Digital Business 4 (2024) 100079

Contents lists available at ScienceDirect

Digital Business

journal homepage: www.elsevier.com/locate/digbus

A new business model in the fine arts realm based on NFT certificates and pearl codes

Eva Maria Kuehn *

TU Wien, Faculty of Informatics, Compilers and Languages Group, Vienna 1040, Austria

ARTICLE INFO

Keywords:
NFT
Fine arts
Business model
Coordination
Digital twin
Real and virtual worlds
Formal model

ABSTRACT

The potential of Non-Fungible Tokens (NFTs) is highly anticipated, particularly in the realm of visual arts. However, current applications within fine arts often involve trivial processes, such as creating digital versions of artworks or replicas of masterpieces as NFT images, and selling only these NFTs. To unlock the full potential of NFTs, more innovative models are needed. This paper introduces a novel model that establishes a permanent link between an NFT and a physical craft object. This linkage is utilized to orchestrate the trade workflow, ensuring a sustained connection between real and digital artifacts. A distinguishing feature is that they can be sold together or seperately and later reunited with a buyer. The NFT serves as a multifunctional certificate, tracing, and communication token.

Through a comprehensive analysis, this paper explores diverse scenarios that may arise in the relationship between the physical object and its digital twin. It presents a systematic and formal description of the proposed model and its various cases, marking a pioneering effort in the field. Noteworthy advantages include the ability to detect plagiarism and fraud. By strategically incorporating stakeholder roles, the model preserves the anonymity of art collectors while extracting valuable information about the ownership of physical artworks. The primary objective is to enhance security in the art trade and foster new business opportunities for stakeholders. As a proof-of-concept, the model was implemented in a real-world scenario on a leading NFT marketplace platform.

1. Introduction

In the dynamic realm of art and craftsmanship, non-fungible tokens (NFTs) have gained significant attention, especially within the visual arts. However, existing applications have predominantly focused on digital artworks or the creation of NFTs as digital replicas of physical masterpieces. A fundamental challenge is that current approaches do not provide sustainable and effective models for the successful utilization of NFTs in the art and crafts sector. Presently, three fundamental categories can be identified: the generation of NFTs for digital art without a physical counterpart, the crafting of NFTs from digital replicas of masterpieces, where the physical artwork usually remains in the museum, and the utilization of digital twins for physical objects, particularly in the luxury segment of fashion. These approaches primarily aim to sell NFTs profitably, with the hope of generating continuous revenue through resale. However, a crucial deficiency exists in the absence of clear models or rules for what happens after the initial acquisition of the NFT. Specifically, there is no support for subsequent sales by partners, and there is a lack of clear connections between the NFT and the physical object in the future.

The aim of this paper is to create an innovative and new business model for the art market using the concept of NFTs. The focus is on valuable, unique items such as works of art, expensive fashion, handmade objects and jewelry. Such items are by nature not officially registered like a car and are considered non-fungible items. The research questions are how to establish a permanent link between an NFT and its physical twin and how this model can contribute to fraud prevention and securing art objects in trade, especially in the context of resale and authentication of physical objects. The highlight of the proposed approach is that it fulfills all of the following requirements:

- The model relies entirely on existing NFT and blockchain platforms and standards, so there are no costs for developing additional software such as smart contracts or off-chain services. The necessary requirements for a suitable marketplace are explained, as well as the reasons why the NFT marketplace Opensea (see Appendix A) was

* Corresponding author.
E-mail address: eva.kuehn@tuwien.ac.at.

https://doi.org/10.1016/j.digbus.2024.100079
Received 1 July 2023; Received in revised form 18 April 2024; Accepted 23 April 2024
Available online 25 June 2024

chosen for the proof-of-concept implementation. The necessary transaction fees are also demonstrated by means of Opensea.
- The model provides for a permanent link between the digital and physical twin, whereby both the NFT and the physical artifact can be sold independently or together, with transactions taking place in either fiat currency or cryptocurrency.
- The model is underpinned by a formal specification in order to prove the correctness of the approach in the many conceivable situations.
- The model can be used in the field of fine arts to prevent fraud.
- The model opens up new "white space" growth opportunities for the Manufacturer.

Another pivotal contribution is the introduction of a new kind of business partner role, termed "Agent". Agents serve as trustworthy partners, who facilitate the joint trading of NFTs and physical objects. They play a key role in verifying the authenticity of physical objects and ensuring that NFTs and physical objects actually correspond. A particular advantage is that there can be many distributed Agents, who may dynamically join, and that the users buying and selling physical and/or digital artifacts can choose their own Agent.

Furthermore, the comprehensive formal analysis of the different scenarios that can occur in this model demonstrates the potentials that arise from tamper-proof and unalterable blockchain information: The importance of using NFTs is systematically and in detail explained with regard to the knowledge that can be gained about the physical object only due to the usage of NFTs according to the model specification.

The major business advantages for the Manufacturer are that it can sell its products as always but in addition it can market them with the digital twin concept which provides the Manufacturer ongoing revenues in form of creator earnings. With the digital twins opportunity the Manufacturer diversifies its existing physical product by creating new, innovative offerings which in the future may also expand to the metaverse (Zalan & Barbesino, 2023).

