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Author(s): Helo, Petri; Hao, Yuqiuge; Gunasekaran, Angappa

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Use of non-fungible tokens in operations and supply chain management

Petri Helo, School of Technology and Innovations, University of Vaasa, PO Box 700, FI-65280 Vaasa, Finland, email: phelo@uwasa.fi *

Yuqiuge Hao, School of Technology and Innovations, University of Vaasa, PO Box 700, FI-65280 Vaasa, Finland

Angappa Gunasekaran, School of Business Administration, Pennsylvania State University-Harrisburg, Middletown, PA, USA

Abstract

Non-fungible tokens (NFT) are secured storage method for unique and non-interchangeable data items. While NFTs are commonly associated with digital arts and the cryptocurrency market, the paper explores their potential in industrial applications, particularly within operations and supply chain management. The paper introduces the technology and key processes of NFTs, providing a foundation for understanding their application in operations and supply chains. The design science method is employed by conducting requirement collection with a small group of experts and based on this a set of potential applications for operations and supply chain management is outlined. Five use case applications are presented from the requirements management point of view. The artifact developed in the process is a sample implementation, demonstrating how NFTs can be practically employed to address specific operational requirements. The results indicate that physical components, digital assets, uniqueness of the entity, contracts, security, and multiple stakeholders collectively enable various use cases where NFTs can provide value.

Keywords: non-fungible tokens, blockchain, operations, supply chain

SDG 9: Industry, innovation and infrastructure

1. Introduction

Non-fungible tokens (NFT) are blockchain-based technology for storing unique and non-interchangeable piece of data. NFTs are based on blockchain technology and present tradable digital assets (Wilson et al. 2021). Blockchain technology is rooted on cryptocurrencies, but the distributed immutable ledger technology has been applied to real processes such as operations and supply chains. Distributed ledgers have solved several problems in tracking and tracing of supply chains by offering a technological solution based on consensus of replicated synchronized data dispersed around the world on different servers. The key strength of blockchain is its ability to secure data from tamper (Kugler 2021).

Apart from the cryptocurrency applications, blockchain technology has solved problems, which are related to digital signatures and stamping. Non-fungible tokens have primarily emerged in digital arts and other digital media such as video collectibles (Trautman 2021), where their use has been predominantly to proof to represent the ownership of the unique digital item. In other words, NFTs ensure that there is only one authentic copy of a digital asset, verifiable through blockchain technology (Sestino et al. 2022).

NFTs offer a promising technology for applications beyond the digital art, much like blockchain has expanded beyond cryptocurrency (Bao and Robaud 2022). A non-fungible token is a digital representation of real-world assets such as art, music, or any other document (Charlmers et al. 2022). Non-fungible tokens are based on blockchain technology and are stored as blocks on the blockchain structure. Unlike cryptocurrencies, NFTs are not fungible, meaning NFTs cannot be interchanged with any other item or asset. Each token contains its own unique identification code and metadata, enabling it to be distinguished from other NFTs. The blockchain structure allows for the content of the NFT to be viewed and shared but does not alter the ownership data stored in the token.

An ongoing debate surrounds the actual value of NFT technologies. The excessive prices have created speculative markets for digital assets and automated mass creation of NFTs for the sake of creating digital assets to be sold has not helped the situation. One of the criticisms has been targeting to the lack of tangible value of the assets. Linking the digital assets to physical assets which would have already existing value could solve this problem. The question of possible NFT applications has been studied before. Gonserkewitz et al. (2022) outlined research addenda based on a systematic literature review. The most discussed items according to this study were related to art collectibles, gaming and metaverse assets. Hammi et al. (2021) described the technological structure of NTF and outlined four possible applications, which are closer to industrial applications. These areas were metaverse, digital twins, proof of property, and authentication applications. However, a more specific potential applications within the industrial context has not been studied extensively.

The developments in the field of operations and supply chain management have been driven by information technology (Holmström et al. 2019) including cloud computing (Cao et al 2017), tracking and tracking applications (Liu et al 2021), machine learning (Agrawal et al 2024), and Internet of Things (Ben-Daya et al. 2019). The Industrial 4.0 is characterized by exponential technological advancements which have the potential to alter how we perform our daily activities. The operations and supply chain management needs to evolve and adapt to these developing technologies to maintain the ability of workers to perform reliable and quality operations. This literature has shown that the industry is continuously looking for technologies to keep pace with the developments of industrial revolution, especially to have better visibility of operations, improvement of efficiency, reduction of costs and emissions, and ensuring a reliable delivery of goods. The operations process involves inspecting and verifying documents related to specifications and origin of raw materials or process steps. These documents are highly susceptible to fraudulent activities such as the manipulation of information or destruction. In recent times there has been a surge in corporate fraud cases.

The purpose of this paper is to study the key characteristics of NFT technology and proposes potential applications for industry. There have been only few studies suggesting supply chain applications for non-fungible tokens. Far et al. (2022) suggested tracking of assets, Joy et al. (2022) proposed the technology as expansion of luxury goods. These papers present the concept in high level, but the actual implementation details are not outlined. We believe that non fungible tokens have a much wider potential. The research problem we set for this study converted into two normative research questions: (RQ1) What are the key features of NFT which can provide solutions to operations and supply chain management? (RQ2) What are the possible NFT applications for the operations and supply chain management? The research method employed for the study is an implementation of design science. Firstly, the requirements are collected from experts or stakeholders and then an artifact – or a technical solution is designed and implemented for the analysis and evaluation. The benefits of this approach are problem-solving orientation, which enables further development based on initial version. The developed artifact should have practical relevance.

The reminder of the paper is as follows: Technology overview, NFT process and current applications are presented. Based on the literature review, we outline the features for NFT technology. Then by using a design science approach with a small expert panel workshop a set of possible application areas are developed. Potential applications are outlines by analysing a set of cases and their requirements. Technical solutions are designed to fulfil the requirements and the solutions are evaluated. Finally, the results are concluded, and a summarizing framework of potential applications is presented.

2. Technology overview

This section an overview of NFTs, their current applications, and their potential link to operation and supply chain management. NFTs are a derivative of blockchain technology, which has been applied to various fields, including sustainability in supply chains (Saberri et al. 2019; Sarkis and Ibrahim 2022; Wang et al 2021; Wang

et al 2019), intralogistics (Bai and Sarkis 2022), cybersecurity building block for zero security supply chains (Collier and Sarkis 2021), and global supply chains (Chaing et al 2020). While blockchain is still maturing, NFTs have some distinct features that differentiate them from other blockchain applications, and making it important to study specific use cases in supply chains.

2.1 Non-fungible tokens

NFTs are digital assets characterized by two key features: uniqueness and secure ownership verification. Each NFT represents a unique item, secured through blockchain's signature creation and verification process, enabling their use in commercial transactions such as royalties and transfers (Wilson et al 2021). In economic terms, fungibility refers to the interchangeability of items with a market and value. Commodities like oil, metal ingots, wood, frozen pork belly are examples of physical fungible items. Cash money and cryptocurrencies are examples of digital fungible items with known and widely available aftermarkets (Wilson et al 2021; Chalmers et al 2022).

On the other hand, non-fungible items are based on uniqueness and thus resulted non-exchangeability. A painting, a statue, a real estate property are examples of unique items which have value but are not exchangeable in a sense that an oil barrel has same value as another oil barrel. Digital non-fungible items are typically similar – a piece of artwork, master record of music or the original video clip of an event. Then main issue is that the value of the non-fungible item is connected to its scarcity (Chohan 2021).

The key properties of NFTs include indivisibility, transferability and security. NFTs are stored on blockchains, which are immutable distributed ledgers initially developed for cryptocurrency but have since found applications in areas like supply chain traceability (Helo and Hao 2019). The structure of a blockchain is based on data elements called blocks, which are citing each other by using a hash checksum to previous link of the chain. Each node is stored in the block. Figure 1 illustrates this in a high level.

