system's behaviour for control experiments. The evaluation of the models included various metrics related to prediction accuracy, control stability, and response time, providing valuable insights into their performance and reliability.

The experimental results showcased the versatility of the model and associated MATLAB code (attachment 1 & 2) for digital twin applications. Real-time monitoring, optimization, and decision-making processes, particularly in blockchain applications, were highlighted as potential applications. The developed models and code can be applied to different systems, enabling the creation of advanced digital twins for enhanced control and analysis.

Overall, the experimental part of the Diploma thesis successfully generated and evaluated non-linear and linear ARX models using collected data. The utilization of a cloud-based models demonstrated the adaptability of the approach, while the versatility of the developed models and code in blockchain scenarios showcased their potential in various industries for improved system control, monitoring, and decision-making.

The connection to blockchain lies in the aspect of ensuring the integrity and immutability of data and code. If there are emissions results that need to be recorded, storing them on a blockchain ensures that the recorded results cannot be altered. Similarly, in the context of digital twin processes, having the code stored on a blockchain prevents unauthorized modification by hackers. The architecture used in this work, with its components such as ABB system, edge devices, browser, edge database, and cloud service, resembles the structure of a blockchain with its individual blocks. This architecture is well-suited for monitoring and decision-making purposes.

A digital twin can use blockchain as a suitable scenario and use case to ensure that the code remains unchanged. This is important in scenarios where processes rely on accurate code execution. For instance, in the presence of Model Predictive Control (MPC) algorithms, blockchain protection prevents unauthorized tampering that could lead to hazardous situations in a factory. Blockchain provides a layer of assurance by confirming that the code has not been altered. The same principle applies to scenarios where a digital twin is monitoring critical infrastructure like a nuclear power plant. Blockchain ensures that the digital twin does not provide incorrect or misleading results. In monitoring applications, blockchain instils trust by guaranteeing that the code remains unaltered.

References

Abadi, M. J., & Khalaj, B. H. (2022). Connectivity through Wireless Communications and Sensors. In S. Chatterjee et al. (Eds.), Wireless Sensor Networks and the Internet of Things: Technology, Protocols, and Applications (pp. 3-58). John Wiley & Sons, Inc. ISBN: 9781119695936. Doi: https://doi.org/10.1002/9781119695868.ch1

Abdelgalil, T., Manolas, V., Maglaras, L., Kantzavelou, I., & Ferrag, M. A. (2021). Blockchain Technology: A case study in supply chain management. In 2021 Third IEEE International Conference on Trust, Privacy and Security in Intelligent Systems and Applications (TPS-ISA) (pp. 331-339). doi:10.1109/TPSISA52974.2021.00036.

Accenture. (2018). Unlocking the potential of blockchain in the chemical industry. Retrieved from https://www.accenture.com/us-en/insight-blockchain-chemical-industry.

Agarwal, U., Rishiwal, V., Tanwar, S., Chaudhary, R., Sharma, G., Bokoro, P. N., & Sharma, R. (2022). Blockchain Technology for Secure Supply Chain Management: A Comprehensive Review. IEEE Access, 10, 85493-85517. doi:10.1109/ACCESS.2022.3194319.

Alfandi, O., Otoum, S., & Jararweh, Y. (2020). Blockchain Solution for IoT-based Critical Infrastructures: Byzantine Fault Tolerance. In NOMS 2020 - 2020 IEEE/IFIP Network Operations and Management Symposium (pp. 1-4). Budapest, Hungary. doi:10.1109/NOMS47738.2020.9110312.

Alkhader, W., Alkaabi, N., Salah, K., Jayaraman, R., Arshad, J., & Omar, M. (2020). Blockchain-Based Traceability and Management for Additive Manufacturing. IEEE Access, 8, 188363-188377. doi:10.1109/ACCESS.2020.3031536.

Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., ... Peacock, A. (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renewable and Sustainable Energy Reviews, 100, 143-174. Doi: 10.1016/j.rser.2018.10.014.

