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Non-fungible tokens (NFTs) for digital twins in the industrial metaverse: Overview, use cases, and open challenges

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ABSTRACT

Recent years have witnessed the emergence of digital twins in the industrial metaverse, significantly transforming sectors such as manufacturing, automotive, oil and gas, and gaming. As a result, these sectors have experienced increased efficiency, innovation, and revolutionary solutions. Non-fungible tokens (NFTs) have the potential to enhance digital twins in the industrial metaverse by offering opportunities for monetization, traceability, and tracking. Moreover, NFTs can reshape the way industries operate by providing superior transparency, asset management, and intellectual property protection. This paper explores the potential of different types of NFTs, including dynamic and composable NFTs, in various applications within the industrial metaverse that heavily relies on digital twins. We present various industrial use cases where NFTs play a major role. Specifically, we design, implement, and test two use cases involving dynamic and composable NFTs. The data processing methods include algorithm development, simulation, and empirical testing within the industrial metaverse framework. Finally, we identify open research areas and future directions for the industrial metaverse.

1. Introduction

The metaverse is a virtual reflection of the physical world that offers immersive social experiences and connections through technologies like virtual reality (VR), augmented reality (AR), and mixed reality (MR). The convergence of the different forms of reality makes the metaverse a bewildering world with many unique features. Moreover, the rise of the metaverse signals a new era of the digital revolution for individuals, businesses, and industries. It opens the door to endless opportunities for collaboration and innovation, resulting in enhanced outcomes and services.

The metaverse relies on digital twins as one of its key components. Digital twins replicate real-world objects, such as machines and humans, including their actions and real-time interactions with the surrounding environment. The quality of the digital twins dramatically improves by harnessing data collected from sensors in the real world, allowing for greater potential to significantly optimize operational costs and increase productivity. Digital twins can be created in a transparent and decentralized way through the use of blockchain (Hasan et al., 2020; Suhail et al., 2022). Blockchain is a decentralized technology that can be used to create digital twins throughout their life cycle and monitor their usage during and after production.

Non-fungible tokens (NFTs) can be used as the digital twins of their physical counterparts on the blockchain. Fig. 1 shows the different applications of NFTs. Unique digital assets such as paintings, event tickets, virtual real estate, and even personal data can be represented with an NFT on the blockchain. NFTs can be categorized by how static or dynamic their represented asset is and by whether the asset is composable or non-composable. NFTs provide proof of ownership, property rights, and authenticity.

1.1. Motivation

To thrive in the fast-changing world, industries and businesses must expand their horizons to address issues related to ownership, sustainability, and the security of data in the immersive digital world. Metaverse and other growing technologies such as digital twins and NFTs can help accelerate the pace of this evolution. Metaverse has changed the way industrial businesses can flourish, and it can make monetization even more feasible with cryptocurrency and NFTs (Goldston, Chaffer, & Martinez, 2022). Hence, we are motivated to showcase

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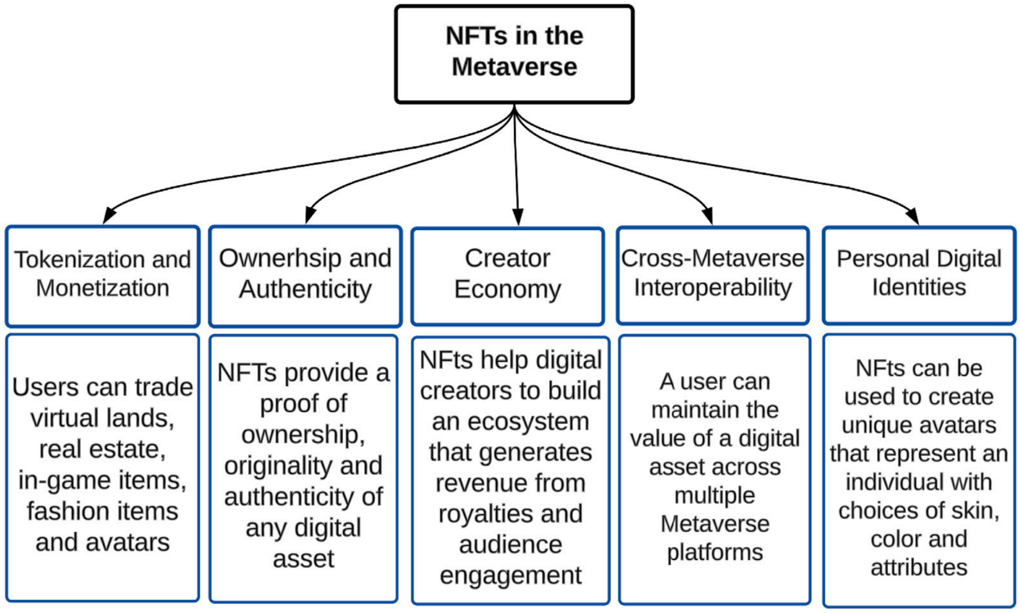


Fig. 1. The different uses of NFTs in Metaverse.

in this paper how the different types of NFTs in the metaverse can pave the way for beneficial solutions that were not possible previously. Below are points that summarize the reasons that motivated us to provide our solution:

- NFTs are still maturing in the literature, and there is not enough information on practical and detailed industrial use cases.
- Digital Twins have evolved to tackle a number of applications, but their representation using NFTs in the metaverse is a work in progress. Therefore, this paper highlights their importance and explores new possibilities.
- NFTs act as a powerful tool for enforcing trust and ownership in industrial applications. Therefore, we show how these benefits made them the building blocks for teleporting physical assets in the industrial metaverse.

Our solution leverages NFTs that are both dynamic and composable and showcases their importance in the virtual world of the industrial metaverse.

1.2. Research methodology

This section describes the research methodology used in this paper to provide an overview of the role of dynamic and composable NFTs in the metaverse for industrial use cases. The study involved a combination of theoretical analysis, use case analysis, design and implementation of industrial use cases, and open challenges and future research discussions.

- **Theoretical Analysis:** In order to develop a theoretical understanding of dynamic and composable NFTs in the industrial metaverse, we conduct a literature review on key concepts such as the metaverse, digital twins, and NFTs. This allowed us to identify current trends and challenges in the field and establish a solid theoretical foundation for our study.
- **Use Case Analysis:** To identify potential applications for dynamic and composable NFTs in elevating industrial applications in the metaverse, we conducted an analysis of existing industrial use cases that could benefit from NFTs. Furthermore, we showcase how the integration of composable and dynamic NFTs with the industrial Metaverse can enhance the performance of these use cases.
- **Design and Implementation of Use Cases:** Two of the presented industrial use cases are designed and implemented to demonstrate the feasibility of our approach, identify potential challenges, and provide proof of concept.
- **Open Challenges and Future Research Discussion:** Key challenges and limitations that impede the adoption of our proposed approach are identified and discussed. Furthermore, potential areas for future research are discussed.

1.3. Contributions

This paper provides an overview of dynamic and composable NFTs for use in the metaverse for industrial applications. By teleporting physical assets into the digital world and augmented reality, NFTs enable trustworthy, decentralized economic interactions and transactions in the industrial metaverse (Momtaz, 2022). NFTs can serve as proof of ownership and originality for physical assets that are represented by their digital counterparts in the industrial metaverse. Our paper shows that it is possible and useful to use different kinds of NFTs to meet the needs of the industrial metaverse and make it easier for different industrial applications to move to this immersive environment. The main contributions of this paper are as follows:

- We showcase how NFTs can be leveraged to tackle challenges in the industrial metaverse that relies on digital twins. We present various industrial use cases that manifest how NFTs can be used for monetization, traceability, and ownership of digital assets in metaverse applications.
- We highlight the significance of NFTs in transferring physical assets to the digital and virtual worlds of the Industrial metaverse in a traceable form with open access control.
- We present the significance and feasibility of utilizing multiple types of NFTs, including dynamic and composable NFTs, for industrial use cases in the metaverse.
- We demonstrate several industrial use cases of NFTs with digital twins that encapsulate the numerous ways the technologies can pave paths into the metaverse.
- We provide a detailed description of the design and implementation, along with smart contract code and testing, of two industrial use cases of dynamic and composable NFTs in the industrial metaverse.

The rest of the paper is organized as follows. Section 2 provides the literature review exploring the convergence of digital twins, blockchain and industrial metaverse. Section 3 defines and shows the features of the metaverse, digital twins, and NFTs. Section 4 presents different industrial use cases of dynamic and composable NFTs in the metaverse. This is followed by a detailed dynamic NFT industrial use case with its implementation and algorithms in Section 5. Another detailed composable industrial NFT use case is in Section 6. Section 8 discusses the generalization aspect, the role of NFTs, and open research challenges. Finally, Section 9 provides the concluding remarks.

2. Literature review

This literature review aims to provide a comprehensive understanding of the interplay and implications of the intersection of blockchain technology, industrial applications, and the emerging metaverse landscape. The use of blockchain in the various industries can elevate performance and efficiency. The transportation sector encounters significant hurdles across its diverse modes, encompassing e-scooters, hyper-loops, and autonomous vehicles, primarily stemming from the absence of regulatory standards and cumbersome decision-making processes. However, the transparency features of blockchain eases data sharing and facilitates accountability as well as data provenance (Singh et al., 2022). Blockchain paved the way for industries that degraded from centralization and lack of accessibility to immutable data. The tamper proof transactions and logs of the distributed ledger helped in expanding the digital universe and embracing wider challenges with innovative solutions (Moosavi, Naeni, Fathollahi-Fard, & Fiore, 2021; Sahin & Eyupoglu, 2022). It also enhanced intelligent manufacturing through safeguarding data validity, streamlining communication within and between organizations, and enhancing manufacturing process efficiency (Mourtzis, Angelopoulos, & Panopoulos, 2023). As a result of its intrinsic features ample industries have utilized its capabilities particularly in conjunction with the groundbreaking metaverse. The concept of the metaverse relies on the human-centric vision of creating an industrial resilient revolution (Agarwal & Alathur, 2023). On the other hand, the industrial metaverse entails the replication of real-world entities such as machinery, manufacturing facilities, urban environments, energy networks, transportation infrastructures, supply chains, and logistical operations within the virtual domain (Kshetri, 2023). The advancement in industry 5.0 relies on the enhanced interaction between the cyber–physical systems and humans. Consequently, the use of digital twins has emerged to create high-dimensional 3-D virtual world clones of the physical processes and assets (Jagatheesaperumal & Rahouti, 2022). The vital essence of the industrial metaverse dwells in the extensive networking of machines and facilities, along with the ubiquitous accessibility to vast volumes of data. The digital twin serves as the core component of the metaverse, seamlessly integrating the physical aspects of the real world with their digital counterparts in virtual clones. As a result of digitization, virtual reality along with gaming environments has spanned in workplaces and industries for educational and training purposes (Bellalouna & Puljiz, 2023). Furthermore, digital twins have unveiled significant opportunities for industries to proactively detect faults, simulate processes, predict outcomes, and develop more robust models (Stavropoulos & Mourtzis, 2022).

Researchers have explored the potential of the metaverse in diverse industrial applications, such as architecture, civil engineering, and project management, by examining the contingent factors crucial for successful implementation (Waqar et al., 2023). The revolutionary metaverse has unleashed immense potential within the hospitality and tourism sector as well. Augmented reality and virtual events create new avenues for trip organizations, engagement, marketing and revenue (Gursoy, Malodia, & Dhir, 2022). Moreover, the metaverse has also sparked interest in the automotive industry. Through virtual simulations and collaborative platforms, manufacturers can innovate more efficiently. Immersive experiences and virtual showrooms can revolutionize marketing campaigns. Additionally, personalized virtual interactions can enhance customer engagement and satisfaction, driving brand loyalty (Kim & Oh, 2022). Furthermore, those benefits have also extended to the fashion industry, where e-prototyping and digital design unleash the creativity of designers and assist consumers in better assessing the suitability of apparel to their choices and preferences (Sayem, 2022). The metaverse empowered by digital twins and built on top of blockchain has opened closed door for a broad spectrum of industrial applications and innovations (Aloqaily, Bouachir, Karray, Al Ridhawi, & El Saddik, 2022).

3. Background

In this section, we provide background information about the metaverse and its closely related concept of digital twins, as well as NFTs. We include their definitions, features, and applications.