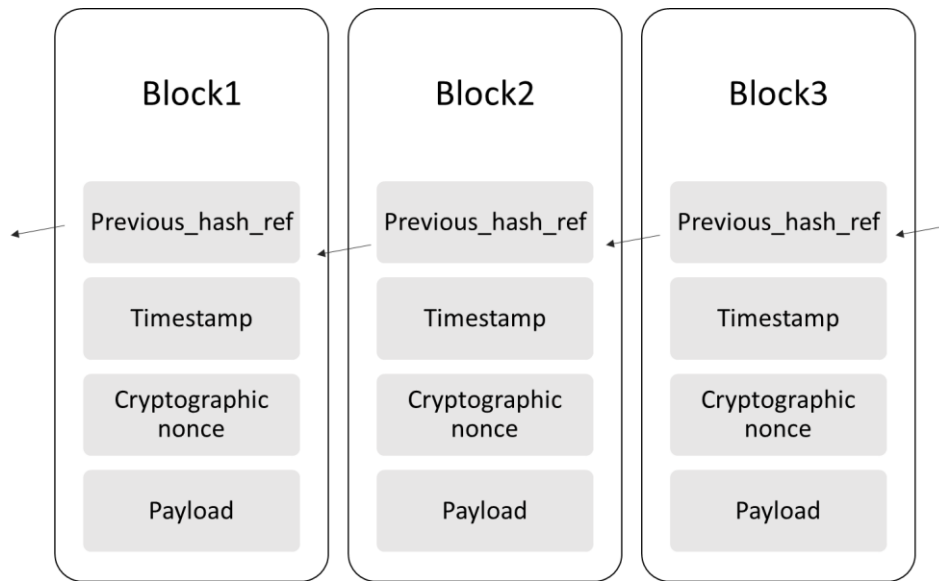


Figure 1. Blockchain structure as a container for information.

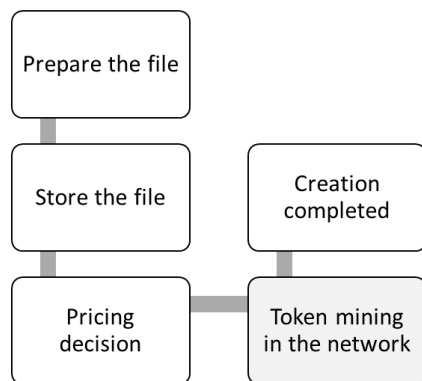
Figure 1. Alt-text. A figure showing an example of blockchain structure, three blocks with payload content, timestamp and cryptographic nonce, then each block citing to previous block hash reference.

Technologically, NFTs are primarily based on Ethereum blockchain and follow the EIP-721 standard, which outlines an interface how to track and transfer NFTs (EIP-721). This technology is based on the stack of Solidity contracts. According to EIP-721 standard, the system has been developed to support ownership of a digital or a physical asset, including but not limited to (1) physical properties, (2) virtual collectibles and (3) liabilities - assets with negative values. ERC-721 compatible smart contract should implement certain interfaces to implement transfer, approval related queries.

In addition to Ethereum network-based implementations also Flow (Flow 2022) and Tezos (2022) based applications have been presented. Low-latency and usability of the protocol has been presented as benefits of these technologies compared to Ethereum/Solidity. As new applications are emerging and better implementations are needed for example ticketing, it is expected that the technology will evolve fast in the near future. One of the potential challenges related to NFT technology is that scalability in terms of large quantities of assets may be limited by the blockchain network (Park et al. 2021).

To create and utilize the NFTs, at least two key processes of NFT transactions are required. These are, firstly, the creation of a new NFT asset from a digital file, and secondly, buying an NFT from a marketplace, which is technically a change of ownership of a digital asset. Other supporting processes include verification, borrowing and loaning, or even termination of the asset. The process steps are illustrated in Figure 2. A specific case of buying and selling is swapping which is similar transaction of ownership combining two sales transactions with zero currency exchanged.

Process 1: Create a new NFT



Process 2: Buy an NFT from marketplace

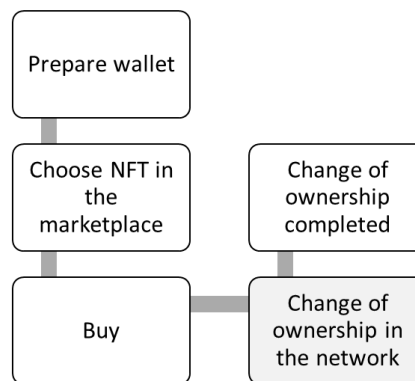


Figure 2. The process steps for creation and buying an NFT digital assets.

Figure 2. Alt-text: Process chart 1: showing steps to create a new NFT: prepare file, store file, pricing decision, token mining, creation complete, Process chart 2: showing steps for buying NFT from a marketplace - prepare wallet, choose the marketplace, buy, change of ownership, completion.

From practical implementation point of view, many blockchain related technologies have had issues with scalability and performance. In order to present improvements, Layer 2 solutions have been presented to improve this. This refers to parallel processing and merging transactions to scale up the network performance. In practice this technology includes Rollups and State Channels which are technological implementations build on top of blockchain layer (Mandal et al. 2023).

2.2 Current applications

The best known NFT implementations are related to digital art sales (Kugler 2021). World record sales price for NFT artwork has been “Everydays: The First 5000 Days” which is an artwork authored by artist Beeple. Christies auction house sold the NFT 69.3 million USD or 39134 ETH by a wealthy collector. A novel cryptocurrency-based market transaction has attracted attention to this technology. Peaking sales valuation of proven unique digital assets have borrowed logics from arts sales.

Only few studies about the NFT market have been conducted. Nadini et al. (2021) analysed several NFT networks and described the trading networks and the key metrics of the then four-year-old market booming. Soaring prices of virtual assets have attracted speculators and there have been all kinds of non-healthy market phenomena. As market of virtual arts are not widely understood, massive amount of automatically generated pixel art has been introduced for speculative markets (Pepescu 2021). In some cases, prices have been pumped

up by selling the asset between linked partners, sometimes even the seller and buyer, have been in reality the same actor. Scams have also been reported and this all has put a bad name for NFTs and market. According to Nadini et al. (2021) 90% of the total volume exchanged on NFTs was related to arts, gaming, and metaverse objects. For this reason, we aim to focus on more operational applications of NFTs in this paper and leave the less actual value adding, or even irrational, activities aside.

The applications of NFTs in business and management has been studied by Anjum and Rehmani (2022). The common factor for the current applications is related to distribution of digital unique files in business: these could be images, audio, video; virtual models, fashion. The e-commerce applications, which has been seen the public are:

- Original digital artworks (Bsteh and Vermeylen 2021)
- Music (Husin et al. 2021)
- Domain names (Sun 2022)
- Event tickets (Regner et al. 2019).
- Fashion products, virtual and physical limited number items (Rodriguez Sanchez and Garcia-Badell 2023).
- Virtual game accessories (Raman and Raj 2021)

Marketplaces for NFTs such as OpenSea have typically a brokering type of business model where they charge 2.5% of the final sale value, and there is no gas cost to create a new NFT item in the market. For successful applications, this kind of centralized marketplace seems to be needed for transparent market pricing (White et al. 2022). A good review of possible use cases is presented by Singh (2022) demonstrating applications beyond the digital arts. Chalmers et al. (2022) also speculated potential applications related to creative industries. When moving toward mass-produced items, researchers of consumer studies have identified the possibility to link NFT with the experience of purchasing or owning a unique item (Alkhudary et al. 2022), which could link to mass customisation of products and smart connected software defined products (Schulz et al 2023).