Angrish, A., Craver, B., Hasan, M., & Starly, B. (2018). A Case Study for Blockchain in Manufacturing: "FabRec": A Prototype for Peer-to-Peer Network of Manufacturing Nodes. Procedia Manufacturing, 26, 1180-1192. ISSN 2351-9789. Doi: 10.1016/j.promfg.2018.07.154.

Asyrofi, R., & Zulfa, N. (2020). CLOUDITY: Cloud Supply Chain Framework Design based on JUGO and Blockchain. In 2020 6th Information Technology International Seminar (ITIS) (pp. 19-23). Surabaya, Indonesia. doi:10.1109/ITIS50118.2020.9321013.

Azangoo, M., Salmi, J., Yrjölä, I., Bensky, J., Santillan, G., Papakonstantinou, N., Sierla, S., & Vyatkin, V. (2021). Hybrid Digital Twin for process industry using Apros simulation environment. In 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) (pp. 01-04). Doi: 10.1109/ETFA45728.2021.9613416.

Azzi, R., Chamoun, R. K., & Sokhn, M. (2019). The power of a blockchain-based supply chain. Computers & Industrial Engineering, 135, 582-592. ISSN 0360-8352. Doi: 10.1016/j.cie.2019.06.042.

Bapatla, A. K., Mohanty, S. P., Kougianos, E., & Puthal, D. (2022). PharmaChain 3.0: Blockchain Integrated Efficient QR Code Mechanism for Pharmaceutical Supply Chain. In 2022 OITS International Conference on Information Technology (OCIT) (pp. 625-630). Bhubaneswar, India. Doi: 10.1109/OCIT56763.2022.0012

Bashir, I. (2023). Mastering Blockchain - Fourth Edition. 4th edition. Packt Publishing.

Bellini, P., et al. (2022). High level control of chemical plants by industry 4.0 solutions. Journal of Industrial Information Integration, 26. Doi: 10.1016/j.jii.2021.100276.

Biswas, B., & Gupta, R. (2019). Analysis of barriers to implementing blockchain in industry and service sectors. Computers & Industrial Engineering, 136, 225-241. Doi: 10.1016/j.cie.2019.07.005.

Bürer, M. J., de Lapparent, M., Pallotta, V., Capezzali, M., & Carpita, M. (2019). Use cases for Blockchain in the Energy Industry Opportunities of emerging business models and related risks. Computers & Industrial Engineering, 137, 106002. Doi: 10.1016/j.cie.2019.106002.

Busse, C., Bozek, E., Pfeiffer, B.M., Maroor, S., & Oppelt, M. (2020). Modern Process Monitoring and Optimization Methods Integrating a Process Simulator into a Distributed Control System. In Computer Aided Chemical Engineering (Vol. 48, pp. 1321-1326). Elsevier.

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. Telematics and Informatics, 36, 55-81. doi: 10.1016/j.tele.2018.11.006.

Deloitte. (2018). The chemistry of blockchain: Opportunities and challenges for the chemical industry. Retrieved from https://www2.deloitte.com/us/en/pages/energy-and-resources/articles/the-chemistry-of-blockchain.html.

Ding, K., Fan, L., & Liu, C. (2021). Manufacturing system under I4.0 workshop based on blockchain: Research on architecture, operation mechanism and key technologies. Computers & Industrial Engineering, 161, 107672. doi: 10.1016/j.cie.2021.107672.

Esmaeilian, B., Sarkis, J., Lewis, K., & Behdad, S. (2020). Blockchain for the future of sustainable supply chain management in Industry 4.0. Resources, Conservation and Recycling, 163, 105064. doi: 10.1016/j.resconrec.2020.105064.

Ferreira, C. M. S., Oliveira, R. A. R., Silva, J. S., & Cunha Cavalcanti, C. F. M. D. (2020). Blockchain for machine-to-machine interaction in Industry 4.0. In P. N. Narvade (Ed.), Blockchain Technology for Industry 4.0: A Secure, Decentralized, Distributed, and Trusted Industry Environment (pp. 99–116).