3.1. Metaverse

The metaverse is a photorealistic and accurate simulation of tangible objects from the real world. It is an evolving virtual mirror of the physical world that provides immersive and simulated social experiences and connections (Mystakidis, 2022). The metaverse is designed to transcend the limitations of physical reality by offering a multiuser platform that combines advanced technologies and defies traditional notions of space and time. Users of the metaverse should be able to replicate and even surpass the experience of living in the physical world in terms of scope and value. The metaverse is often referred to as a next-generation internet that is universal, persistent, and immersive, existing in a three-dimensional virtual space (Nevelsteen, 2018).

To bridge the gap between the real and virtual worlds, researchers have applied the reality-virtuality continuum (Wu & Ho, 2022). The continuum describes how reality can be expanded to include a new virtual digital world. Hence, the term extended reality (XR) is a broad definition used as an umbrella that encompasses all types of technologies that create immersive and interactive environments that are impossible in the real world. These technologies include MR, AR, and VR (Ong, Tan, Lam, & Koh, 2021). While reality deals with experiences that take place in the actual material world around us, these reality alternatives are a combination of the digital and physical worlds.

MR is a form of reality that combines the physical real world with the digital world, as well as the real with the possible. On the other hand, AR is a form of reality where the physical world is integrated with digital information, shadowing the actual reality and making it accessible to users. Moreover, VR is a completely digital world with three-dimensional spaces, graphics, and representations of the real world (Farshid, Paschen, Eriksson, & Kietzmann, 2018). Using VR can be extremely immersive, and experiences can be disorienting when returning to the real world since it requires a special headset that transfers the user to a different mindset. Therefore, virtual tours are used by museums, filmmakers, and real estate agents to give their clients an interactive experience that is too close to reality.

The metaverse is a complex world that integrates different forms of reality, resulting in unique features and experiences. Equipped with physical hardware, users can fully immerse themselves in this extended experience (Hwang & Chien, 2022). The metaverse leverages holograms, avatars, and 3D renderings to recreate the virtual world. Moreover, Metaverse is persistent, meaning that its interactive presentations can be explored for extended periods of time, allowing users to transition between various activities, including gaming, productivity, and creativity (Ali, Naeem, Kaddoum, & Hossain, 2022).

The shared environment that Metaverse provides makes it ideal for social interactions and multiplayer activities. Organizations are assessing the feasibility of incorporating Metaverse into their business models to enhance their performance (Dwivedi et al., 2022). For example, Facebook has rebranded itself as ‘Meta’, and interest in Metaverse has been shared by other tech companies including Microsoft, Nvidia, Unity, and Roblox (Bale, Ghorpade, Hashim, Vaishnav, & Almaspoor, 2022).

3.2. Digital twins

The concept of digital twins is a fundamental building block of the metaverse. Digital twins are digital replicas of physical objects, systems, machines, and even humans (Hasan et al., 2020). The data collected by sensors from the real world is used to create and update the digital twins (Tao & Qi, 2019), enhancing the synchronization between the physical and virtual worlds (Ali et al., 2022).

Digital twins are virtual clones of physical entities that replicate their actions and reactions in real-time (Uhlemann, Schock, Lehmann, Freiberger, & Steinhilper, 2017). They offer numerous benefits, such as increasing the precision of industrial supply chains, aiding in decision-making during manufacturing, and improving the efficiency of the design and simulation stages. Additionally, digital twins allow for proactive decision-making, reducing costs and creating a more sustainable industrial environment in the long run (Tzachor, Sabri, Richards, Rajabifard, & Acuto, 2022). These digital models also move data bidirectionally, offering instant feedback based on IoT sensor information and enabling users to interact with 3D models in real-time. Digital twins can range from small physical counterparts to larger digital replicas such as factories, networks, and cities (Shahat, Hyun, & Yeom, 2021).

Throughout the product lifecycle, digital twins can bring together industrial development teams from different disciplines to communicate transparently and effectively, from design and engineering to building, assembling, and operating (Wang, Zhang, et al., 2021). They also enhance safety by ensuring quality assurance, testing, and quality control. Furthermore, digital twins can now replicate matter in its different states–solid, liquid, and gas–and at microscopic and macroscopic levels (Lv, Xie, Li, Hossain, & El Saddik, 2022). The type of information feeding a digital twin determines whether it is static or dynamic, reflecting either the state of a physical counterpart at a specific moment or providing a continuous state that changes in real-time (Kholopov, Antonov, Kurnasov, & Kashirskaya, 2019). As a result, digital twins must undergo credibility assessment through their lifecycle using Verification, Validation, and Uncertainty Quantification (VVUQ) techniques to ensure they serve their purpose effectively (Shao, Hightower, & Schindel, 2022).

Digital twins can be pervasively used to elevate ecosystems and industries (Mourtzis, 2023). Research shows that the agricultural sector can seize great opportunities by engaging advanced technologies, including digital twins, in its development. Digital twins can be clones of both living and nonliving things. Digital twins of different kinds of plants and animals can be used for early disease detection and identifying the underlying factors that might deteriorate their well-being. Digital twins of non-living things, such as machinery and equipment, can help in cost reduction (Pylianidis, Osinga, & Athanasiadis, 2021).

Moreover, digital twins can be utilized in building smart cities (Dembski, Wössner, Letzgus, Ruddat, & Yamu, 2020; Deng, Zhang, & Shen, 2021). Urban intelligent planning requires intensive knowledge of visualization. Therefore, digital twins play a major role in the management of operations and the construction of smart cities. The possible hazards, side effects, and planning outcomes can be foreseen ahead of time, which can help in building and creating a successful innovative city (Deren, Wenbo, & Zhenfeng, 2021). This digital model would depend on sensors and IoT devices on manholes, bridges, traffic lights, and many other physical objects in the city to successfully bridge the gap between the actual city and the modeled twin.

Digital twins have also shown promising results in being an essential aiding tool in the healthcare industry (Alazab et al., 2022; Angulo, Gonzalez-Abril, Raya, & Ortega, 2020). Digital twins can assist in establishing better diagnoses in telemedicine. For example, using data analytics can help in the rehabilitation of patients and provide a more personalized healthcare experience (Rivera et al., 2019). Although digital twins are still considered an emerging technology in the healthcare industry, they are paving their way and proving their potential. In addition to the medical field, digital twins have altered the way manufacturing takes place. Organizations are driven to pursue the use of digital twins in their production because of the flexibility gained in the design phase. Proactive and flexible decisions that meet the current market demands are important factors that make corporations seek the use of groundbreaking digital twin technology. Defects predictions and prevention, as well as enhanced system testing, are all cost-effective drivers that are leveraged through digital twins (Neto, Deschamps, da Silva, & de Lima, 2020).

3.3. Non-fungible tokens

NFTs can serve as digital twins for their physical counterparts on the blockchain. NFTs tokenize unique digital assets, including artwork, collectibles, videos, images, and other multimedia assets. NFTs provide proof of ownership and proof of purchase in a trustless trading environment, enabling trading between two parties without intermediaries (Hasan et al., 2022). Additionally, NFTs protect the rights of owners and creators by serving as proof of originality and authenticity (Das, Bose, Ruaro, Kruegel, & Vigna, 2021). Fig. 1 illustrates the different uses of NFTs in Metaverse. They facilitate trading through the tokenization of digital assets. They protect the rights of digital creators empowering the creator economy by serving as proof of ownership, authenticity, and originality. Using NFTs, trading can also be maintained across multiple Metaverse platforms ensuring smooth interoperability. They are also powerful unique tools that serve as identities in virtual events and meetings.

The surge in demand and interest in NFTs has led to the emergence of NFT marketplaces for trading NFTs through direct sales and auctions. The Ethereum standard ERC-721 is used for minting a unique NFT for each asset it represents, unlike fungible tokens based on the ERC-20 Ethereum standard, which are interchangeable (Das et al., 2021). Each NFT has a unique identifier (tokenId) and an associated metadata file that contains information about the NFT and its attributes. The metadata is usually in the form of a JSON file stored outside the blockchain, typically in decentralized storage (Wang, Li, Wang & Chen, 2021).

NFTs can be differentiated based on the metadata attached to them and can also be grouped into categories based on the number of NFTs included within them. There are different types of NFTs: (Pylianidis et al., 2021).

- **Static**: These NFTs have fixed metadata that does not change over time, making them suitable for artwork, identity verification, and collectibles. Because their attributes are immutable on the blockchain, static NFTs are considered secure and permanent once minted (Beckman, 2021).
- **Dynamic**: These NFTs can have variable metadata after minting on the blockchain and are known as Dynamic NFTs (dNFTs) (Chalmers, Fisch, Matthews, Quinn, & Recker, 2022). There are two types of dNFTs: reactive and proactive. Reactive dNFTs change their metadata in response to certain conditions being met, such as changes in weather conditions. Proactive dNFTs, on the other hand, have predetermined changes to their metadata, which are triggered at specific times or events. Dynamic NFTs can be used to represent real-world objects, such as lands with houses that are renovated or rebuilt, or other assets that change over time. They can also be used for cases where the metadata depends on reading from external APIs or Internet of Things (IoT) sensors, making them responsive to real-world scenarios. dNFTs are also used in video games where a character's features vary as the game progresses. This creates a unique and personalized gaming experience for the player. dNFTs can be created in smart contracts using oracles that are connected to external APIs. Oracles help in gathering off-chain information and aggregating the data for decision-making based on certain thresholds in the smart contract. If the threshold is met, the metadata of the NFT is changed

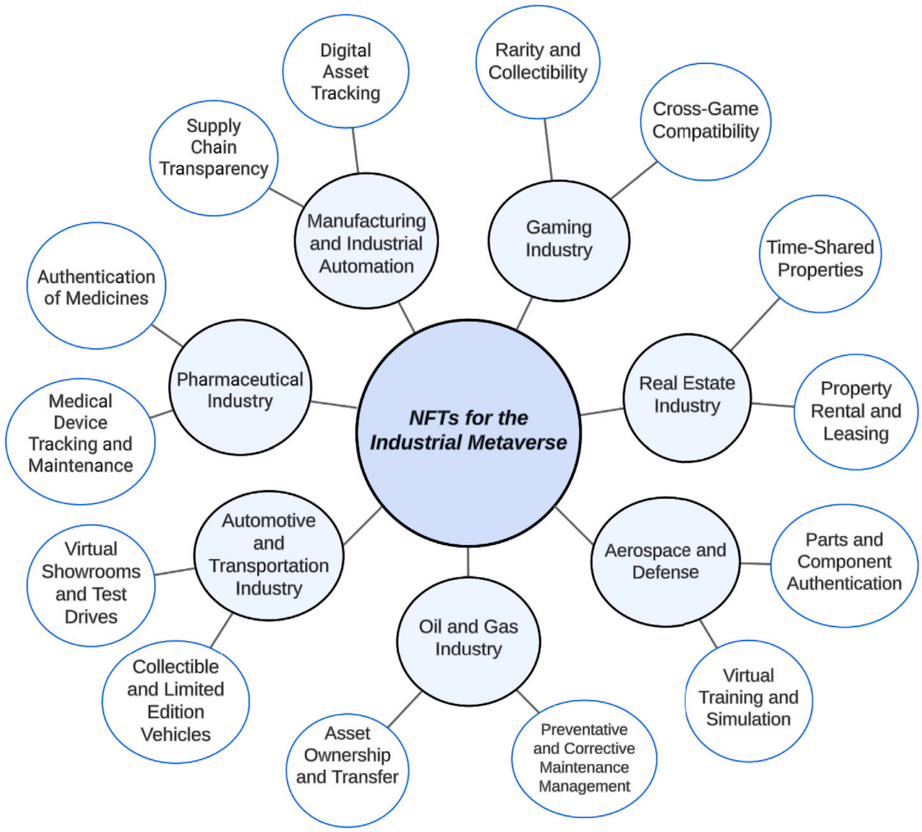


Fig. 2. NFTs for the industrial metaverse.

accordingly. Another way to create dNFTs is by using verifiable random functions, which depend on randomness to alter the metadata of the dynamic NFT (Solouki & Bamakan, 2022). This method ensures that the changes made to the metadata are truly random and cannot be predicted by any party.