The implementations of NFTs have not been spread in great speed. The challenges identified by the literature (Ali et al. 2023) include similar barriers seen with blockchains, including slow and expensive processing (Wang 2021), privacy (Uribe and Waters 2020), legal (Rehman et al. 2021), and security related (Menezes 2018) matters, as well as concerns of environmental impacts (Jiang 2021). This might be the reason also for that despite industrial applications have been presented too, but many of these are laboratory experiments or proofs of concepts. Chiacchio et al. (2022) presented an NFT based solution for the tracking and tracing items in the pharmaceutical supply chain. Similar approach was piloted by Omar and Basin (2020) in the same industry. Cybersecurity of Internet of things also requires methods, where linking the virtual and real objects could add value. Arcenegui et al. (2021) have presented a concept how IoT devices mapping can be done safely by using NFTs.

Several related concepts are looking for applications. Web3 is an umbrella concept covering several related technologies (Ray 2023), including (1) NFT - Non-Fungible Tokens, the scope of this paper, but also (2) DApps - Decentralised Applications, which aims for development of decentralized software applications often related to exchange of blockchain based assets, (3) DeFi – Decentralized Finance, which refers to protocols and other supporting technology alternative financial exchanges, and (4) DAO - Decentralized Anonymous Organisation, which are organisations that can govern certain operations such as purchasing assets anonymously. The common factor behind all these is a set of new decentralized applications for the web, often based on blockchain technologies, but for different purposes. As probably the widest concept is decentralized society (DeSoc) is a concept considering other social related bonds that financial transactions (Ohlhaber et al. 2022).

When moving closer to domains of operations and supply chains, Decentralized Physical Infrastructure Networks (DePIN) is a practical concept. This refers to distributed ledgers technology combined with crypto-economic elements combined somehow with physical networks. This could be related to the governance of information technology-based assets such as telecommunication systems, cartography assets, energy networks. Schuhmacher and Hummel (2016) demonstrated the concept with intralogistics in a learning factory. Technology has been also proposed for logistics collaboration (Pan 2024), and decentralized governance of autonomous cyber-physical systems (Nabben et al. 2024).

Physical Internet can be considered as a related concept (Sternberg and Norrman 2017), although it does not necessarily need DePIN technology to be implemented but such implementations have been presented in several application areas., for example logistics (Meyer et al. 2019), production and inventory system (Liu et al. 2024), Internet of Things (Tran-Dang et al. 2020).

2.3 Technology in operations and supply chains

These digitalization technologies offer significant potential to transform operations and supply chains, driving operational excellence, cost reduction, improved customer satisfaction, and competitive advantage. Organizations can strategically adopt and integrate advanced technologies based on their specific needs and objectives to gain a competitive edge in the evolving digital landscape. Digital twin is a central component of Industry 4.0 driven by modelling, data fusion, collaboration, and service. Digital twin contains dimensions of physical asset, virtual and connecting parts (Tao et al. 2018). The concept has been applied in manufacturing (Kritzinger et al. 2018), design and service applications (Liu et al. 2021), where digital models are maintained up to date with the physical installations current state (Schleich et al. 2017). The requirement of having a virtual simulation of the physical asset has been discussed (Tao et al. 2018), but generally there is a consensus about the key characteristics of digital twin approach (Liu, 2021; Jones et al. 2020).

The enabling technologies for the digital twin include physical, model, connectivity, service, and data technologies (Qi et al. 2021). These five elements build the five-dimension digital twin model, which provides

the links between virtual models, physical entities, and services by using digital twin data. In practice, this means IoT type of data collection, edge and cloud storage of the data, software architecture to process data and provide a control mechanism to interact between virtual and physical models.

On the other hands, in is very important to secure the virtual replicas and verifiable ownership of the virtual copy. NFTs associated with digital twins can store information about the asset's specifications, maintenance history, performance data, and other relevant details. Mouris and Tsoutsos (2022) have introduced a concept where NFTs are used to protect ownership of 3D models used in engineering the products. This approach suggests linking NFT to licencing the manufacturing of physical products. The challenges of circular economy and product life cycles is a problem identified by Van Nguyen et al. (2023). Based on a literature review, they propose that use of smart contracts technology in non-fungible tokens could be applied handling royalties for second hand product sales for closed-loop supply chains. Table 1 presents the research gaps identified in the literature. The use of non-fungible tokens in operations and supply chain management remains low, with only a limited number of real-life applications currently being used. Despite the potential, real-life implementations of blockchains, smart contracts and non-fungible tokens in industrial application has been less than anticipated. The identified barriers identified in the literature include scalability, transaction risks, market risk and regulatory risks (Biwas & Gupta, 2019). Technology adoption related barriers have also been identified as an important factor for slow progress (Kouhizadeh et al. 2021).

Table 1. Non-fungible token literature gaps identified.

Topics identified	Research gap	References
Implementation challenges of NFTs	Solutions are needed for blockchain related governance, intellectual property rights, security, technology maturity.	Ali, O., Momin, M., Shrestha, A., Das, R., Alhadj, F., and Dwivedi, Y. K. (2023) Hammi, B., Zeadally, S., & Perez, A. J. (2023).
Future possibilities	Literature review shows potential uses cases in categories of digital collectibles, arts, video games, metaverse.	Gonserkewitz, P., Karger, E., and Jagals, M. (2022). Davies, J., Sharifi, H., Lyons, A., Forster, R, and Elsayed, O. K. S. M. (2024).
Application examples	Fruit supply chain tracking example Pharmaceutical supply chains	Menanno, M., Savino, M. M., and Accorsi, R. (2023) Chiacchio, F., D’Urso, D., Oliveri, L. M., Spitaleri, A., Spampinato, C., and Giordano, D. (2022).

We can conclude from the recent works that the literature gap in existing research on NFTs in operations and supply chains remains underexplored compared to other blockchain technologies. Technology developments are taking place, which can enable innovation in product authentications and finance related solutions. From the operations and supply chain management application side point of view, there is a need for demand for visibility and transparency and especially sustainable practices and product safety.

3. Materials and method

Use of blockchains in operations and supply chain management has been discussed widely. Technical solutions have been proposed for ensuring the validity of transactions (Helo and Hao, 2019), transparency (Francisco and Swanson 2018), project installations (Helo and Shamsuzzoha, 2020) and sustainability (Saber et al. 2019), and security (Xu et al. 2021). Much less proposals have been given for NFTs application.

3.1 Design science research method

This study employs design science approach. Design science is a research method developing and validating prescriptive knowledge in operations management and information systems (Johannesson and Perjons 2014). The approach focuses on how things should be by introducing artifacts that aim to solve the presented problem (Dresch et al. 2015). The approach is useful providing systematic and robust methods for developing artifacts,

such as concepts, methods, and tools for practical implementation. The approach is human-centric and aligns with service design research. Design science is known for its usefulness for relevance for practice and is sometimes referred to as problem-solving research (Holmström et al. 2009).

The process aims to develop solutions for real-life problems and follows six steps (Figure 3). The first step is problem definition, where the aim and the scope of the problem is defined. The second step sets criterion for the solutions, requirements in other words. The third step is the design of the technical solution, the artifact, which is followed by the fourth step is the implementation of the design. The fifth step is the evaluation of the artifact against the requirements, or the criterion set in the step number two. This step is done often merged with the communication step (# 6).