Fu, Y., & Zhu, J. (2019). Big Production Enterprise Supply Chain Endogenous Risk Management Based on Blockchain. IEEE Access, 7, 15310-15319. doi: 10.1109/

Haughton, J., Kraft, M., Sikorski, J. J. (2017). Blockchain technology in the chemical industry: Machine-to-machine electricity market. Applied Energy, 195, 234-246. ISSN 0306-2619. doi: 10.1016/j.apenergy.2017.03.039.

Heinijoki, A. (2021). Software Configuration of a Three-tank Pilot-plant. Bachelor's thesis, Kemian tekniikka ja prosessit, Aalto University. Retrieved from http://urn.fi/URN:NBN:fi:aalto-202202011611.

Helo, P., Suorsa, M., Hao, Y., & Anussornnitisarn, P. (2014). Toward a cloud-based manufacturing execution system for distributed manufacturing. Computers in Industry, 65(4), 646-656. ISSN 0166-3615. doi: 10.1016/j.compind.2014.01.015. (Available at: https://www.sciencedirect.com/science/article/pii/S0166361514000311)

Hopkins, J. L. (2021). An investigation into emerging industry 4.0 technologies as drivers of supply chain innovation in Australia. Computers in Industry, 125, 103323. ISSN 0166-3615. doi: 10.1016/j.compind.2020.103323.

Hughes, L., Dwivedi, Y. K., Misra, S. K., Rana, N. P., Raghavan, V., & Akella, V. (2019). Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda. International Journal of Information Management, 49, 114-129. (Available at: https://doi.org/10.1016/j.ijinfomgt.2019.02.005)

Jain, R., Gupta, A., & Jain, A. (2018). Internet of things in industrial engineering and management: Current trends and future directions. Journal of Industrial Engineering and Management, 11(3), 1-16.

Jain, S. M. (2023). Decentralization and Web3. In A Brief Introduction to Web3. Apress, Berkeley, CA. Available at: https://doi.org/10.1007/978-1-4842-8975-4_1

Javaid Mohd, A., Haleem, A., Singh, R. P., Khan, S., & Suman, R. (2021). Blockchain technology applications for Industry 4.0: A literature-based review. Blockchain: Research and Applications, 2(4), 100027. doi: https://doi.org/10.1016/j.bcra.2021.100027

Jayashri, N., Rampur, V., Gangodkar, D., Abirami, M., Balarengadurai, C., & Anil Kumar, N. (2023). Improved blockchain system for high secured IoT integrated supply chain. Measurement: Sensors, 25, 100633. ISSN 2665-9174. doi: 10.1016/j.measen.2022.100633.

Kang, T., Peng, H., Xu, W., Sun, Y., & Peng, X. (2023). Deep Learning-Based State-Dependent ARX Modeling and Predictive Control of Nonlinear Systems. IEEE Access, 11, 32579-32594. doi: 10.1109/ACCESS.2023.3263180.

Ko, T., Lee, J., & Ryu, D. (2018). Blockchain technology and manufacturing industry: Real-time transparency and cost savings. Sustainability, 10(11), 4274. ISSN 2071-1050. doi:10.3390/su10114274.

Kortela, J. (2019a). Factory of Future setup of ABIO [PDF document]. Aalto University Research Group of Process Control and Automation.

Kortela, J. and Tadesse, Y. (2022c). A Study on Optimizing Signal Path in Model Predictive Control of Three-Tank Pilot System Using Reference Architecture. In Access FAC 2023 - Conference Proceedings, Aalto University School of Chemical Engineering. Available at: https://www.ifac2023.org/.

Kortela, J., Jämsä-Jounela, S-L., Tonteri, P., & Ahonen, A. (2019b). Factory of the Future Automation Set Up for Process industries. In Automaatiopäivät 23: Extended Abstracts (pp. 95-96). Oulu, Finland: Suomen Automaatioseura.