- **Single**: These NFTs are minted to represent a unique and distinct asset. They are designed to hold a single token ID and a unique set of metadata associated with the asset.
- **Composable**: A composable NFT refers to an NFT that contains other NFTs within it, allowing them to be traded as a single entity in a single transaction. For example, groups of ERC-20 and ERC-721 tokens can be embedded inside an ERC-721 NFT. The ERC-998 standard is a proposed Ethereum standard for composable ERC-721 NFTs (Ishida et al., 2019), and it maintains the parent and child relationship through a mapping mechanism (Anon, 2023a). By using composable NFTs, an ownership tree can be created. The proposed ERC-998 standard provides two approaches for encompassing NFTs, which can be selected based on the specific implementation and application requirements:
  - **Top-down**: Composable NFTs of this type serve as containers that hold other NFT composables. The parent is an ERC-721 NFT that encompasses other ERC-721 or ERC-20 NFTs as children. The parent can be queried for their children's contracts. A top-down composable can be a child of another top-down composable, but cannot be a child of a non-composable single NFT (Omar & Basir, 2020).
  - **Bottom-Up**: Composable NFTs of this type are attached as children to other NFTs. They can be queried for their parent NFT, and multiple bottom-up composables can be attached to a single regular ERC-721 NFT (Anon, 2023b).

NFTs encompass a broad spectrum of applications that have revolutionized the world of digital art and collectibles by providing proof of ownership, property rights, and authenticity. With the tokenization of digital art, royalties can be preserved and assigned after each resale, thanks to NFTs (Rehman, Zainab, Imran, & Bawany, 2021). The gaming industry has also been transformed with NFTs, as avatars can now have their own upgraded features and skills. Composable NFTs are perfect for encompassing the evolving player and their purchased upgrades (Karapapas, Pittaras, & Polyzos, 2021). Fig. 2 showcases the different industries that NFTs revolutionized in the industrial metaverse. NFTs have the ability to teleport physical objects into digital assets in Metaverse and can be utilized in several industries. NFTs enable the aerospace and defense industry to provide realistic virtual training and simulation in the industrial metaverse. In the real estate industry, they can streamline the rental leasing process by tokenizing lease agreements and terms. Moreover, tokenizing collectible and limited edition vehicles eases trading in NFT marketplaces for the automotive and transportation industry. Additionally, the pharmaceutical and chemical industry can tokenize maintenance records, device specification, and calibration data to ease the tracking of medical devices as well as enhance their maintenance service. Similarly, the manufacturing industry has elevated its proficiency by utilizing NFTs for digital asset tracking and supply chain transparency. 3D models and renderings can be tokenized as NFTs to ease tracking and tracing as well as protect intellectual rights and properties. On the other hand, the oil and gas industry can use NFTs to increase the efficiency and collaboration between the different teams for preventative and corrective maintenance measures.

4. Use cases

There are several industrial applications that exploit composable and dynamic NFTs in the industrial metaverse. This section highlights the role of the different types of NFTs in the industrial metaverse.

4.1. Assembly of components in the manufacturing industry

The manufacturing industry requires the use of many components and sub-components that are assembled to create the final product. If any of the parts are not accurately measured or visualized correctly then it might not be a perfect fit in the final product. The design stage before manufacturing is a critical process. Therefore, modeling and prototyping can be good solutions that save on time and costs (Manuri, Gravina, Sanna, & Brizzi, 2022). Digital twins aid the Manufacturing Execution Systems (MES) by providing precise simulations and modeling as well as data analytics which leads to proactive decision-making (Cimino, Negri, & Fumagalli, 2019). Creating digital twins for each physical counterpart and testing it in Metaverse, would benefit the engineering team to overcome hurdles, get consumers to engage actively in the building process, and reduce maintenance as well as replacement costs (Lin, Xiangli, Li, Liang, & Li, 2022). Each DT is represented on the blockchain as an NFT. The NFT would hold all the information of the owner's details and can be composed of other NFTs. The metadata of the NFT can change as its status changes while getting assembled. For instance, if the owner is changed or if it gets resized, mended, or altered, its metadata will also change. Therefore, the assembly of components for manufacturing exploits the usage of dynamic and composable NFTs as digital twins in Metaverse.

4.2. Gaming industry

Virtual gaming platforms are the new emerging hype that youngsters are attracted to. A video game would not only have characters to interact with but a whole universe. An interactive scenery where users can exchange digital currency for virtual goods is what makes Web3 games the most engaging (Vidal-Tomás, 2022). A socialistic environment is built where multiplayer games depend on players from the real world to join forces and collaborate together in the virtual world. Additionally, virtual games have an immersive and persistent world that is designed to create the best user experience. Using technologies such as NFTs and Metaverse the creation of games like Roblox, using 3D gaming engines like Unity and Epic Games became possible (Jungherr & Schlarb, 2022). Digital twins of the real actual objects, as well as people, are used to create a realistic virtual environment for the players to get immersed in. NFTs are used as proof of ownership and for the tokenization and monetization of virtual goods (digital twins) (Christodoulou, Katelaris, Themistocleous, Christodoulou, & Iosif, 2022). Moreover, character upgrades are also NFTs that are bought by the players to access the attributes of the evolving character. An avatar of the player is a composable NFT that encompasses all the perks of children's NFTs when upgraded. It is also a dynamic NFT that depends on the external environment to respond and evolve accordingly.

4.3. Real estate industry

Building interest in a piece of land or property to own or rent calls for a tour at the destination to closely identify its details and carefully analyze it. The real estate industry can greatly benefit from Metaverse. Interested clients can have virtual tours of the properties that caught their attention. Lands as well as properties in the real world can have digital replicas in the virtual world. The virtual counterparts would have the exact details of the physical tangible asset they represent. Interested clients can live the experience of touring a property by entering its divisions and viewing the landscape and scenery without physically relocating to the location. The land as well as any property built on it can make use of NFTs as proof of ownership (Far, Bamakan, Qu, & Jiang, 2022). The status of the house as well as the land keeps changing with time, therefore, the metadata of the NFT gets altered as well. Hence, dynamic NFTs can be used to represent the real estate digital twins on the blockchain Anon (2023c). Adding a floor to an existing house changes the metadata of the house NFT. The new metadata should capture any changes that took place to keep the records transparent and reliable as time passes. Furthermore, a house for rent for example can encompass its furniture and valuable pieces which could also be represented as NFTs to maintain its ownership details as well as record its status on the chain. Hence, both composable and dynamic NFTs can be used in the virtual world of Metaverse to change the future of the real estate industry.

4.4. Preventative and corrective industrial maintenance

Urban structures such as bridges, railways, subterranean passages, and tunnels require regular monitoring and maintenance to prevent hazardous conditions. Similarly, the diagnostic process for gas pipes and underwater cables can be challenging and risky. To improve assessment results and build a data analytics model, digital twin models (DTMs) of these physical structures can be equipped with IoT sensors. The digital replicas accurately simulate their physical counterparts, improving simulation and visualization (Nguyen, Kang, Jang, & Shim, 2022). The assembled components that make up these structures, such as gas pipes and cables, can be procured from different vendors. NFTs can be used to prove ownership of each component, and the entire structure can be represented by a composable NFT that encompasses all of the individual NFTs. The information held within the metadata of the NFTs is dynamic and can change based on the maintenance status resulting from real-time sensory data. By using Metaverse, the DTMs can be virtually viewed as 3-D models, and the reliable information saved within the NFTs can facilitate stakeholder collaboration for better decision-making. The industrial metaverse also helps detect component degradation early and provides proactive inspection and maintenance (Zheng et al., 2022), which is crucial for applying preventative measures and making informed decisions during corrective maintenance and component assembly.

5. Dynamic industrial NFT use case in metaverse: preventative and corrective maintenance

This section focuses on the use case of dynamic NFTs in Metaverse for preventative and corrective maintenance. In this industrial use case, work orders are managed by a Facility Manager (FM) responsible for maintaining equipment, tools, and allocated resources in a site. Preventative maintenance (PM) is regularly performed maintenance to reduce the likelihood of failure and machinery downtime while the equipment is in operation. Effective maintenance management schedules regular PM to increase efficiency, optimization, and cost reduction. With the help of Internet of Things (IoT) sensors, readings from machinery and physical assets are analyzed to determine the frequency of PM. Corrective Maintenance (CM) is required to identify and repair a fault that hinders equipment functionality. CM takes place when a machine breaks down and requires restoration, reassembly, realignment, or replacement. Metaverse provides a visualization tool for physical assets and equipment without the need to disassemble machinery components. PM and CM are required in challenging sectors such as oil and gas as well as underwater pipeline systems in industrial systems. Pipelines are essential in transporting hazardous liquids and gases. Any faults can lead to leakage and disrupt the progression of the process. Using Metaverse, maintenance management can be improved, leading to a profound impact on a company's profitability.

The proposed solution for maintenance management in the metaverse using dynamic NFTs and smart contracts is illustrated in Fig. 3. To create a transparent and reliable ledger with the immutable status of physical assets, dynamic NFTs are minted for each piece of machinery or physical asset used by the oil and gas site. The Original Equipment Manufacturer is responsible for supplying machinery for the site, while the Facility Manager (FM) oversees maintenance management including preventative and corrective maintenance. To monitor the

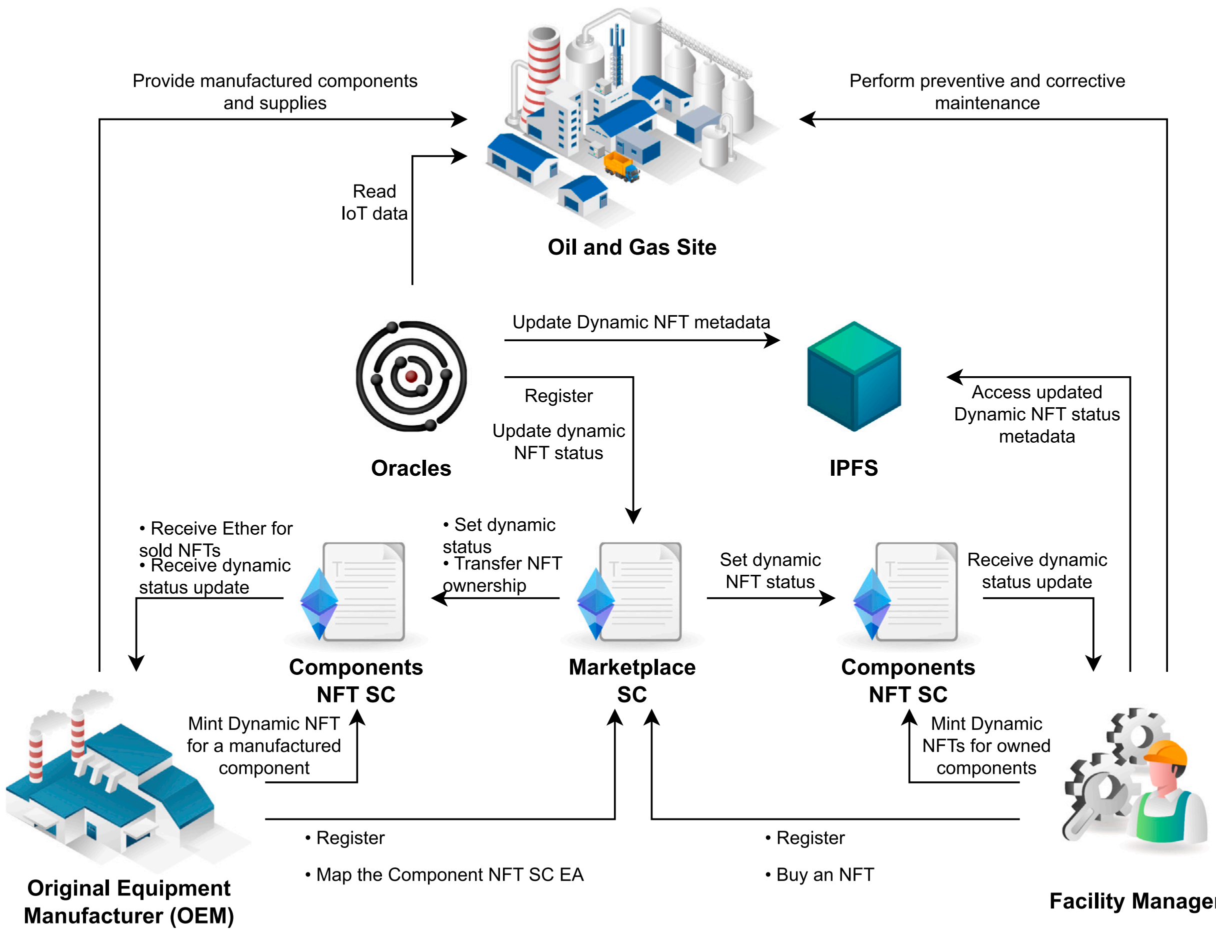


Fig. 3. System diagram of the preventative maintenance and corrective maintenance industrial use case using dynamic NFTs in the industrial metaverse.

deteriorating levels of the machinery, IoT sensors are mounted on all equipment used in the site. Smart contracts on the Ethereum blockchain are used to mint dynamic NFTs for each machinery, while oracles serve as the communication channel between the IoT sensors and the blockchain. They extract the IoT data and update the status on the chain every X minutes as determined by the FM. This change is then reflected in the DT in Metaverse and the NFTs on the chain. Each NFT has metadata representing it, which is saved off the chain on the InterPlanetary File System (IPFS). To accommodate the altering nature of the dynamic NFTs, IPNS, which is the mutable filing system, is used in our solution. Additionally, a Domain Name Service (DNS) link is used to associate an arbitrary path to a domain in IPFS. When the NFT is first minted, its URI (DNS link) would point to the IPFS file. When the metadata JSON file is updated, the URI would point to the latest version of the metadata. The oracles and other stakeholders are registered on the chain through the marketplace smart contract (SC), and registered oracles then update the NFT status through the marketplace SC. All status changes are saved in the logs as events for each NFT. The most up-to-date status is available in a mapping for each NFT, and the DNS link to the updated metadata is available as part of the attributes of the NFT.