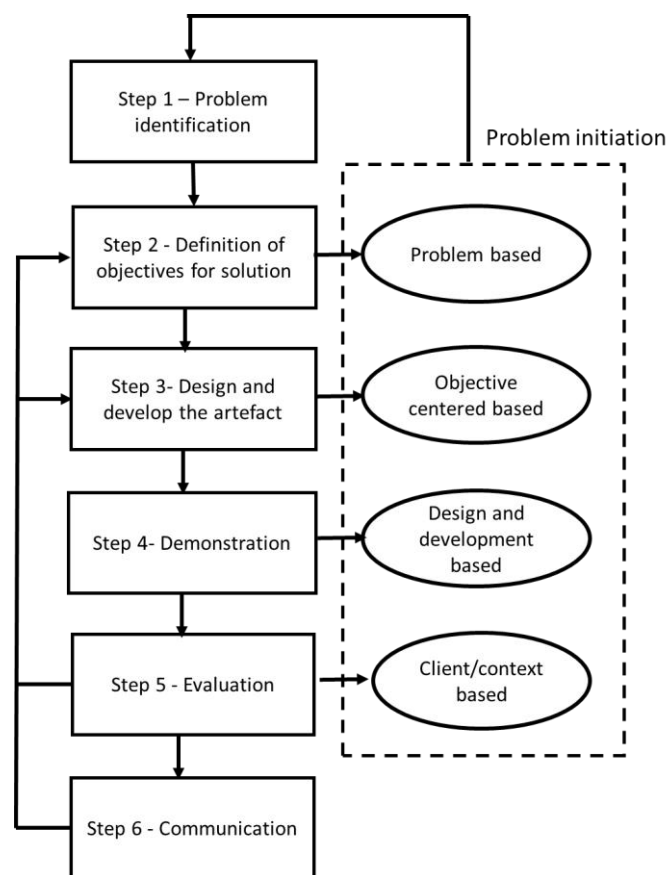


Figure 3. Process of design science (Von Brocke et al. 2020).

Figure 3. Alt-text: A process chart showing the six steps of design science approach - problem definition, objectives, design the artifact, demonstration, evaluation, communication.

Some of the earlier papers, such as Van Nguyen et al. (2023) have outlined potential blockchain and non-fungible tokens based on analysing literature. Design science approach has been used to create technical solutions related to specific problems related to blockchains, for example event processing at IKEA company (Sund et al. 2020), and cloud manufacturing for sheet metal (Helo et al. 2021). The research approach of this

study aims to continue this work and identify a potential set of real-life problems and propose technical implementations. In this process five domain experts working with information systems related to production/operations management and supply chains were selected and interviewed with semi-structured interview questions and asked to generate potential use cases, where NFT could provide a solution for a problem in the field. One can argue that this may cause a bias in responses, but on the other hand, understanding the NFT possibilities requires certain information system knowledge. The purpose of the setup was to generate and implement potential applications based on possible needs which could be highlighting the technical possibilities of NFTs.

The first session took two hours and after four weeks the solutions were presented for the evaluation and communication. All experts had background in managing software development projects in operations and supply chain for more than five years and had a technological understanding of NFT technology. None of the experts had actual implementation experience of non-fungible tokens in operations and supply chain.

The first step of method employed for this study was organised as a focus group interview, which aimed to generate possible use cases where NFT technology could present solutions. In this step, supply chain operations reference model SCOR, as seen in table 2, was shown to participants to highlight the five elements of management processes. Then the participants were asked to develop possible use cases for non-fungible tokens which could be developed as proof of concept.

Table 2. Supply Chain Operations Reference model processes SCOR (2017).

Management process	Description	Examples
Plan	Planning the supply chain operations to balance demand and supply	Forecasting Scheduling Production planning
Source	Processes related to procuring materials	Sourcing Supplier selection Purchasing Logistics/transportation
Make	Processes related to production of goods	Production/operations Quality control Product serial numbers Bill of materials Labelling
Deliver	Processes related to delivery of goods	Order fulfilment Inventory control Warehousing Customer delivery process Product traceability
Return	Return material flow from customers to manufacturing and vendors	Logistics/transportation Circular economy
Enable	Process related to management of supply chains	Business management Key performance indicators Contracts Risk management

3.2 Problem identification and requirements collected

Technology-Organization-Environment (TOE) framework has been widely discussed in the context of blockchain adoption in supply chain management (SCM) (Chittipaka et al., 2023), and it provides a good insight that different factors influence the adoption of emerging technologies. In alignment with previous research, this study also integrates the TOE framework into the design of the study's methodology. By doing so, the experts were asked about the key factors impact the adoption of NFTs in SCM. The technological dimension focuses on the capabilities and advantages of NFTs, while the organizational dimension considers the firm's readiness and leadership support. The environmental context considers external pressures such as regulatory requirements and market competition. This approach allows for a structured investigation, ensuring that all relevant aspects of NFT adoption are addressed within the scope of our research.

The first step in the process is the problem identification. Based on ideas collected from the group, a set of five potential use cases were selected. Then the requirements were outlined for each use case and short description describing the objectives and details of the problem. The selected problems to be solved were the following:

- Use case 1: Unique products - additive manufacturing
- Use case 2: Serialization of products
- Use case 3: Certificates
- Use case 4: Internet of Things
- Use case 5: Letter of Credit

The requirements collection was done according to framework of considering the following items: physical component, digital files, uniqueness, contract, security, and stakeholders involved. Figure 4 was created to show a flow picture of supply chain and how potential technology implementations of NFTs could take place on various operations.

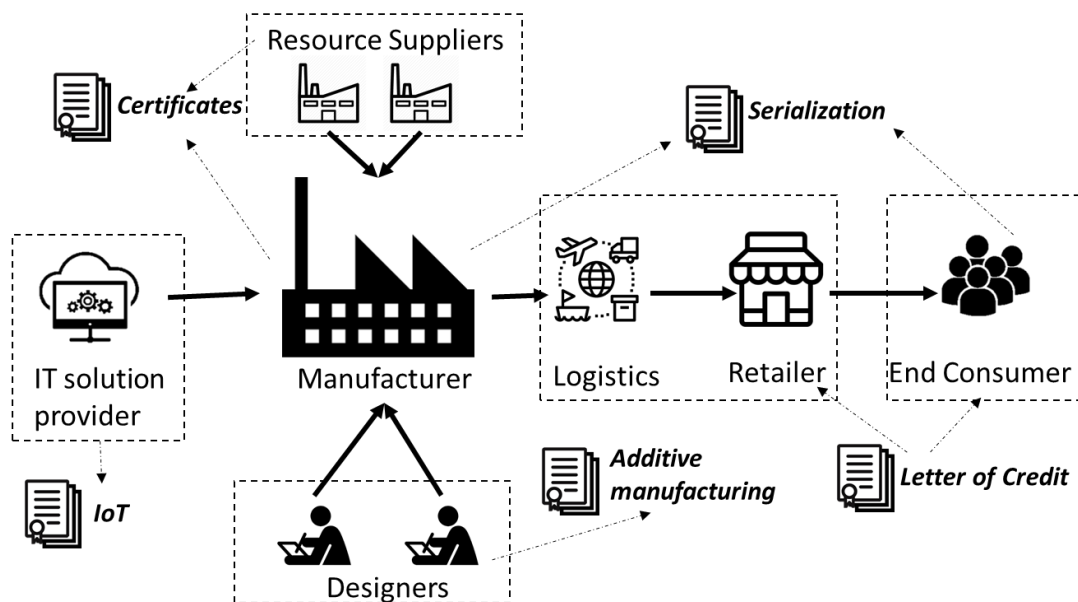


Figure 4. The potential use cases of using NFT in operations and supply chain management.

Figure 4. Alt-text: A figure showing the potential use cases in a form of a supply chain connecting IT solution providers, the manufacturer, logistics, retailers, end consumers, and designers.

The selected areas were presented by the expert panel, and it is obvious that this does not cover all possible applications of non-fungible tokens in supply chain management. One could expect to consider additional possibilities related to such as demand forecasting, procurement, inventory management, production planning, manufacturing, quality control, and other examples provided in table 2.

Based on the requirements analysed for each case, a simple technical implementation was proposed for each case and the implementation team-built examples. In practice this means, developing a simple Solidity contract based NFT and what properties and functionality each use case would need. The reason for this technology

selection was that Solidity contract technology is accessible for both development environments as well as test networks for piloting the software implementations.