KPMG. (2018). Blockchain in the chemical industry: Opportunities and challenges. Retrieved from https://assets.kpmg/content/dam/kpmg/xx/pdf/2018/09/blockchain-in-the-chemical-industry.pdf.

Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. International Journal of Information Management, 39, 80-89. (Available at: https://doi.org/10.1016/j.ijinfomgt.2017.12.005)

Kumar, R., & Tripathi, R. (2019). Traceability of counterfeit medicine supply chain through Blockchain. In 2019 11th International Conference on Communication Systems & Networks (COMSNETS) (pp. 568-570). Bengaluru, India. IEEE Access doi: 10.1109/COMSNETS.2019.8711418.

Kurpjuweit, S., Schmidt, C. G., Klöckner, M., & Wagner, S. M. (2021). Blockchain in Additive Manufacturing and its Impact on Supply Chains. Journal of Business Logistics, 42(1), 46–70. (Available at: https://doi.org/10.1111/jbl.12231)

Lee, H. D., Guo, K., Souza, L. F. S., & Lee, J. M. (2021). Application of Digital Twin to Monitor and Optimize Utility Process. In 2021 21st International Conference on Control, Automation and Systems (ICCAS) (pp. 376-381). Jeju, Korea, Republic of. doi: 10.23919/ICCAS52745.2021.9649804.

Li, X., Li, J., & Wang, L. (2020). Digital technologies for sustainable chemical production. Journal of Environmental Management, 264, 110912.

Li, Z., Barenji, A. V., & Huang, G. Q. (2018). Toward a blockchain cloud manufacturing system as a peer-to-peer distributed network platform. Robotics and Computer-Integrated Manufacturing, 54, 133-144. ISSN 0736-5845. doi: 10.1016/j.rcim.2018.05.011.

Lim, M. K., Li, Y., Wang, C., & Tseng, M.-L. (2021). A literature review of blockchain technology applications in supply chains: A comprehensive analysis of themes, methodologies and industries. Computers & Industrial Engineering, 154, 107133. (Available at: https://doi.org/10.1016/j.cie.2021.107133)

Lin, Y., Gao, Z., Du, H., Niyato, D., Kang, J., Deng, R., & Shen, X. S. (2023). A Unified Blockchain-Semantic Framework for Wireless Edge Intelligence Enabled Web 3.0. IEEE Wireless Communications, 1-9. doi:10.1109/MWC.018.2200568.

Lobachev, E., Mahmoud, M. N., & Patooghy, A. (2022). Blockchain-based Smart Supply Chain Management. In 2022 9th International Conference on Dependable Systems and Their Applications (DSA) (pp. 203-208). Wulumuqi, China. doi: 10.1109/DSA56465.2022.00035.

Lohmer, J., & Lasch, R. (2020). Blockchain in operations management and manufacturing: Potential and barriers. Computers & Industrial Engineering, 149, 106789. ISSN 0360-8352. doi: 10.1016/j.cie.2020.106789.

Louhi, L. (2023). Modeling of a helical coil heat exchanger [bachelor's thesis, bachelor's degree Program in Engineering, Program in Chemical Engineering, Major in Chemistry and Materials Science].

Lu, Y. (2019). The blockchain: State-of-the-art and research challenges. Journal of Industrial Information Integration, 15, 80-90. ISSN 2452-414X. doi: 10.1016/j.jii.2019.04.002.

Manogaran, G., Alazab, M., Shakeel, P. M., & Hsu, C.-H. (2022). Blockchain Assisted Secure Data Sharing Model for Internet of Things Based Smart Industries. IEEE Transactions on Reliability, 71(1), 348-358. doi: 10.1109/TR.2020.3047833.

Nasiri, B. (2017). A modern teaching environment for process automation (master's thesis, Aalto University, School of Chemical Engineering).