5.1. Implementation

The smart contract (SC) code[1] is written using Solidity and the Remix IDE. The solution comprises two smart contracts: the Marketplace SC and the Components NFT SC. The ERC721 OpenZeppelin library is used for the NFT functions and transactions. We edited the ERC721URIStorage SC, available in the library, to tailor it to our solution's objectives. We added functions and attributes related to dynamic NFTs, such as status updates, token hashes, and price, to satisfy the project's requirements. In our implementation, Original Equipment Manufacturers (OEMs), assemblers, suppliers, and component owners can be sellers and buyers. Facility Managers (FMs) are the buyers, while OEMs are the sellers. All participating entities, regardless of their role, must be registered on the chain via the marketplace SC. Oracles must also be registered and are responsible for linking IoT sensors on manufactured components to the blockchain NFTs. Fig. 4 represents a sequence diagram of the interactions between stakeholders and oracles with the Marketplace SC and Components NFT SC. The diagram illustrates how registration takes place through the marketplace SC on the chain. OEMs can mint NFTs for the manufactured components, and oracles bridge the gap between the off-chain and on-chain worlds by updating the status of the physical components to their dynamic digital twins, mapped as dynamic NFTs in the Components NFT SC. If a component is sold to a different owner, the ownership of that component's NFT is transferred to an FM.

Algorithm 1 facilitates the registration process for suppliers, facility managers, and oracles. Each entity involved in a transaction on the blockchain has a unique Ethereum Address (EA), which must be registered with the marketplace smart contract (SC). In addition, NFT owners have their own component NFT SC, where NFTs are minted. The EA of the component NFT SC must also be added to a mapping in the marketplace SC. This allows the marketplace to access the NFTs when a FM requests to purchase an NFT or when an oracle needs to update the status of a dynamic NFT. Algorithm 1 also demonstrates how the EAs of the component NFT SCs owned by the NFT owners are added to

[1] https://github.com/smartcontract694/DynamicUseCase

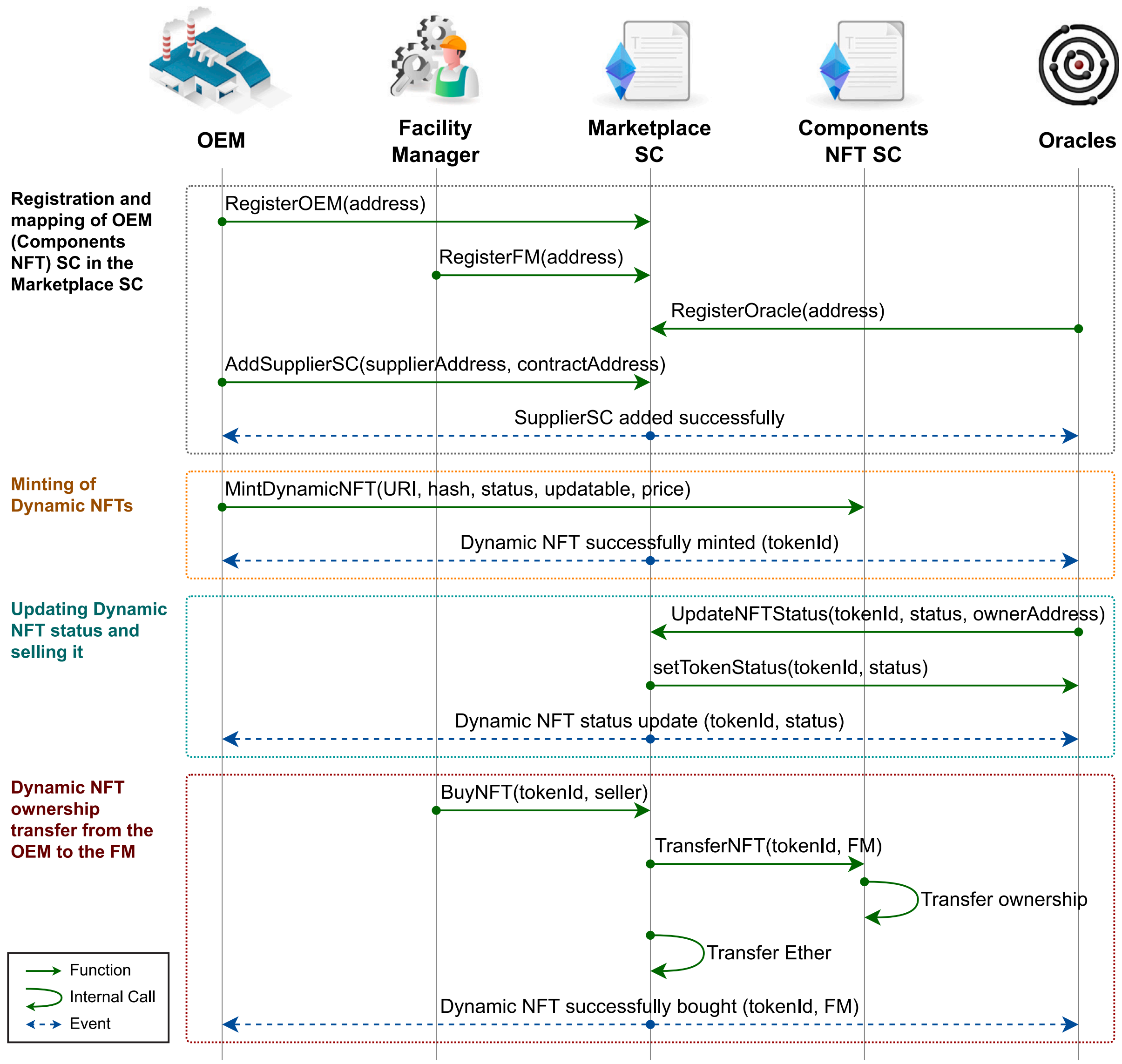


Fig. 4. Sequence diagram of the smart contract interactions between the facility manager and original equipment manufacturer.

the marketplace SC. The registration process for any entity can only be carried out by the marketplace SC, and the addition of the component NFT SCs' EAs to the 'supplierContracts' mapping in the marketplace SC can only be performed by a registered supplier.

Algorithm 2 is utilized by the OEM (supplier) of the assembled components to create an NFT for each component. The owner of the NFT provides various pieces of information such as the metadata's URI, token price, status, token IPFS hash of the stored metadata, and a boolean. The "updatable" boolean is set to true if it is a dynamic NFT with updatable metadata, and false if it is a static NFT. Once the NFT has been successfully minted on the chain, an event is emitted to notify listeners about the availability of a new token along with its token ID. In Algorithm 2, the marketplace SC EA is authorized to modify the status of a dynamic NFT or to allow the transfer of ownership during a trade.

Algorithm 3 demonstrates how the oracles update the status of a dynamic NFT on the blockchain to match the deterioration levels of the physical component. The time interval for the update is determined by the facility manager and supplier. The oracles perform the update through the marketplace SC using the Ethereum Address (EA) of the component owner SC and the NFT's token ID. Moreover, a facility manager may request to purchase an NFT through the marketplace SC. In such a scenario, the marketplace SC triggers the transfer ownership function in the components NFT SC, and the transfer of ownership takes place after exchanging Ether with the current owner. After the purchase, the EA of the FM becomes the owner of the NFT.

5.2. Testing and evaluation

This subsection presents the performance assessment, cost evaluation, and security analysis of the dynamic industrial NFT use case.

- **Performance Assessment**
  The smart contracts were thoroughly tested in the Remix IDE, revealing no compilation or runtime errors. Testing encompassed various functions such as registration, dynamic NFT minting, and ownership transfers using Ethereum addresses for the FM, OEM, marketplace, and oracle. Event logs were examined to verify the correctness of the emitted events, caller addresses, and function outputs. Fig. 5 illustrates a sample event emitted post-successful dynamic NFT minting by the OEM, with six arguments providing essential details. The caller's EA (argument 0) in this testing scenario is that of the OEM. Additional arguments include the token ID (argument 1), IPNS DNS link (argument 2) for accessing the updated metadata of the dynamic NFT, IPFS hash of the

Algorithm 1: Marketplace SC: Registration

Input : caller, User, MarPlaEA, Sellers, Buyers, Oracles, sellerContracts, sellersSC

$caller$: EA of the transaction caller
$User$: EA of the user to be registered
$Sellers, FMs, Oracles$: Mappings that hold the EAs of all suppliers, FMs and oracles respectively
$sellerContracts$: Mapping which has all EAs of the supplier SCs
$supplierSC$: EA of the SC of a supplier
$MarPlaEA$: EA of the marketplace
if $caller == MarPlaEA$ **then**
  $RegisterUser \in Suppliers \,||\, FMs \,||\, Oracles$
  if $User \in Suppliers$ **then**
    Add $suppliersSC \in supplierContracts$
    Emit an event announcing New Components Supplier SC added Successfully using $supplierSC$ and $User$
  end
else
  Preview an error and return the contract to the previous state.
end

Algorithm 2: ComponentsNFT SC: Minting a Dynamic NFT

Input : caller, owner, URI, tokenHash,status, price, updatable

$caller$: EA of the transaction caller
URI: variable holding the URI of the NFT metadata
$tokenHash$: IPFS hash of the first NFT metadata
$updatable$: boolean to indicate a dynamic NFT
$owner$: EA of the OEM or assembler or supplier
$status$: integer indicating the status of dynamic NFT
if $caller == owner$ **then**
  $tokenID{+}{+}$
  Mint NFT using $tokenID$,$status$, $tokenHash$,URI, $price$, and $updatable$
  $setApprovalForAll(MarketplaceEA, true)$
  Emit an event announcing the successful minting of a dynamic NFT
else
  Preview an error and return the contract to the previous state.
end

original metadata file (argument 3), NFT price (argument 4), and a boolean (argument 5) indicating that the minted NFT is dynamic and updatable. The complete list of transactions conducted during testing is available on GitHub.[2]

- **Cost Evaluation**
  Cost evaluation is critical for our use case as it provides insights into the financial implications of deploying and executing smart contracts within the dynamic industrial NFT ecosystem. Understanding the costs associated with various functions helps stakeholders make informed decisions about resource allocation and optimization strategies. For this evaluation, we used an Ether price of 3245 USD and a gas cost of 67 Gwei, sourced from Etherscan on 27th February 2024 (Etherscan, 2024).
  Based on Table 1, several key insights can be drawn regarding the cost evaluation of our dynamic industrial NFT use case. The

Algorithm 3: Marketplace SC: Updating and Selling Dynamic NFT

Input : caller, Oracles, status, tokenID

$caller$: EA of the transaction caller
$status$: integer indicating the status of dynamic NFT
$ownerSC$: EA of the SC of the NFT owner
$Oracles, FMs$: mapping that has EAs of registered oracles, FMs respectively
if $caller \in Oracles$ **then**
  $ComponentsNFT(ownerSC).setokenStatus(tokenID) = status$
  Emit an event announcing the successful status update of a dynamic NFT
else if $caller \in FMs \wedge msg.value == price$ **then**
  $ComponentsNFT(ownerSC).Transfer$
  $NFTOwnership(tokenID, FM)$
  Emit an event announcing the successful ownership transfer of the dynamic NFT
else
  Preview an error and return the contract to the previous state.
end

Table 1
Cost evaluation of the dynamic industrial NFT use case.