4. Results – development of artifacts and analysis

The problem identification and description phases were followed by a design and implementation phase where selected use cases were solved by creating an artifact, a smart contract using non-fungible token modelling. Then, based on the implementation, the use case was evaluated according to five key feature criteria of non-fungible tokens.

4.1 Additive manufacturing – unique product instances

Unique product instances are commonly used in mass customization type of production. A production line may produce a great volume of goods, which all have a unique individual configuration enabled by assembly-to-order type of production or other postponement type of practices (Boone et al. 2007). Typically, the products have a serial number, and “as-built” bill-of-materials is stored for the future needs of maintenance. Non fungible tokens could be used as a unique digital twin part of a unique product.

Problem identification and description. Use of additive manufacturing technology brings the customization of production into a new level (Gao et al. 2015). For this reason, it was selected to highlight the case of uniqueness of the product in operations. Additive manufacturing is method for characterized by conversion of digital model to physical product. Managing intellectual property of such geometry may be financially important for the company owning the rights for the design. A geometry file with running parameters is very valuable as it contains the exact manufacturing information (see Figure 5). The challenge related to managing manufacturing information of additive manufacturing is that geometry files of the products are often easily converted to 3D printing and thus safe managing intellectual property may be a complex task. One might argue that additive manufacturing is not a mainstream problem in operations/supply chain management. However, the technology is emerging, and it can be considered as a disruptive one. Chevet (2018) anticipated that blockchain technology and non-fungible tokens would be reshaping value chains in creative industries. Currently this has emerged in arts field. Current manufacturing portals are often based on sharing 3D printing sample parts for free. Licensing the right to manufacture a product is challenging as there is very limited ways to ensure that the file has been used only once or for another amount of allowed verbatim copies. Digital rights management is a challenge for distributed global manufacturing also safety and security reasons. Pirated parts present a problem in aerospace and automotive industries. For pharmaceuticals industry it may a question of life and death.

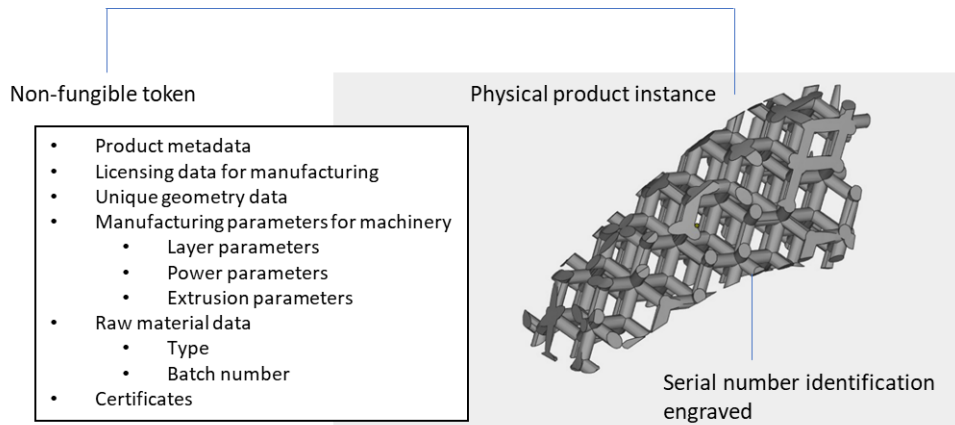


Figure 5. An example of complex unique geometry generated for additive manufacturing and link to non-fungible token.

Figure 5. Alt-text. A figure of component which looks like a mesh type of structure.

Based on discussion, the focus group described a potential problem which an NFT applications for additive manufacturing could solve. The key idea was to provide a solution for digital asset management – how ownership of and unique design could be transferred to additive manufacturer. The ownership of the asset should be verified easily the system should consider of potentially managing a limited series of manufacturing of the asset. In this case the digital asset is the STL file carrying the geometry of the part to be printed and the physical part is the printed part. Table 3 shows the requirements for the use case 1.

Table 3. Requirements for the Additive Manufacturing use case.

Requirement	NFT possible solution
Physical component	Product manufactured, stamped or engraved identification code.
Digital files	Manufacturing data for additive manufacturing; geometry file
Uniqueness	Each product instance created from the model, e.g. parts which are produced as unique copies engineered for certain specification.
Contract	Licensing manufacturing rights from copyright holder to make a product.
Security	Illegally produced product instances
Stakeholders	Designer Manufacturer

NFTs are often used to represent ownership of unique digital objects that do not have real object equivalents, e.g. digital art. But this new technology also allows the tokenized ownership of a 3D model equivalent of a

real and unique object. These two entities are interlinked; one represents the real and the other represents the virtual. There can only be one authentic NFT equivalent of any real object.

Design and implementation of the artifact. Based on the requirements collected a simple implementation of NFT for managing a single file package for additive manufacturing was created (see code snippet below Figure). The implementation has been done with Solidity and the contract includes *fileName*, which should refer to an STL file used for 3D printing; as well as description (e.g. part dimensions, suggested materials, copyright) and owner property information. The constructor function initializes the properties once the asset is created.

As demonstrated in Appendix I, the creator of NFT can sell or give the asset by using *transferOwnership* function. Printing a copy could be integrated to transferring the ownership of the asset back to its creator. A more sophisticated code could also implement a counter for prints so the number of prints could be limited to e.g. 100 pcs and the consumption would be maintained in the file. This kind of functionality requires integration to machinery.

Evaluation and communication. The limitation of this approach is that NFT does not solve the problem of protecting physical access or making illegal copies. Digital right management type of tools are still needed in the digital twin. Non fungible token solves just part of the process, linking safely the digital asset stored in NFT with the physical asset. For this reason, the conclusion is that NFT provides a partial solution for the problem but still requires a deep integration with other systems. Use of an NFT for every single product instance may not be feasible solution in all cases. It would probably generate a lot of data and in some cases just blockchain based serial numbering could fulfil the requirements. However, in case of uniquely engineered design as described in mass customization, combining the raw material traceability for demanding applications and possibility to combine this with life-cycle data of using the part long time, would justify a digital twin stored in non-fungible token form.

4.2 Serialization

Serialization in the context of production/operations is originating from pharmaceutical industry where regulation has forced the industry to improve the traceability of product into the consumer-packaged primary packaging level. Counterfeit medicines and sale of expired medicine in fake packages has caused severe problems and reduced trust in the products. Serialization has solved these problems as tracking and tracing can be from the downstream of the supply chain.

Problem identification and description. Tokenization of physical assets is a possible implementation area for smart connected products and blockchains (Weingärtner 2019). Secure anti-counterfeit actions in the pharmaceutical industry are a potential applier of non-fungible tokens (Omar and Basir 2020). Each product can be assigned a unique identifier or serial number, which can be converted into an NFT. This NFT can store information about the product, including its manufacturing details, component sources, quality certifications,

and any relevant documentation. This helps track the product throughout its lifecycle and enables verification of its authenticity.

A generic supply chain-based serialisation application was suggested by the group members as a potential application to solve the traceability. In this example, each product package is linked from primary package (such as pill plate) to secondary retail packaging (cardboard consumer box) to wholesale packages (bundles, cases) which are linked to pallet level tracking. Figure 6 shows the hierarchy from logistics point of view.