Nuttah, M. M., Roma, P., Lo Nigro, G., & Perrone, G. (2023). Understanding blockchain applications in Industry 4.0: From information technology to manufacturing and operations management. Journal of Industrial Information Integration, 33, 100456. ISSN 2452-414X. doi: 10.1016/j.jii.2023.100456.

Patil, A. S., Tama, B. A., Park, Y., & Rhee, K. H. (2018). A framework for blockchain based secure smart greenhouse farming. In CSA-CUTE 17: Advances in Computer Science and Ubiquitous Computing (pp. 1162-1167). Springer Singapore.

Puthilibai, G., Benil, T., Chitradevi, S., Devatarika, V., Kumar, D. R. A., & Padma, U. (2022). Securing IIoT sensors communication using blockchain technology. In 2022 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS) (pp. 1-4). Chennai, India: IEEE. doi: 10.1109/ICPECTS56089.2022.10047053.

Qi, Q., & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. IEEE Access, 6, 3585-3593. doi: 10.1109/ACCESS.2018.2793265.

Reddy, K. R. K., Gunasekaran, A., Kalpana, P., Sreedharan, V. R., & Kumar, S. A. (2021). Developing a blockchain framework for the automotive supply chain: A systematic review. Computers & Industrial Engineering, 157, 107334. doi: 10.1016/j.cie.2021.107334.

Risso, L. A., Devós Ganga, G. M., Godinho Filho, M., de Santa-Eulalia, L. A., Chikhi, T., & Mosconi, E. (2023). Present and future perspectives of blockchain in supply chain management: A review of reviews and research agenda. Computers & Industrial Engineering, 179, 109195. doi: 10.1016/j.cie.2023.109195.

Sansana, J., Joswiak, M.N., Castillo, I., Wang, Z., Rendall, R., Chiang, L.H., & Reis, M.S. (2021). Recent trends in hybrid modeling for Industry 4.0. Computers & Chemical Engineering, 151, 107365.

Smith, R.S. (2004). Robust model predictive control of constrained linear systems. In Proceedings of the 2004 American Control Conference (Vol. 1, pp. 245-250). Boston, MA, USA. doi: 10.23919/ACC.2004.1383612.

Sundarakani, B., Ajaykumar, A., & Gunasekaran, A. (2021). Big data driven supply chain design and applications for blockchain: Action research using case study approach. Omega, 102, 102452. doi: 10.1016/j.omega.2021.102452.

Tadesse, Y. (2020). State of the art process automation systems (master's thesis, Aalto University, School of Chemical Engineering).

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415. doi: 10.1109/TII.2018.2873186.

Tavana, M., Nasr, A. K., Ahmadabadi, A. B., Amiri, A. S., & Mina, H. (2023). An interval multi-criteria decision-making model for evaluating blockchain-IoT technology in supply chain networks. Internet of Things, 22, 100786. ISSN 2542-6605. doi: 10.1016/j.iot.2023.100786.

Weyer, S., Meyer, T., Ohmer, M., Gorecky, D., & Zühlke, D. (2016). Future modeling and simulation of CPS-based factories: an example from the automotive industry. Ifac-Papersonline, 49(31), 97-102.

Yang, X. (2021). Blockchain-Based Supply Chain Finance Design Pattern. In IHMSC 2021: 13th International Conference on Intelligent Human-Machine Systems and Cybernetics (pp. 200-203). doi: https://doi.org/10.1109/IHMSC52134.2021.00053.

Yu, C., Jiang, X., Yu, S., & Yang, C. (2020). Blockchain-based shared manufacturing in support of cyber physical systems: Concept, framework, and operation. Robotics and Computer-Integrated Manufacturing, 64, 101931. ISSN 0736-5845. doi: 10.1016/j.rcim.2019.101931.

Zhang, Y., Lu, X., & Wang, X. (2019). Quantum computing for optimizing complex chemical reactions. Journal of Chemical Physics, 150(12), 124106.