Function	Gas usage	Cost to execute (Ether)	Cost to execute (USD)
Marketplace SC Deployment	920,808	0.0617	200.20
Components NFT SC Deployment	2,837,272	0.1901	616.87
RegisterFM	46,378	0.0031	10.08
RegisterOEM	46,399	0.0031	10.09
RegisterOracle	46,356	0.0031	10.08
RevokeFM	24,521	0.00164	5.33
RevokeOEM	24,455	0.00164	5.32
RevokeOracle	24,433	0.00	5.31
addChildren	50,887	0.0034	11.06
mintNFT	219,580	0.0147	47.74
UpdateDynamicNFTstatus	56,827	0.00381	12.36
BuyNFT	80,481	0.00539	17.50

deployment of smart contracts for the marketplace and components NFT functionalities incurs significant gas usage and costs, reflecting the complexity and resource requirements of these contracts. On the other hand, functions such as registering FM, OEM, and Oracle, as well as revoking their registrations, have relatively lower gas usage and costs. Minting dynamic NFTs and updating their status also contribute to moderate gas usage and costs. The variability in gas usage and associated costs across different functions highlights the importance of optimizing resource allocation and efficiency. Fig. 6 presents the normalized gas usage and costs (in Ether and USD) for better visualization and comparison, allowing stakeholders to identify areas of potential optimization and prioritize resource allocation based on cost-effectiveness.
  This evaluation provides developers with valuable insights into the efficiency and performance of their smart contracts. By analyzing the costs associated with each function, developers can identify bottlenecks and areas for improvement, allowing them to optimize gas usage and reduce overall expenses. Focusing on certain functions with high gas usage and costs enables developers to implement targeted optimization strategies, ultimately enhancing the financial sustainability and performance of the dynamic industrial NFT ecosystem.

- **Security Analysis**
  In the context of smart contracts, security analysis is crucial to ensure the integrity and reliability of the deployed code. Given the immutable nature of blockchain transactions, any vulnerabilities present in the smart contracts can have far-reaching consequences, including financial losses and reputation damage.

[2] https://github.com/smartcontract694/DynamicUseCase

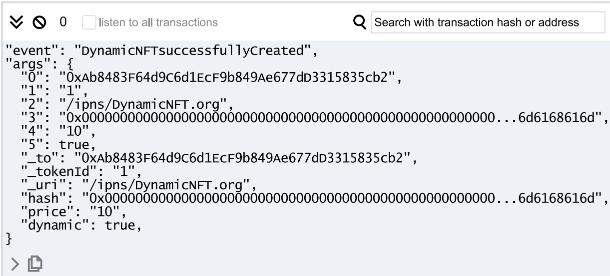


Fig. 5. Event emitted after successfully minting a dynamic NFT.

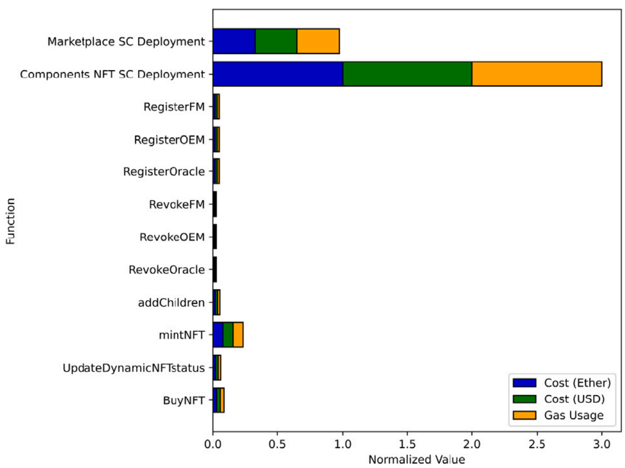


Fig. 6. Normalized gas usage and costs in Ether and USD of the dynamic industrial NFT use case smart contract.

For our security analysis, we employed the Slither tool, a robust security analysis framework specifically designed for Solidity smart contracts (Feist, Grieco, & Groce, 2019). Slither utilizes static analysis techniques to detect a wide range of vulnerabilities, helping developers identify and mitigate potential security risks. During our analysis, we identified a significant number of issues within the smart contracts, categorized as shown in Fig. 7(a). While the majority of these issues were informational, optimization, and low-level in nature, we also encountered nine medium-level vulnerabilities. Notably, there were no high-level vulnerabilities detected. However, we took a proactive approach to address each identified issue diligently.

By carefully reviewing and addressing these vulnerabilities, we ensured that our smart contracts are free from potential security risks. Fig. 7(b) illustrates the resolution of these vulnerabilities, demonstrating our commitment to maintaining a secure and robust smart contract environment. Additionally, the full details of the detected vulnerabilities are available on GitHub.[3]

6. Composable NFT use case in metaverse: Gaming industry

This section illustrates a detailed use case of composable NFTs in the gaming industry. The gaming industry has seen significant growth with the emergence of NFTs and the metaverse world. Avatars are created to represent users and enable them to play in the virtual world. These avatars can be upgraded based on their game level, strength, powers, and owned digital artifacts and collectibles. In-game purchases using cryptocurrency enhance the gaming experience and satisfaction for players. Digital artifacts can be acquired through in-game purchases and can be traded and resold to other players, making them valuable digital assets that require ownership tracking. Avatars and digital artifacts are NFTs in the game, serving as proof of ownership that can be traced and tracked on the blockchain. To demonstrate the use of composable NFTs in Metaverse, we have developed three smart contracts: Avatar NFT SC, Digital Artifacts NFT SC, and Gaming Management SC. Fig. 8 displays a system diagram of the gaming setup in Metaverse, where the Avatar is created by the game avatar creator and the digital artifacts are created by the digital artifact creator. Trading and monetization of NFTs occur through the blockchain and smart contracts. Different approaches for creating composable NFTs exist, such as the ERC 998 Ethereum standard, nested NFTs, and capsule NFTs. These approaches involve having a parent NFT with other NFTs attached to it, creating a single NFT that can be sold together and can have more NFTs added to it in the future.

6.1. Implementation

In this section, we provide a detailed explanation of the algorithms used in the smart contract code,[4] which includes the implementation of composable NFTs in the gaming industry. The registration and minting of a single NFT are not discussed here as they are similar to the algorithms presented in the previous section (algorithms 1 and 3). The NFT structures used in the gaming management smart contract (SC) to build relationships between NFTs include the token ID, owner's Ethereum address (EA), original creator's EA, and the number of composable. Our design uses a composable NFT, which has a parent (avatar NFT) and children (digital artifact NFTs). The relationship between the parent and children NFTs is a top-down relationship built using mappings. Firstly, a mapping is made between the EA of the NFT owner a mapping of the NFT's original creator, and the avatar NFT structure. Then, a second mapping is used, mapping the avatar NFT's original creator's EA to a mapping between the avatar NFT's token ID and an array of digital artifact NFTs. The first mapping is called GameAvatars, and the second one is called ComposableAvatar (CompAV). The smart contract code enables users to mint composable NFTs, buy NFTs, and add NFTs to existing composables. Digital artifact NFT creators and avatar creators can trade NFTs and create composable NFTs for their avatars that are used in a game. Fig. 9 illustrates the interactions that can occur between an avatar creator and a digital artifact creator. In a gaming environment, multiple avatar creators and digital artifact creators could exist, and they all need to register through the Gaming Management SC. NFT creators should enter their SC addresses in the Gaming Management SC to allow trading of the NFTs. They can then mint NFTs in their SCs and buy from one another through the Gaming Management SC. Composable NFTs can be created from an avatar NFT and one or multiple digital artifact NFTs.

Algorithm 4 outlines the process of creating a composable NFT. To create one, a user must own an avatar NFT and one or more digital artifacts. The resulting composable NFT will have a top-down parent–child relationship, with the avatar NFT as the parent and the digital artifacts as the children. The function requires the caller to be registered and part of the avatar creators' mapping list, and to own all the NFTs used to create the composable NFT. As shown in Algorithm 4, the ownership of all NFTs is verified using the 'ownerOf' function from the Openzeppelin library of the ERC 721 smart contracts. If any verification fails, the smart contract reverts back to the previous state. Assuming all checks pass, the digital artifact NFTs are added to the composable avatar (CompAV) mapping, and an event is emitted to announce the successful addition of the children's digital artifacts to the NFT.

[3] https://github.com/smartcontract694/DynamicUseCase

[4] https://github.com/smartcontract694/composableUseCase

```
Compiled with solc
Number of lines: 3329 (+ 0 in dependencies, + 0 in tests)
Number of assembly lines: 0
Number of contracts: 15 (+ 0 in dependencies, + 0 tests)

Number of optimization issues: 0
Number of informational issues: 463
Number of low issues: 7
Number of medium issues: 9
Number of high issues: 0

ERCs: ERC721, ERC165

+-----------------+------------+--------------+------------+--------------+--------------------+
|       Name      | # functions |     ERCS     | ERC20 info | Complex code |      Features      |
+-----------------+------------+--------------+------------+--------------+--------------------+
|     console     |    381     |              |            |      No      |      Assembly      |
|       Math      |     14     |              |            |     Yes      |      Assembly      |
|     Strings     |     5      |              |            |      No      |      Assembly      |
|     Address     |     13     |              |            |      No      |      Send ETH      |
|                 |            |              |            |              |    Delegatecall    |
|                 |            |              |            |              |      Assembly      |
| IERC721Receiver |     1      |              |            |      No      |                    |
|     Counters    |     4      |              |            |      No      |                    |
|  ComponentsNFT  |     58     | ERC165,ERC721 |            |      No      |      Assembly      |
|   Marketplace   |     13     |              |            |      No      |    Receive ETH     |
|                 |            |              |            |              |      Send ETH      |
|                 |            |              |            |              | Tokens interaction |
+-----------------+------------+--------------+------------+--------------+--------------------+
```

(a) Summary of the detected vulnerabilities in the smart contract using Slither before mitigation.

```
Compiled with solc
Number of lines: 3331 (+ 0 in dependencies, + 0 in tests)
Number of assembly lines: 0
Number of contracts: 15 (+ 0 in dependencies, + 0 tests)

Number of optimization issues: 0
Number of informational issues: 0
Number of low issues: 0
Number of medium issues: 0
Number of high issues: 0

ERCs: ERC721, ERC165

+-----------------+------------+--------------+------------+--------------+--------------------+
|       Name      | # functions |     ERCS     | ERC20 info | Complex code |      Features      |
+-----------------+------------+--------------+------------+--------------+--------------------+
|     console     |    381     |              |            |      No      |      Assembly      |
|       Math      |     14     |              |            |     Yes      |      Assembly      |
|     Strings     |     5      |              |            |      No      |      Assembly      |
|     Address     |     13     |              |            |      No      |      Send ETH      |
|                 |            |              |            |              |    Delegatecall    |
|                 |            |              |            |              |      Assembly      |
| IERC721Receiver |     1      |              |            |      No      |                    |
|     Counters    |     4      |              |            |      No      |                    |
|  ComponentsNFT  |     58     | ERC165,ERC721 |            |      No      |      Assembly      |
|   Marketplace   |     13     |              |            |      No      |    Receive ETH     |
|                 |            |              |            |              |      Send ETH      |
|                 |            |              |            |              | Tokens interaction |
+-----------------+------------+--------------+------------+--------------+--------------------+
```

(b) Summary of the detected vulnerabilities in the smart contracts using Slither after mitigation.

Fig. 7. Security analysis of the dynamic industrial NFT use case smart contract.