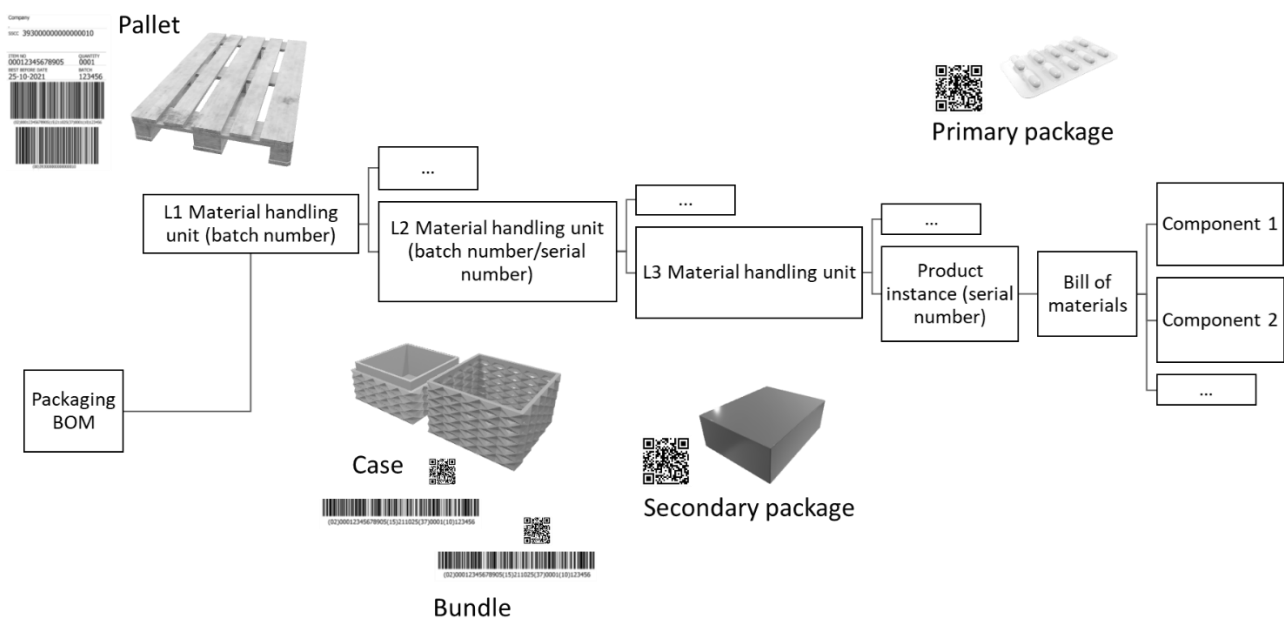


Figure 6. Pharmaceutical serialization levels and bill of materials structure.

Figure 6. Alt-text. A figure of pills connecting to box, connected to a plastic crate connected to a pallet by bar codes.

Table 4 shows the requirements for this use case. The key stakeholders are manufacturer of the product and the end consumer, but also all participants along the supply chain, vendors, transportation companies, warehouses, wholesalers, retailers could contribute the creation of data and verify the authenticity of the product and package.

Table 4. Requirements for the serialization.

Requirement	NFT possible solution
Physical component	A unique material handling unit: for example, crate, box, container, pallet.
Digital files	Product serial number data and manufacturer information related to this
Uniqueness	Each product instance created from the model, validity of the product
Contract	Verification of source of the product origin
Security	Counterfeit products
Stakeholders	Manufacturer End-consumers Other stakeholders in the supply chain

Design and implementation of the artifact. This Solidity contract defines a struct called Product, which stores the information for our pharmaceutical product. The mapping tokenIDToProduct links the NFT token ID to the right Product. The manufacturer uses function createProductNFT to create new serial number implementations (NFTs). This function links manufacturing information into the payload. This type of contract can be extended to handle ownership transfer to other stakeholders in the supply chain. The code for this function is shown in Appendix II.

Evaluation and communication. The implemented smart contract was very plain and straightforward. It solves creation of link between product serial number and the shipping data. More complex functionality could have been designed to support several production steps in the supply chain. This implementation stores only the key information. In the discussions, it was noted that such implementation in real-life would need links to enterprise resource planning systems, manufacturing execution systems, transportation management systems or something similar responsible for the master data in the production process. Another critical note for this use case was the processing speed of creation of new contracts. In case of high-volume manufacturing, such as the pharmaceutical example, the performance and the cost of using Ethereum network would not be feasible.

4.3 Certificates

Certificate of authenticity (COA) is related to trade and logistics of many finished goods, components, and raw materials. Certificate of authenticity may be needed for several reasons. Traditional examples from supply chain are related to show evidence that product is original, made in a certain location, approved for the use and produced according to certain standards to proof those custom fees and taxes are completed as required.

Problem identification and description. Sustainability data is an increasingly important driver for certificates. Companies need to ensure their customers and end-users that sustainability has been considered along the supply chain. There are three types of concerns related to sustainability:

- Socially sustainable sourcing aims to show that society is considered in the supply chain. Use of slaves, prisoners or child labour are major concerns for some labour-intensive industries.
- Environmental traceability is driven by reported GHG emissions. Companies want to show that calculated GHG emissions are traceable in the supply chain. Additionally, firms aim to show that no natural resources such as water, forest has not been used extensively in places which could endanger nature.
- Economic sustainability is related often to fair trade. Companies want to show that people working in low-cost operations, factory workers, farms are getting decently paid.

Certifications, compliance documents, and licenses related to operations and supply chains can be transformed into NFTs. These NFTs can securely store the necessary information, such as certification authorities, expiration dates, and audit records. By associating NFTs with compliance documents, stakeholders can easily access and verify the authenticity of certifications and compliance-related information. Another related possible technology is product passport, which is an EU driven initiative to standardise environmental reporting for products and report the footprint in a standard format – Digital Product Passport (Walden et al. 2021). Technical interoperability is enabled by common requirements and standard layouts (Jensen et al 2023). However, product passport does not link to unique product instance level as in the serialisation example proposed in this use case. Table 5 shows the requirements collected in a high-level use case.

Table 5. Requirements for the Certificate use case

Requirement	NFT possible solution
Physical component	QR code printed in the physical product, T-shirt, jersey, coffee bag, vintage wine bottle.
Digital files	Certificate of material used, process used, workforce, resources
Uniqueness	Each product item or production batch with a long life-cycle and possibility of being traded later.
Contract	Certificate of authenticity
Security	The product has the features promised
Stakeholders	Source (vendor, mine, harvest) Manufacturer End-consumer

Design and implementation of the artifact. The implementation in Appendix III shows a sample contract of coffee bean bag certificate of origin implementation in Solidity. This code creates a certificate of origin which links producer name, the country of origin, lot number for production and certain processing parameters such

as harvest date and roast date. The information is linked to a person who processed the manufacturing operations. The hypothetical certificate can be verified by the end users.

Evaluation and communication. The implementation of Certificate of Origin is closely related to previous serialisation use case. The key differences are that instead of product package level link a lot or batch number may be used, and the main purpose is to authenticate the product itself. A possible limitation of this implementation is that product labelling system needs to be built to support the link to non-fungible token. A possible enabling feature is that financial transactions, such as wholesale level buying and selling of assets may be linked to batch level certificates.

4.4 Asset ownership of IoT device

Internet of Things is changing operations and supply chains by introducing smart connected products. One of the key features of end products is that IoT enables changing the functionality of the product by software updates. A user may have a license to operate equipment under certain terms and condition for a period agreed in the service level contract. Software and the functionality may be updated over the air. This kind of features have been visible in products ranging from smart watches to new passenger cars. Safe use of equipment required licensed software distributions and matching hardware to software link (OTA updates).

Problem identification and description. Industrial Internet of Things is a domain, which has requirements of security related to asset management. NFTs can be used to represent ownership and transfer rights of IoT within the supply chain, such as equipment, machinery, or inventory. By associating an NFT with an asset, the ownership and transfer of that asset can be securely recorded on the blockchain, providing a tamper-proof and auditable record of ownership history. Arcenegui et al (2021) presented an approach to bind physically IoT devices to NFTs by using physically unclonable functions. Sghaier and Basir (2020) have introduced an NFT based approach for decentralized cybersecurity framework for authentication, authorization, and accounting (AAA). Wang et al. (2022) demonstrated a blockchain-based digital twin management architecture to ensure information sustainability for physical IoT devices.

The focus group selected IoT applications and cybersecurity of assets as third potential use case of the NFTs. Table 6 illustrates the requirements collected for the connected smart product with IoT.