Zhao, J., & Li, Y. (2022). Supply chain security evaluation model and index system based on a 5G information system. Neural Computing and Applications, 34(15), 12271–12281. doi: https://doi.org/10.1007/s00521-021-06584-5.

Zhu, K., Fuh, J. Y. H., & Lin, X. (2022). Metal-Based Additive Manufacturing Condition Monitoring: A Review of Machine Learning Based Approaches. IEEE/ASME Transactions on Mechatronics, 27(5), 2495-2510. doi: 10.1109/TMECH.2021.3110818.

Zia, K., Turjo, M. D., Khan, M. M., Kaur, M., & Zaguia, A. (2021). Smart Supply Chain Management Using Blockchain and Smart Contract. Scientific Programming, 2021, 6092792. ISSN 1058-9244. doi: https://doi.org/10.1155/2021/6092792.

APPENDIX 1: Helical coil whole data

Matlab code

```matlab
load('flowmeter_a.mat'); % cold flow l/hour
load('flowmeter_b.mat'); % hot flow l/hour
load('temp13_cold_water_out.mat'); % celcius degrees
load('temp14_cold_water_in.mat'); % celcius degrees
load('temp15_hot_water_in.mat'); % celcius degrees
load('temp16_hot_water_out.mat'); % celcius degrees
flowmeter_a = ts_flowmeter_a_1_second.Data;
flowmeter_b = ts_flowmeter_b_1_second.Data;
temp1_hot_water_out = ts_temp13_cold_water_out_second.Data;
temp2_hot_water_in = ts_temp14_cold_water_in_second.Data;
temp3_cold_water_in = ts_temp15_hot_water_in_second.Data;
temp4_cold_water_out = ts_temp16_hot_water_out_second.Data;
data1 = flowmeter_a;
writematrix(data1,'flowmeter_a.csv');
data2 = flowmeter_b;
writematrix(data2,'flowmeter_b.csv');
data5 = temp1_hot_water_out;
writematrix(data5,'temp13_cold_water_out.csv');
data3 = temp2_hot_water_in;
writematrix(data3,'temp14_cold_water_in.csv');
data4 = temp3_cold_water_in;
writematrix(data4,'temp15_hot_water_in.csv');
data6 = temp4_cold_water_out;
writematrix(data6,'temp16_hot_water_out.csv');
data_whole = [data1 data2 data3 data4 data5 data6];
writematrix(data_whole,'helical_coil_whole_data2.csv');
fig1 = figure;
subplot(3,2,1);
plot(flowmeter_a);
subplot(3,2,2);
plot(flowmeter_b);
subplot(3,2,3);
plot(temp2_hot_water_in);
subplot(3,2,4);
plot(temp1_hot_water_out);
subplot(3,2,5);
plot(temp3_cold_water_in);
subplot(3,2,6);
plot(temp4_cold_water_out);
```

APPENDIX 2: A linear ARX model data results

Matlab code

```
load('digital_twin_online_testi_20230517.mat');
start1 = 10;
Input_exp1 = [digitaltwintesti202305172.flowmeter_a(start1:end) digitaltwin-
testi202305172.flowmeter_b(start1:end) digitaltwintesti202305172.tempera-
ture14(start1:end) digitaltwintesti202305172.temperature15(start1:end)];
Output_exp1 = [digitaltwintesti202305172.temperature13(start1:end) digitaltwin-
testi202305172.temperature16(start1:end)];
modeloutput_y1 = digitaltwintesti202305172.modely1(start1:end);
modeloutput_y2 = digitaltwintesti202305172.modely2(start1:end);
Ts = 1;
u1 = Input_exp1;
y1 = Output_exp1;
nldata = iddata(y1,u1,Ts);
load('helical_coil_arx_model_2.mat');
figure
compare(nldata, sys)
figure
resid(nldata,sys)
figure
hold on;
plot(y1(:,1),'r');
plot(modeloutput_y1,'b');
hold off;
figure
hold on;
plot(y1(:,2),'r');
plot(modeloutput_y2,'b');
hold off;
```