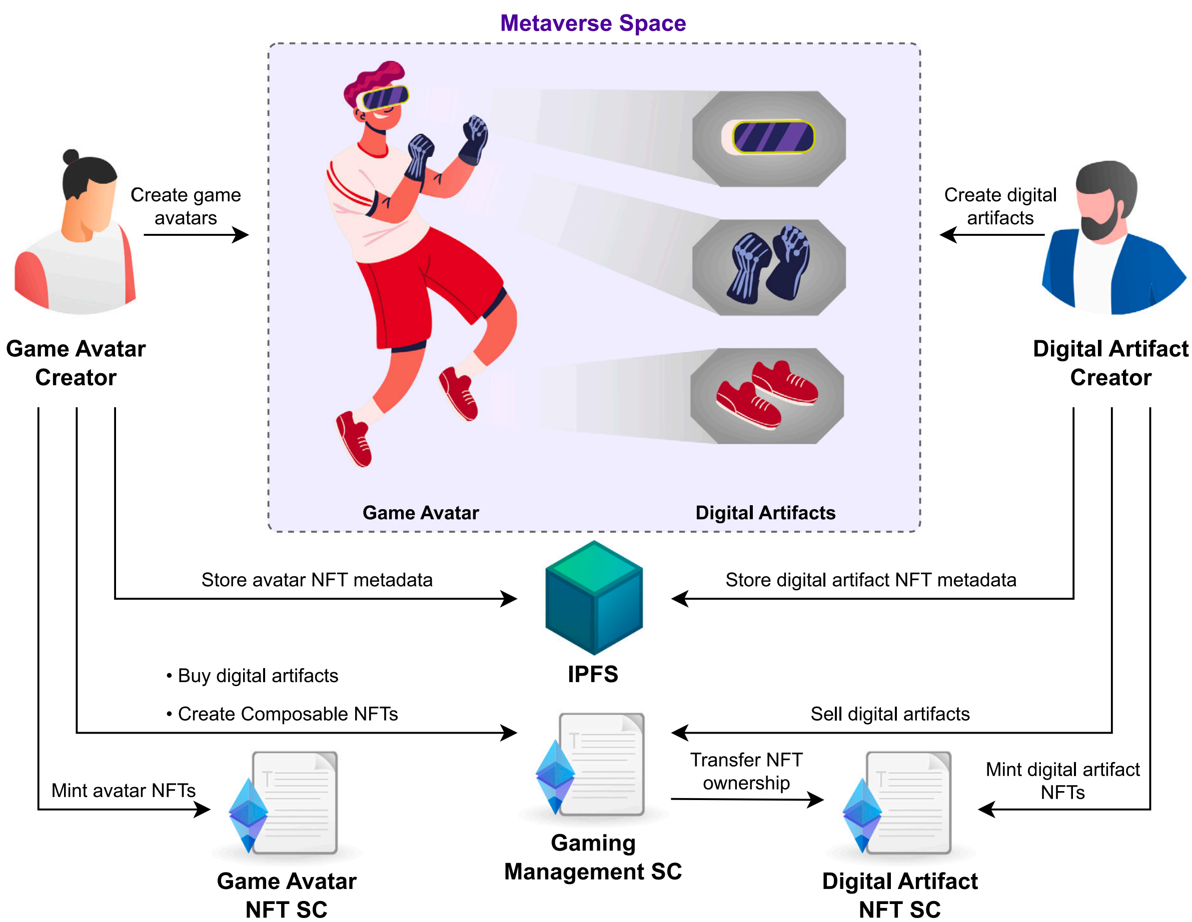


Fig. 8. System diagram of the gaming use case using composable NFTs in Metaverse.

Algorithm 5 outlines the process of creating a parent avatar NFT, which can then be used to build a composable avatar. To create a parent avatar NFT, the caller of the function must be a registered avatar creator, and the avatar NFT must already be owned by the function caller. The function checks the ownership of the avatar NFT using the 'ownerOf' function in the NFT's original creator's smart contract. Once all verifications are passed, the avatar NFT is added to the 'Game Avatar' mapping, which is a mapping of the owner's EA to a mapping of the original creator's EA to the avatar NFT structure. When digital artifacts are added to the parent avatar, a composable NFT is created and added to the 'Composable Avatar' mapping.

Algorithm 6 presents the process of adding digital artifact NFTs to an existing parent or composable avatar NFT. The avatar NFT can already be part of the composable avatar NFT and added using algorithm 5, or it can be a pre-existing one with both an avatar NFT and digital artifacts created using algorithm 4. If the owner wants to add more digital artifacts to the top-down composable, they must be registered with their smart contract address. The caller must be the

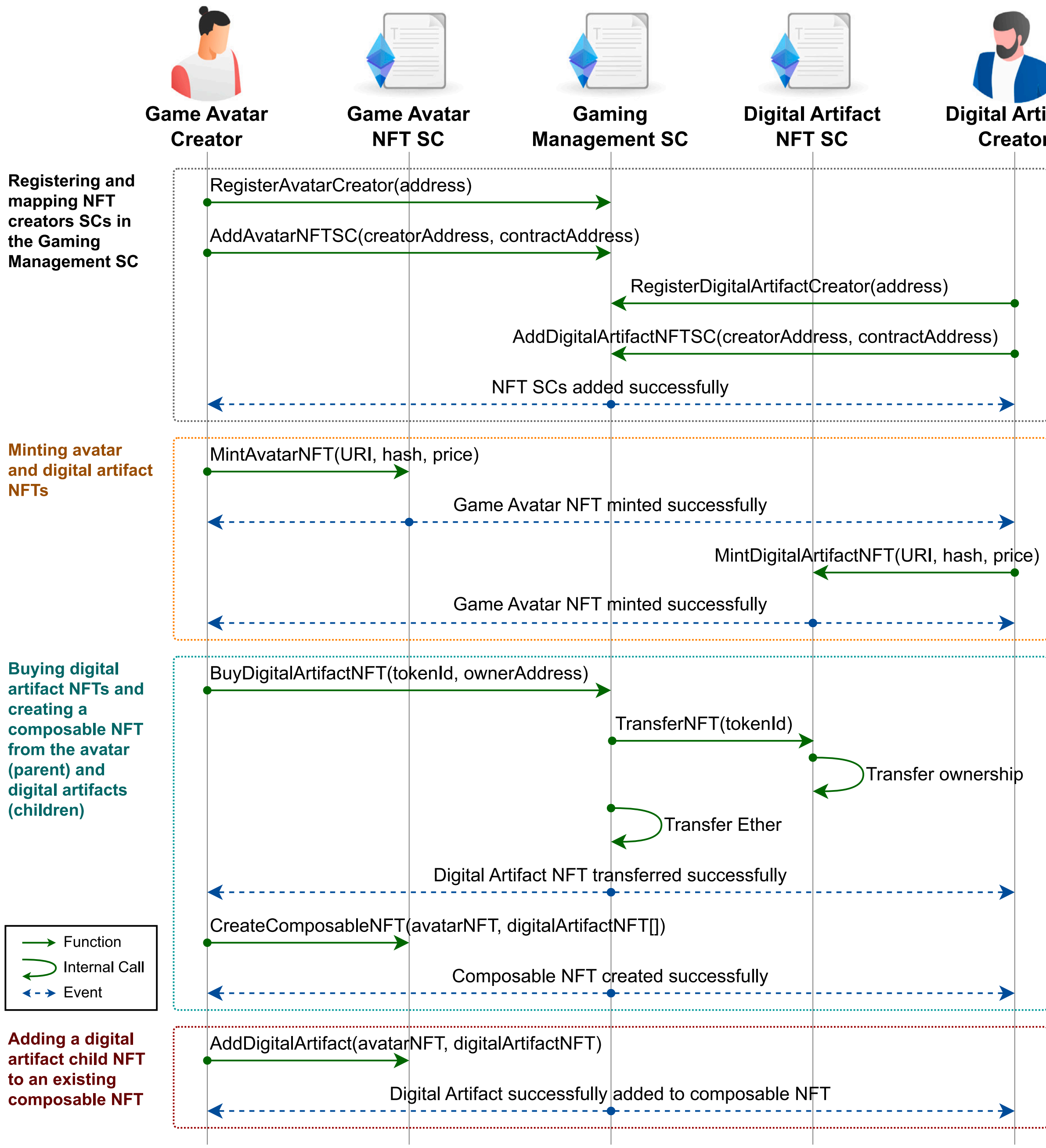


Fig. 9. Sequence diagram of the gaming industry use case showing the interactions between the different actors.

current owner of the digital artifact NFT. This function can be used to add one or multiple digital artifacts, and therefore, it takes an array of digital artifact NFT structures as an argument. A loop is used to iterate through the size of the passed array, and after all checks are passed, the new elements are pushed to the composable avatar mapping. An event is emitted at the end to announce the successful addition of the digital artifacts to the composable avatar.

6.2. Testing and evaluation

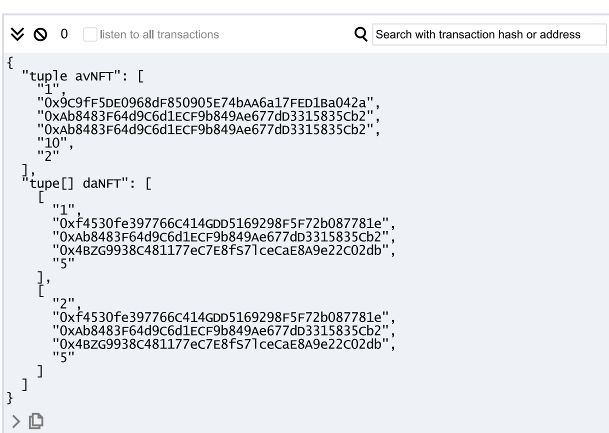
This subsection presents the performance assessment, cost evaluation, and security analysis of the composable NFT use case in the metaverse.

- **Performance Assessment** In this particular use case, three smart contracts have been written using the solidity language and thoroughly tested for compilation, run time, and logical errors to ensure proper execution and logical flow. Fig. 10 depicts the input information entered by the avatar creator to create the composable NFT, where the first input parameter is an avatar NFT structure and the second is an array of digital artifact NFT structures. The avatar NFT structure has six elements, including the token ID, which is ‘1’ for the avatar NFT. The first three EAs represent the SC address where the NFT was minted, the owner’s EA, and the original creator’s EA. This is followed by the price, which is 10 Ether, and the number of composables that will be added, which is two in this case. On the other hand, each digital artifact NFT structure in the array has five elements, with the token ID, SC address where it was minted, owner’s EA, and original creator’s EA. These three parameters are followed by the price, which is 5 Ether. After successful execution and minting of the composable NFT, the event ‘Composable NFT Successfully Created’ is emitted as part of the logs. Fig. 11 displays the logs

Algorithm 4: Gaming Management SC: Creating a Composable NFT

Input : caller, AvatarNFT, digitalArtiNFTs

$caller$: EA of the transaction caller
$AvatarNFT$: Structure containing the avatar NFT attributes
$daNFT$: Array of digital artifact NFTs structures
$RegisteredAvatarCreators$: Mapping with EAs of registered avatar creators
$artifactsNFTContracts$: Mapping between EAs of digital artifact creators and their SC addresses
if $caller \in RegisteredAvatarCreators$ **then**
  AvatarNFTSC = avatarNFTContracts[caller]
  if *caller == AvatarNFTSC.ownerOf(avNFT.tokenID)* **then**
    forall $i \in daNFT.length$ **do**
      if *daNFT[i].originalCreator* ∈ *RegisteredAvatarCreators* **then**
        DegiArtSC = artifactsNFTContracts[daNFT[i].OC]
        if *caller != DegiArtSC.ownerOf(daNFT[i].tokenID)* **then**
          Return to previous state. Error.
        end
      else
        Break. Return Error
      end
    end
    avNFT ∈ GamersAvatars[caller][avNFT.OC]
    forall $i \in daNFT.length$ **do**
      $CompAV[avNFT.OC][avNFT.tokenID] += daNFT[i]$
    end
    Emit ComposableNFTCreatedSuccessfully(avNFT.tokenID, daNFT.length)
  end
else
  Preview an error and return the contract to the previous state.
end

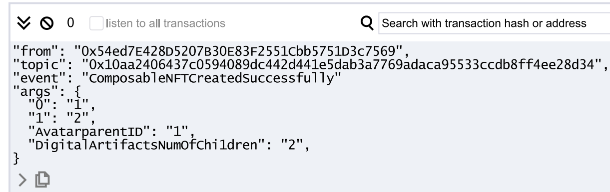


{
 "tuple avNFT": [
  "1",
  "0x9C9fF5DE0968dF850905E74bAA6a17FED1Ba042a",
  "0xAb8483F64d9C6d1ECF9b849Ae677dD3315835Cb2",
  "0xAb8483F64d9C6d1ECF9b849Ae677dD3315835Cb2",
  "10",
  "2"
 ],
 "tupe[] daNFT": [
  [
   "1",
   "0xf4530fe397766C414GDD5169298F5F72b087781e",
   "0xAb8483F64d9C6d1ECF9b849Ae677dD3315835Cb2",
   "0x4BZG9938C481177eC7E8fS71ceCaE8A9e22C02db",
   "5"
  ],
  [
   "2",
   "0xf4530fe397766C414GDD5169298F5F72b087781e",
   "0xAb8483F64d9C6d1ECF9b849Ae677dD3315835Cb2",
   "0x4BZG9938C481177eC7E8fS71ceCaE8A9e22C02db",
   "5"
  ]
 ]
}

Fig. 10. Input data entered to create a composable top-down NFT.

after creating the composable NFT by the avatar creator, which used an Avatar NFT as a parent and two children's digital artifact NFTs.