Table 6. Requirements for the IoT use case.

Requirement	NFT possible solution
Physical component	IoT tracking device or smart connected product with a serial number.
Digital files	Certificate of material used, process used, workforce, resources
Uniqueness	Each software has been distributed to run on a certain hardware.
Contract	Use of software license
Security	Avoiding illegal software copies. Non tampered software configuration to avoid cyber security attacks.
Stakeholders	Software vendor End-consumer edge device

Design and implementation of the artifact. A simplified NFT implementation of the solution was developed to link the device and its current software (Appendix IV). The licencing may have locations and possible range of uses linked to the hardware. In this example, for the software update functionality, there is no separate method, but a new NFT contract is created overriding the old one.

Evaluation and communication. The proposed solution needs to be deployed in a cloud-based server solution managing the connectivity and data collection from IoT devices. Technically, the proposed smart contract may solve the functional needs described, but regular software updates in a large fleet of devices may present a challenge of expensive Ethereum network utilisation. For this reason, other contract types should be recommended for real-life applications.

It should be noted that a standard blockchain implementation could fulfil some of the requirements very well. A more special use case would be when user purchases a complex smart connected device from the manufacturer an NFT would be transferred to digital wallet confirming the validity of license of using the device and its services. In case the ownership of the device would be changed to another organisation, the records of asset history would be transferred to the new owner. NFTs are originally designed to include rich metadata and large data payloads. This could perhaps also enable more complex ownership structures such as fractional ownership.

4.5 Letter of Credit

Finance related applications of blockchain have been typically related to cryptocurrencies. Potential uses cases for the auditing point of view have been presented by Dingelstad (2021). There are speculations and the non-

fungible tokens can present central building blocks for value systems in so called parallel societies (Wang et al 2021).

Problem identification and description. The fourth application of supply chain side proposed was a letter of credit, which could be used for releasing payment based on receiving goods by using decentralized finance. This is an operational tool in supply chain management used to control triggering the release of goods from one point to another. This is also an important part of supply chain finances in the global operations (Gomm, 2010). Typically, this part is heavily governed by banking industry and includes heavy service fees, which might present a business itself for the supply chain operators and enabling transactions between multiple stakeholders without a broker or middleman. Supply chain finance studies are few, but it should be noted that blockchain based trading systems having the release of goods functionality has been proposed by Rajashekaragouda et al. (2020) and Chang et al. (2019). Table 7 shows the requirements collected for the letter of credit use case.

Table 7. Requirements for the Letter of Credit use case.

Requirement	NFT possible solution
Physical component	N/A – or the released goods
Digital files	Payment of goods
Uniqueness	Shipping batch of goods, e.g. container number
Contract	Release goods once financial transaction has been received.
Security	Ensuring
Stakeholders	Selling vendor Buying customer Clearinghouse

Design and implementation of the artifact. Appendix V shows the solution proposal code snippet of the smart contract. The key functionality is related to creating the letter of credit with basic data and then the fulfilment process, which releases the good upon safe receiving of the funds. The letter of credit can be used only once and cannot be transferred to other stakeholders.

Evaluation and communication. The conclusion from the evaluation discussion was that the implementation needs to be approved by both buyers and sellers as well as financial institutions processing the payment. Standardized structure should be followed instead of the simplified proposed in the implementation. From smart contract processing cost and speed point of view Ethereum based NFT may present a real-life solution.

4.5 Analysis of results

The developed artifacts created to solve the problems presented by the expert panel are all somewhat limited. The applications need to be integrated to external information systems and the business cases may have requirements which the Solidity contract running on Ethereum network may not solve in real-life. These performance outcomes can limit the practical applicability of the technology proposed in this study. However, similar principles may be implemented with other technologies.

From outcomes and impact point of view, the use cases and the artifacts show that non-fungible tokens can impact authentication of goods, transparency and traceability of supply chains throughout the product life cycle. The serial number level linking to physical asset should also reduce issues with illegal licences and counterfeit products. Financial transactions in the supply chains can drive more advanced and innovative solutions for traditional documents such as letter of credit. Table 8 summarises the five case studies and the potential for processes and decision making.

Table 8. Summary of design science process steps for each use case identified in the problem identification.

	Use case 1: Unique products - additive manufacturing	Use case 2: Serialization of products	Use case 3: Certificates	Use case 4: Internet of Things	Use case 5: Letter of Credit
Step 1 – Problem identification	Managing production rights for unique designs.	Traceability of products from manufacturing to consumers	Ensuring the authenticity of the product	Managing authorized IoT device assets	International trade, releasing payment
Step 2 – Definition of objectives	Link to physical asset, digital asset management of designs	Linking material handling units and unique product serial number in a safe way	Physical product linked to the origin	Right to use a software or service in a computing device	Safe automated way to release payment upon receiving goods
Step 3 – Design of artifact	Smart contract for claiming ownership of STL file	Smart contract providing possibility to verify the validity of the product	Smart contract for creating a certificate of authenticity, verification of the document	Linking software version and IoT computer, verification of software licence	Letter of credit document as a smart contract
Step 4 – Demonstration	Additive manufacturing design - Ownership transfer function	Pharmaceutical Linking product manufacturer, batch number, shipping date and material handing unit numbers, verification	Coffee - Smart contract creating the link between origin, lot number and name of manufacturer, verification of certificate	IoT – device, licencing agreement for using software and service in a smart connected device	Finance document for releasing goods
Step 5 – Evaluation	Partial technical solution for digital rights, does not solve the actual file copy problem.	Partial technical solution, which needs integration to operational ERP systems. Processing speed of creating an asset and verification.	Product labelling system needs to be built to support the link to non- fungible token.	Managing a large fleet of IoT devices and frequent software updates may generate expensive network use	Partial solution, needs to be integrated with actual banking system
Step 6 - Communication					

The technological progress of blockchain applications in operations and supply chain management has been limited. There have been critical notes about the actual applicability, and it is important to reflect these to non-fungible tokens, which is a clear derivative solution from blockchains. NFTs are a specific application of blockchain technology, but there are notable differences in how these two are applied and adopted in the context of supply chains.

While non-fungible tokens technology present possibilities for applications related to operations and supply chains, there are several factors which are reducing the speed of real-life implementations. The technology is relatively new and still rooted heavily to digital arts. The users may also perceive limited value due to technological reasons. There are very few implementation frameworks available, and these are mainly based on Ethereum framework. This means that cost of running the network and the performance may present barriers. Running the service on Ethereum network may involve costs such as gas fee, smart contract deployment and minting costs for NFTs. The cost per NFT could be varying between 0.05 EUR to 200 EUR, which might be significant cost in higher volumes. Also, latency in Ethereum network is significant factor. Even on lower congestion times, processing an NFT may take several minutes, and worst-case scenario could be several hours. This reduces practical usability. Other solutions such as Solana or Hyperledger may present better cost effectiveness, but use of these technologies require deep understanding of software. Lack of standardization and regulatory scrutiny also present barriers.

5. Discussions

Several papers have demonstrated various non-finance applications based on blockchain technology. Non-fungible tokens present an interesting opportunity to utilise blockchain in a combination with digital assets. The research problem of this paper was to analyse potential applications of NFTs for operations and supply chain management. We identified the key features (RQ1) of non-fungible tokens in supply chain management. The results show that NFT structures find their strength in their five main benefits, namely: enhanced security, greater transparency, instant traceability, increased efficiency and speed, and its potential for automation. The specific features of NFT which solutions may be expected in the future are often combining the physical assets and virtual design space or other information related value-added item. Table 9 shows a typology for development for potential application areas based on two dimensions: tangible/intangible product, and fungible-hybrid-non-fungible product feature. NFTs are related to both non-fungible and hybrid dimension. Blockchain applications can be used for fungible solutions.

Table 9. Typology for application areas.