- **Cost Evaluation**



"from": "0x54ed7E428D5207B30E83F2551Cbb5751D3c7569",
"topic": "0x10aa2406437c0594089dc442d441e5dab3a7769adaca95533ccdb8ff4ee28d34",
"event": "ComposableNFTCreatedSuccessfully"
"args": {
  "0": "1",
  "1": "2",
  "AvatarparentID": "1",
  "DigitalArtifactsNumOfChildren": "2",
}

Fig. 11. Logs after successfully creating a composable top-down NFT.

Table 2
Cost evaluation of the composable NFT use case in the metaverse.

Function	Gas usage	Cost to execute (Ether)	Cost to execute (USD)
GamingManagement SC Deployment	2,102,803	0.1409	457.18
DigitalArtifacts SC Deployment	2,691,383	0.1803	585.15
AvatarNFT SC Deployment	2,691,275	0.1803	585.12
RegisterAvatarCreator	46,333	0.0031	10.07
RegisterArtifactCreator	46,356	0.0031	10.08
RevokeAvatarCreator	24,522	0.0016	5.33
RevokeArtifactCreator	26,522	0.0018	5.77
mintNFT (Digital Artifact)	193,340	0.01295	42.04
addArtificatNFTSCs	50,844	0.00341	11.05
mintNFT (Avatar)	193,292	0.01	42.02
createComposableNFT	459,885	0.0308	99.99
addDigitalArtifactToComposableNFT	170,527	0.0114	37.08

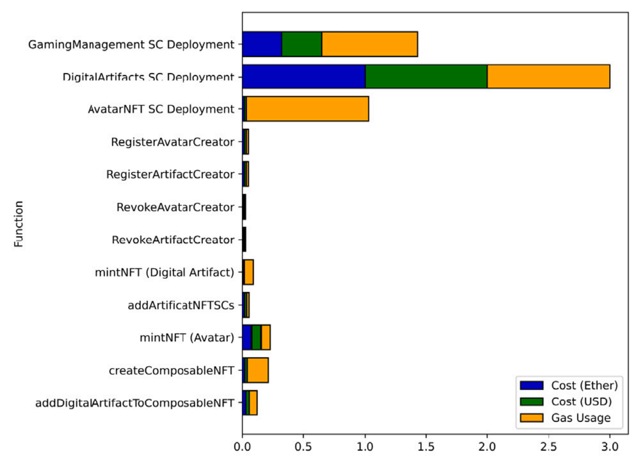
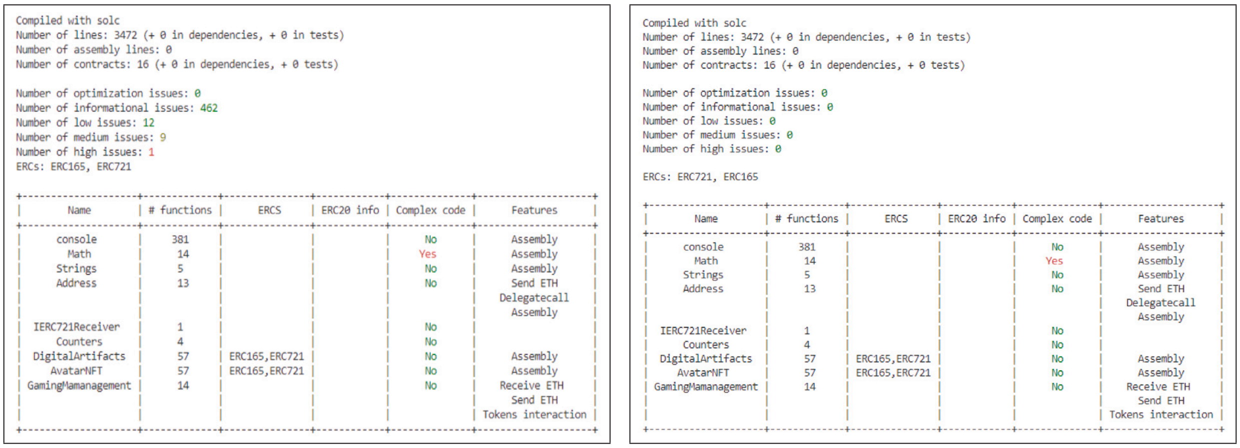


Fig. 12. Normalized gas usage and costs in Ether and USD of the composable NFT use case in the metaverse smart contract.

Cost evaluation for the composable NFT use case in the metaverse is conducted similarly to the previous use case to provide insights into the financial implications of deploying and executing smart contracts within this context. For this evaluation, an Ether price of 3245 USD and a gas cost of 67 Gwei, obtained from Etherscan on 27th February 2024 (Etherscan, 2024), were used.

Based on Table 2, several key insights can be drawn regarding the cost evaluation of this gaming industry use case. The deployment of smart contracts for gaming management, digital artifacts, and avatar NFT functionalities incurs significant gas usage and costs, reflecting the complexity and resource requirements of these contracts. Similarly, functions such as registering avatar creators, artifact creators, and minting various types of NFTs contribute to moderate to high gas usage and costs. The variability in gas usage and associated costs across different functions highlights the importance of optimizing resource allocation and efficiency within the gaming industry context. Fig. 12 presents the normalized gas usage and costs (in Ether and USD) for better visualization and comparison, allowing stakeholders to identify areas of potential optimization and prioritize resource allocation based on cost-effectiveness.



(a) Summary of the detected vulnerabilities in the smart contract using Slither before mitigation.

(b) Summary of the detected vulnerabilities in the smart contracts using Slither after mitigation.

Fig. 13. Security analysis of the composable NFT use case in the metaverse smart contract.

Table 3
Comparison of our implemented solution with other existing solutions.

	Liu et al. (2020)	Rachana Harish, Liu, Li, Zhong, and Huang (2023)	Tran et al. (2023)	Our solution
Blockchain Type	Hyperledger Fabric	Consortium PoA Ethereum	Private PoA Ethereum	Public or Private Ethereum Blockchain
DT Flexibility and Adaptability	Not implemented	Implemented but not standardized	Not implemented	Standardized (NFT-based), dynamic, and composable
Decentralized	✓	✓	✓	✓
Transparent and Auditable	✓	✓	✓	✓
Traceability	✓	✓	✓	✓
Mode of Operation	Private	Private	Private	Can be either Public or Private
Data Storage	Off-chain/On-chain	Off-chain/On-chain	Off-chain/On-chain	Off-chain/On-chain
Infrastructure Cost	High	High	High	Public mode: None, Private mode: High
Transactions Cost	Low	Low	Low	Public mode: High, Private mode: Low
Security	✓	✓	✓	✓
Scalability	✓	✓	✓	✓
Transactions Per Second (TPS)	165–250	24.07–45.68	140–150	15 (Public), 140–150 (Private)
Latency (Seconds)	0.8–1	5.56–10.55	1.2–3.8	13–15 (Public), 1.2–3.8 (Private)

This evaluation provides developers with valuable insights into the efficiency and performance of their smart contracts within the gaming industry. By analyzing the costs associated with each function, developers can identify bottlenecks and areas for improvement, allowing them to optimize gas usage and reduce overall expenses. Focusing on certain functions with high gas usage and costs enables developers to implement targeted optimization strategies, ultimately enhancing the financial sustainability and performance of the composable NFT use case in the metaverse.

- **Security Analysis**
  Similar to the previous use case, we conducted a security analysis of our smart contracts using Slither. During the security analysis process, we identified a significant number of issues within our smart contracts. These issues were categorized based on their severity, with the majority falling into the informational and low-level categories. However, it is crucial to address any high-level vulnerabilities promptly, as they pose the greatest risk to the security of the system. In our analysis, we detected one high-level issue and 12 medium-level issues, which we prioritized for immediate resolution.
  Fig. 13(a) illustrates the categorization of these vulnerabilities. To ensure the robustness and security of our smart contracts, we diligently addressed all identified issues and implemented appropriate mitigation measures. Fig. 7(b) showcases the resolution of these vulnerabilities, demonstrating our commitment to maintaining a secure and reliable system. Additionally, the full details of the detected vulnerabilities are available on GitHub.[5]

Algorithm 5: Gaming Management SC: Add Parent Avatar NFT to an Owner

```
Input : caller, avNFT
caller: EA of the transaction caller
avNFT: GameAvatar structure
if caller ∈ RegisteredAvatarCreator then
    AvatarNFTSC = avatarNFTContracts[caller]
    if caller == AvatarNFTSC.ownerOf(avNFT.tokenID) then
        GA[msg.sender][avNFT.OC] += avNFT
        Emit an event announcing the successful addition of the Avatar NFT to the owner
    else
        Error. Return to previous state.
    end
else
    Preview an error and return the contract to the previous state.
end
```

7. Comparative assessment and benchmark analysis for the implemented use cases

This section compares our solution with other state-of-the-art solutions in the same domain to demonstrate the novelty of our approach. Our solution can be deployed on either a public or private Ethereum blockchain, hence some metrics in Table 3 include two values for our solution. While we have introduced two different use cases, we will

[5] https://github.com/smartcontract694/composableUseCase

Algorithm 6: Gaming Management SC: Add Children Digital Artifact NFTs to an Owner

```
Input : caller, avNFT
caller: EA of the transaction caller
avNFT: GameAvatar structure
if caller ∈ RegisteredAvatarCreator then
    AvatarNFTSC = avatarNFTContracts[caller]
    if caller == AvatarNFTSC.ownerOf(avNFT.tokenID) then
        DegiArtSC = AFNFTCont[daNFT.OC]
        if caller == DegiArtSC.ownerOf(daNFT.tokenID) then
            size ← CompAV[avNFT.OC][avNFT.tokenID].length
            forall iinsize do
                if CompAV[avNFT.OC][avNFT.tokenID][i].tokenID == daNFT.tokenID then
                    Break, return error
                end
            end
            CompAV[avNFT.OC][avNFT.tokenID] += daNFT
            CompAV[avNFT.OC][avNFT.numOfcompos++]
            Emit an event digital artifact successfully added to composable NFT
        end
    else
        Error. Return to the previous state.
    end
else
    Preview an error and return the contract to the previous state.
end
```

compare them with the others as one since our focus is on decentralizing and tokenizing physical assets in the form of digital twins on the blockchain. The comparison is based on benchmark analysis, and the metrics are shown in Table 3.

Our solution stands out in the domain of decentralized digital twins by leveraging dynamic and composable Non-Fungible Tokens (NFTs), a feature not present in the compared solutions. The utilization of dynamic NFTs allows for the representation of real-world assets that may evolve over time, such as machinery condition and maintenance history, ensuring that digital twins accurately reflect the dynamic nature of physical assets. Moreover, the incorporation of composable NFTs enables the assembly of complex digital representations by combining multiple NFTs representing different aspects of an asset, further enhancing the granularity and richness of digital twin data. This dynamic and composable nature of NFTs empowers organizations to create immersive and data-rich representations of physical assets, driving innovation and efficiency across the industrial value chain. Additionally, the use of standardized NFTs improves interoperability by ensuring compatibility and seamless integration with existing systems and platforms, fostering greater data exchange and collaboration within the industrial metaverse ecosystem.

In terms of decentralization, transparency, and audibility, our solution aligns with other existing solutions, ensuring that transactions are traceable and securely recorded on the blockchain.

Regarding the mode of operation, our solution stands out as it can be deployed on either public or private Ethereum blockchains, offering flexibility to organizations based on their requirements. Additionally, our solution utilizes both off-chain and on-chain data storage, similar to other solutions, ensuring efficient data management. However, the infrastructure cost for our solution varies depending on the deployment mode, with lower costs for public mode compared to high costs for private mode.

In terms of transaction costs, our solution incurs high costs in public mode due to the Ethereum network's gas fees, while costs are lower in private mode since they can be configured in the genesis block of the blockchain. Security and scalability are key features of our solution, aligning with other solutions in the domain. However, it is essential to note that our solution conducted thorough security analysis for the smart contracts to ensure they are free from vulnerabilities, a measure not mentioned in the other solutions. This underscores our commitment to providing a secure and robust platform for decentralized digital twins in the industrial metaverse.

Finally, in terms of Transactions Per Second (TPS), our solution exhibits lower TPS and higher latency in public mode compared to other solutions due to the nature of the Ethereum blockchain. In private mode, TPS and latency are comparable to existing solutions, ensuring efficient transaction processing and response times.

8. Discussion

This section gives an analysis of the main findings, open challenges, and limitations of the study, as well as practical implications for the development of composable and dynamic NFTs for digital twins in the industrial metaverse.

8.1. Summary of main findings

This paper showcases the enormous potential of composable and dynamic NFTs in revolutionizing industrial applications using the metaverse. The presented use cases provide evidence of the feasibility and effectiveness of utilizing these NFTs to teleport the physical world into an industrial digital replica. By leveraging composable and dynamic NFTs, they become more flexible and useful within virtual environments, unlocking the potential for enhanced interactive and immersive experiences in the metaverse. Additionally, the adaptability of composable and dynamic NFTs in various industrial use cases, including real estate, is highlighted. However, challenges persist in the development and integration of this technology, necessitating expertise in blockchain, smart contract development, and metaverse technology, as well as a thorough understanding of user requirements and behaviors in the metaverse. This paper's results offer valuable insights into the potential of composable and dynamic NFTs for industrial applications in the metaverse and provide a foundation for future research in this field.

8.2. The role of NFTs in the industrial metaverse

NFTS are a way to bridge the physical and digital worlds into the industrial metaverse in a trusted, secure, and transparent manner. NFTs have provided the means to teleport a physical object that can be converted to a digital twin to exist as an NFT in the industrial metaverse. The expanding and widespread adoption of NFTs and decentralization have supported the immersive nature of the metaverse. NFTs are unique certificates of ownership and originality that have also allowed the monetization of assets in the industrial metaverse. Evidently, digital assets are notorious for being easy to fake and steal. However, NFTs provided a way to easily trace the ownership of digital assets and have paved the way for trusted royalties from the resale of digitally produced and manufactured goods and products. NFTs have made in-app purchases more secure and mitigated issues related to trust and fraud. Additionally, NFTs have proven that VR landscapes can be fertile ground for minting and trading in a trustworthy environment. Consequently, they have provided supply chain transparency where raw materials are tracked through every step in their life cycle across the chain, from their source to manufacturing and delivery. By using NFTs as proof of ownership and originality, they have enabled product authentication in the industrial metaverse and contributed to counterfeit prevention.

8.3. Open challenges and limitations

While the use of composable and dynamic NFTs in the industrial metaverse presents great potential, some open challenges and limitations need to be addressed to fully realize their benefits. In the following subsection, we discuss some of the key challenges and limitations for NFTs in the industrial metaverse.

- **Technical Challenges and Limitations**
  Several technical challenges and limitations need to be addressed in the development and integration of NFTs for industrial applications in Metaverse. These include:
  - **Scalability:** Scaling NFTs in the industrial metaverse is a significant challenge, particularly in handling a growing number of users and transactions for industrial purposes. Existing blockchain technology may struggle to cope with the increasing volume of transactions, resulting in delays and higher costs.
  - **Interoperability:** The lack of interoperability between NFTs on various Metaverse platforms can curtail their effectiveness and versatility. To address this issue, it is important to establish common standards and protocols.
  - **Complexity of Smart Contracts:** The development and implementation of smart contracts for NFTs can be a complex and challenging task. Vulnerabilities in smart contracts can result in the loss of NFTs and their associated value.
  - **Security Concerns:** NFTs are vulnerable to hacking, theft, and fraud, which can compromise the integrity of the data they represent. Robust security measures are necessary to safeguard NFTs and ensure their accuracy.
    Integration Challenges: Integrating NFTs with existing industrial applications and systems can be a challenge. Developers must ensure that NFTs can interact seamlessly with various platforms and systems while maintaining their functionality and security.
- **User Challenges and Limitations**
  There are user challenges and limitations that must be taken into consideration to enable the widespread adoption and effective use of NFTs in the industrial metaverse. These include:
  - **User Adoption:** The employment of NFTs in the industrial metaverse is still at a nascent stage, despite their increasing popularity in recent years. Users may not grasp the concept and significance of NFTs entirely, or they might be reluctant to invest in them, constraining the potential utilization of NFTs in the metaverse.
  - **User Behavior:** Like any other virtual space, there is a possibility of misusing and engaging in unethical behavior within the metaverse. With regards to NFTs, this can entail the fabrication and dissemination of fake NFTs, the utilization of NFTs for illegal activities such as money laundering, and exploiting susceptible users for financial profit.
  - **User Experience:** Although NFTs can enhance the user experience in the metaverse, their ineffective implementation can lead to a complex and perplexing user experience. Users may face challenges in comprehending how to buy, sell, and trade NFTs and may encounter technical difficulties in executing these tasks. Furthermore, the utilization of NFTs can necessitate a high level of technical knowledge and proficiency, which can pose a hurdle for certain users.
  - **User Privacy:** The use of NFTs in the industrial metaverse may pose a threat to user privacy, as personal data can be vulnerable to breaches and misuse. This can lead to the exposure of personal information related to NFT transactions or the tracking and monitoring of user and business activities. Such privacy concerns may discourage users from adopting NFTs in the metaverse. For example, it might be difficult to manage the privacy of the patient in a medical application for the healthcare industry in the metaverse. The leakage of personal or business information will lead to a plethora of data circulating around an enormous virtual world. This can lead to a violation of ethics and the deterioration of the mental health of patients (Marzaleh, Peyravi, & Shaygani, 2022).
- **Security and Privacy Challenges and Limitations**
  To ensure the successful development and adoption of NFTs in the industrial metaverse, security, and privacy must be taken seriously. The following are some of the possible challenges and limitations regarding security and privacy for NFTs in the metaverse:
  - **Unauthorized Access and Theft:** Theft and unauthorized access to NFTs pose a significant financial risk for users in the industrial metaverse. To prevent this, secure storage solutions like cold wallets, multi-factor authentication, and encryption techniques can be used. However, these solutions can also create complexity and usability issues, especially for users who lack technical expertise.
  - **Smart Contract Vulnerabilities:** The use of smart contracts in NFTs poses the risk of vulnerabilities and bugs, which can lead to the theft or loss of NFTs and other assets stored on the blockchain. Developing secure smart contracts requires expertise in blockchain and programming, and even experienced developers can make errors that can be exploited by attackers. Additionally, the use of third-party smart contracts can increase the risk, as the security and reliability of these contracts are beyond the control of individual users.
- **Environmental and Energy Challenges and Limitations**
  Another important set of challenges and limitations that come with the development and use of metaverse technologies, including NFTs, are environmental and energy-related. These include:
  - **Increasing Demand for Energy:** As metaverse technologies expand, their energy needs are expected to increase significantly, resulting in potential environmental consequences such as increased greenhouse gas emissions that contribute to climate change. Moreover, the computational resources powering Metaverse technologies and NFTs can require significant amounts of energy, both in quantity and cost, posing challenges for users with limited access to affordable and reliable energy sources.
  - **Maintenance and Upgrade Challenges:** As metaverse technologies become increasingly complex and resource-intensive, there is mounting concern regarding the difficulties that may arise during their maintenance and upgrading. This predicament may necessitate a greater dependence on outdated technology and, consequently, result in a heightened susceptibility to security vulnerabilities. Additionally, users may encounter challenges in remaining up-to-date with the latest technological advancements in the industrial metaverse, potentially curtailing their capacity to reap the platform's full benefits (Di Pietro & Cresci, 2021).

8.4. Social and ethical challenges and limitations

The following are several social and ethical challenges and limitations to consider in the development and use of metaverse technology:

- **Social Inequalities and Biases:** Access to metaverse technology and its applications can be easier for developed countries. This would widen the gap between developing and developed countries in terms of access to Metaverse benefits and advantages. The inequalities might lead to the development of notorious social norms and issues in poor and underdeveloped countries.
- **Data Ownership and Control:** The increasing immersion and personalization of Metaverse experiences lead to the accumulation and storage of extensive user data, encompassing personal preferences, behaviors, and interactions. This development poses concerns regarding data accessibility, usage, and user autonomy. In the absence of appropriate safeguards and regulations, the amassed data may be misused for detrimental objectives, including targeted advertising and even surveillance.
- **Reality and Virtuality Boundaries:** As individuals become more immersed in the metaverse, there is a possibility that the lines between reality and virtuality may become less clear. This shift in priorities towards virtual experiences may cause individuals to neglect their real-life interactions and responsibilities, ultimately resulting in social isolation, mental health problems, and other adverse effects.
- **Ethical and Social Norms Concerns:** The metaverse is an immersive world where users might misuse it and break away from reality. Some users might suffer from over-addiction which can lead to mental and physical damage in the real world. Social norms and interactions in the real physical world might change and become more cumbersome with more users leaning towards the Metaverse and embracing its social virtual platform interactions. Gaming in the metaverse is mainly captivating the younger generations. Gaming management and exploring the full world of a game are challenges that parents and child mentors might face when guiding youngsters to avoid mishaps (Park & Kim, 2022).

8.5. Practical implications

The practical implications of using dynamic and composable NFTs for digital twins in the industrial metaverse are noteworthy. The first implication is the potential enhancement of the user experience by offering more flexibility and interactivity in virtual environments. This may result in increased user engagement and immersion, rendering the metaverse a more engaging and enjoyable platform for users. The adaptability of these NFTs to various use cases, including real estate, is the second implication that may lead to the development of new applications and services within the metaverse. Such advancements could potentially establish new business models and revenue streams for creators and developers. Additionally, the utilization of NFTs can offer creators and artists a chance to earn money and gain acknowledgment for their inputs, thereby fostering a more sustainable environment for content production in the metaverse. Furthermore, the adoption of dynamic and adaptable NFTs has the potential to address certain obstacles encountered in conventional digital twin technology, such as concerns regarding the privacy and security of data. Overall, using dynamic and composable NFTs for digital twins in the metaverse has significant potential to revolutionize virtual environment interaction and engagement and could lead to new and innovative applications in the future.

8.6. Generalization

In this paper, we have chosen two industrial use cases to study in detail and present the design, implementation, and testing results. However, dynamic and composable NFTs for teleporting digital and physical assets into the industrial metaverse play a vital role in several other applications and use cases. The presented framework can be applied in the fields of medicine, smart cities, supply chain and automation, manufacturing, and agriculture. Dynamic NFTs enable the reflection of a changing external state into the metadata. Composable NFTs contribute to creating a structure in a structure. A top-down approach is presented in this paper, but a bottom-up approach is equally important and can be utilized based on the application's needs and requirements. We have shown how the ERC-721 library that is used for minting single NFTs can be adapted to mint dynamic and composable NFTs. Moreover, our code and added functions have been explained in detail to allow reusing their functions and arguments to achieve the objectives of diverse applications and use cases. The smart contracts provided can be utilized as building blocks for other applications and scenarios that require the use of dynamic and composable NFTs in the industrial metaverse.

9. Conclusion and future research directions

The synergistic integration of the metaverse, digital twins, and blockchain technologies offers promising avenues for transforming industrial applications, revolutionizing processes, and enhancing efficiency, security, and innovation in diverse sectors. In this paper, we have showcased the roles and uses of dynamic and composable NFTs in the industrial metaverse, which relies heavily on digital twins. We showed their potential through detailed industrial use cases and gave details on how they were designed and built.

The ability to teleport physical objects into the metaverse and the relationship between assets in the physical world have been explored, showcasing the versatility of these NFTs. Our paper explores various ways in which NFTs carve out pathways within the industrial metaverse, particularly focusing on their impact in the gaming industry and maintenance sectors. We presented sequence diagrams, implemented algorithms using smart contract code and discussed testing results. We also showcased the feasibility of our implemented solutions through comprehensive cost and security analyses. Our work highlights the dynamic and transformative potential of NFTs, demonstrating how they can fundamentally reshape the operations of industries.

Future research challenges have also been identified to ensure the effective and reliable use of the metaverse in various applications. Further exploration can be done in several research directions. These include investigating the effectiveness of composable and dynamic NFTs in domains such as education, healthcare, and entertainment. Integrating these NFTs with emerging technologies like virtual and augmented reality can enhance the immersive experience in the industrial metaverse, warranting further study. Additionally, technical challenges related to scalability, interoperability, and security need to be addressed through continued investigation. Identifying and addressing these limitations will contribute to the successful implementation of composable and dynamic NFTs. Furthermore, analyzing the social and ethical implications of utilizing these NFTs in the metaverse, particularly in terms of privacy and ownership, would provide valuable insights.

Overall, this study highlights the immense potential for future research in the field of composable and dynamic NFTs in the industrial metaverse. Continued exploration and investigation will drive the next wave of industrial evolution and facilitate the full realization of its potential.

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Haya R. Hasan: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Mohammad Madine:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Ahmad Musamih:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization. **Raja Jayaraman:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Khaled Salah:** Writing – review & editing, Validation, Project administration, Conceptualization. **Ibrar Yaqoob:** Writing – review & editing, Validation. **Mohammed Omar:** Writing – review & editing, Funding acquisition.

Data availability

No data was used for the research described in the article.

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