Fungible/non-fungible item	Fungible item	Hybrid	Non-fungible item
Tangible/intangible			
Tangible physical item	Commodity product	Certified physical product: CoA	Unique physical product with serial number
Hybrid	Commodity product with CoA: gold ingot, certified wood,	Product service systems – contract tokens for producing branded goods	Licensed unique product created with additive manufacturing
Intangible	Coin, token	Token for authorized software access	Software licensed for a certain product

The literature analysis and the use case development analysis allowed us to develop potential operations and supply chain management related applications for the NFTs. This experimentation has shown that:

- (1) NFT and BC have different characteristics – A lower number of transactions compared to SCM are often related to non-fungible items, at the same time the required life cycle of the data may be several years as non-fungible items are durable and high value.
- (2) Value creation is linked to uniqueness of the physical item, which is a non-fungible feature. Value creation may be related to assets value or transactions which are elements producing asset value.

Five different applications were proposed based on expert interview and for each use case a sample application was proposed for the area of operations and supply chain management (RQ2). By using this approach, we proposed (1) additive manufacturing licencing mechanism to manage production, (2) serialisation system for pharmaceutical products linking the shipping information to product manufacturing data, (3) Certificate of origin for products where authenticity is importance, e.g. coffee bean example, (4) a system to manage cyber security of smart connected IoT devices, and (5) a letter of credit system to release payments upon a successful approval of the receiver. The potential of non-fungible tokens can be compared with previously published blockchain applications. Blockchain has been applied to similar types of applications as presented in this paper. Global trade tracking and tracing applications are mentioned in the literature reviews (Chang et al. 2020). Also specific industrial needs in pharmaceutical (Ghadge et al. 2022) and food related products (Li at al. 2021). The wider expected impacts on transportation industry (Koh et al. 2020) and the structural changes in global networks (Dolgui and Ivanov 2020) have also potential. The challenge is that academic research has been carried out but during the past years but adoption of blockchain based technologies in operations and supply chain management has been limited (Kamble, Gunasekaran, and Arha 2019). Empirical studies related to blockchain adoption have shown that facilitating conditions, technology readiness and technology affinity of

the company are the factors which moderate the effects of using blockchain technology in supply chain context (Wong et al 2020).

Combining these piloting results with the findings of literature review we suggest three propositions for the future research in the field of operations and supply chain management. The technology builds on top of the blockchains but has its unique features, which can enable some possible outcomes. Firstly, security in the supply chains needs new types of mechanisms supported by scalable technology (Cheung et al., 2021). The concept of zero trust supply chains aims to build structures to support such needs (Collier and Sarkis 2021). Use case 3: Certificates and use case 4: Internet of Things are examples of hardening of security in supply chain operations by use of NFTs. We propose that:

(P1) Proposition 1. NFT technology is a potential security and authentication of origin and processing steps.

Authentic and verified origins of raw materials, licensing rights (Giegling 2022), and product service system links are needed for enhanced products and circular economy needs (Walden et al., 2021). Product data such as emission records, service history or ownership history have all requirement of storing immutable information for a long period of time. Use cases 1: unique products for additive manufacturing and number 2 serialization of products are examples of such applications. Based on this we propose:

(P2) Proposition 2. NFTs can provide a technology backbone for product passports and intellectual property of product service systems.

Product identity needs to be managed often at a level of serial numbers instead of production batches. Tokenization and serialization of products has been presented in medical industry to fight the counterfeit products (Rajora, 2022) and improving recycling of plastics (Wankmüller et al. 2023). Expensive commodities have similar types of needs. On our analysis part use case 2 serialization of products and use case 5: Letter of Credit presents potential solutions for these types of problems. We suggest the following:

(P3) Proposition 3. NFT is a potential technology for tokenization of products and assets for supply chain finance transactions.

However, it is important to note that the implementation of NFTs in supply chain operations requires careful consideration of data privacy, security, and interoperability with existing systems. Additionally, collaboration among supply chain stakeholders and standardization efforts are crucial to maximize the benefits of NFTs in operations and supply chain management. The expected challenges related to implementation are in line with prior literature. Usability of the non-fungible tokens is limited by slow confirmation process and gas related costs, privacy and data inaccessibility, legal and governance related open questions, various security concerns, extensibility in the long run, environmental aspects due to mining impacts and intellectual property rights (Ali et al., 2023).

An additional remark related to implementation challenges of NFTs in the context of operations and supply chain management was that the alignment of NFT technologies and the great number of international standards on digital supply chain data requires more planning. Currently, standards such as GS1 Serial Shipping Container Code or data exchange related standards have not considered this technology. For this reason, it would be expected to have first successful implications with large corporations having a significance control power over their supply chains. Later, other industries can adapt the best practices from these industries.

6. Conclusions

The paper has aimed to made contributions by exploring the use cases of NFTs in the context of operations and supply chain management. The examples provided demonstrate that NFTs offer intriguing opportunities for industrial applications within these domains. With the increasing importance of digital components in product development, manufacturing, and supply chain related systems, NFTs can play an important role in authenticating licenses for accessing unique operation features. The possible impact of non-fungible tokens on operational processes is comparable to blockchains. Security of intangible tokens can provide solutions where centralised solutions are not feasible due to long life-cycle of the physical asset or changing stakeholders in the market. Non-fungible tokens can link to financial transactions, such as change of ownership, rights to manufacture, rights to use software or a service, or automated transactions or material release. Linking non-fungible identification with serial numbers of parts and products can provide a long-term documentation for authenticity, origin and manufacturing details related to safety, security and sustainability.

The results of this study can be compared to studies conducted in the field of blockchain applications in operations and supply chains. It can be expected that the barriers for implementation are similar in non-fungible tokens as technology has similar challenges in implementation and cost of processing (Mathivathanan, 2021).

This study has limitations. The implementation of proposed use cases has not been very thorough as the purpose has been to develop a proof-of-concept type of descriptions to answer the research question. Most definitely, all possible application areas have not been identified in this paper. Also, in terms of implementation, one can say that most use cases described follow a similar pattern, generating a sequential number in response to a minting request. This approach is rather trivial and does not address specific challenges like validation of the minter provided information, detection of minting multiple NFTs based on the same data, which would be needed for actual wide scale application implementation. Also, the functionality of the contracts is limited. The sample codes could generate hash values based on input instead of using sequential numbers and access control, permissions could have been enhanced.

Further research is needed to study the propositions presented, but the possibilities of non-fungible tokens should be explored further in practical applications. For example, it can be argued that non-fungible tokens are not needed for all applications. Blockchain itself can solve several related use cases. However, non-fungible tokens can improve traceability, visibility, safety and security when the need is uniquely representing the production and operations. This should be the case when ownership and life-cycle related features are

important for the product instance level tracking and tracing. Non-fungible tokens can add value compared to plain blockchain implementation when the cases are related to high level uniqueness, e.g. for authenticity, ownership transfer, intellectual property of licensing, product safety, or other special value tied to product service bundle. Safety of pharmaceuticals, luxury items, expensive wines, intellectual property of a custom-made unique 3D prints and special software installed on an IoT device are examples of possible domains where a higher resolution solution could be highly appreciated. The case examples presented were developed based on expert panel proposals and it must be admitted that some of the cases could be implemented with plain blockchain implementation. The conceptual difference presented in the framework aims to help to evaluate when use of non-fungible tokens should make sense and when use of it would be an overkill.

By identifying and exploring the potential use cases of NFTs in operations and supply chain management, this paper sets the stage for future research and development in this area. It highlights the need for practical implementation studies and the importance of understanding how NFTs can bring tangible benefits to various stakeholders within the operations and supply chain ecosystem. However, further research is necessary to develop and test these applications in real-world settings. Conducting proof-of-concept studies will provide valuable insights into the feasibility and practicality of implementing NFTs within operations and supply chains. Additionally, understanding the managerial implications of utilizing NFTs can pave the way for their effective integration into existing systems.

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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