The proof-of-concept of the model is demonstrated using an example application for handmade crocheted products.

The paper is structured as follows: Section 2 contains a systematic literature review of related approaches that establish a permanent link between an NFT and a physical craft object and where this sustained connection is completely and clearly specified. Section 3 gives the needed background on NFT technologies and standards. Section 4 details the research steps. Section 5 introduces a new coordination model for coupling NFTs with physical handcrafted artworks and presents its general informal specification as well as a selected part of its formal specification. Section 6 shows a real use case from the arts and crafts domain on Opensea that realizes this model. Section 7 discusses and evaluates the advantages of the new model. Section 8 summarizes the findings.

2. Literature review

A systematic literature analysis has been carried out that shows that there is currently no approach that fulfills all the requirements mentioned in section 1: use of existing NFT and blockchain platforms, creating a permanent connection between the digital and physical twin, provision of a formal specification of the model, prevention of fraud through counterfeiting, and white space growth opportunities for stakeholders. The search strategy is detailed in Appendix B.

2.1. Combining real and virtual worlds

In the context of combining real and virtual worlds in general, the new notion of "phygital" has been coined, which stands for physical plus digital. (Mele et al., 2023) is a systematic literature review on this topic, stating that "research into the theoretical development of this phenomenon is lacking" and "the term phygital lacks a clear definition and offers several interpretations." 13 different and not coherent definitions of the term "phygital" are presented. As an outcome, the authors say that "phygital experience can be a radical change for value co-creation, and how this can happen has not yet been investigated" and that "more research should address the fact that phygital can not only refer to the customer, but also needs to address the broader phygital transformation process and multiple actors." The paper mentions blockchain and NFTs as enabling smart technologies in this context. So we see that this is a rather new field, and precise definitions and models are still lacking.

There are high expectations of phygital NFTs, but also many unsolved problems yet: (Umashankar, 2023) calls phygital NFTs a "transformation of blockchains", but does not show a detailed model for this. (Howell, 2022) claims that "phygital NFT has come up as one of the most significant phygital experiences for users" and envisions that "the physical NFTs representing fine art could be traded just like the real artwork" and that "on the other hand, NFT artwork can also be redeemed for obtaining physical art in the future" and envisions the usage as certificates, and highlights the potential of new revenue models for creators. However, no applications and models are mentioned that provide an everlasting connection between artifacts belonging to these different worlds. (Wilson et al., 2022) points out clearly that the long term linkage between physical and virtual artifacts is a challenge, because the information that NFTs hold about the physical object is just a snapshop at a point in time: "... ensuring the originating provenance is accurate, and that off-chain information linked to NFT content is properly safe guarded and secure over the long term remain primary concerns for stakeholders."

(Chandra, 2022) calls the NTF associated with a physical object a "virtual twin". The paper classifies NFTs according to their affordances: "virtual assets (e.g., virtual arts and games); hybrid assets (e.g., virtual tickets and music albums with a physical presence); as a physical/virtual interface (e.g., sneakers and watches with a virtual presence); and as a metaverse asset (e.g., a weapon, skin, or land within the metaverse)."

(Du et al., 2022) analyzes how artists may use NFTs to sell their artworks. The paper differentiates between digital art (stand-alone), profile pic (generative art), and phygital art (linking physical art with the NFT). It states that there are not yet any notable cases of the phygital art and that new models "will shift the dynamic between the artist and the buyer, the role of the intermediaries (auctions, galleries, online platforms)." The conclusion is that "[NFT] marketplaces are still in the process of reaching a point where users can find a more healthy and safe trading experience on digital assets. Sooner than later, NFTs may be linked to some physical counterparts (as utility NFTs)." So also these authors consider the idea of phygital art as a not yet explored approach.

In summary, none of the shown examples implements a sustained connection between real and digital artifacts. For this, the blockchain would have to somehow interact with external parties, as the physical artifact exists off-chain. Moreover, no formal specifications or formal analyzes of such NFT models exist beyond implementations on blockchain and NFT marketplace platforms. However, these are important so that users will trust and accept the model.

2.2. Selected examples of NFTs in fine arts

In the following we summarize concrete examples for the usage of NFTs in fine arts.

An obvious application is to create a digital artwork and to reference it from the NFT's metadata via the image URI (e.g., Beeple (Lyubchenko, 2022)). The creation of an NFT on an NFT marketplace is easy and can be done by users, capable of creating a crypto wallet, or it can be generative, e.g., CryptoKitties, CryptoPunks, and Bored Ape Yacht Club (see Appendix A). Opensea allows the creator (artist) to configure so-called "creator earnings", which guarantee revenues everytime the NFT is being resold. Therefore, a huge number of NFTs of this kind can be found in the arts rubric of Opensea. The coordination workflow starts with the creation of the NFT, followed by minting and trading. No physical artifact is connected with the NFT.

Museums (e.g., Belvedere, British Museum, Eremitage, Metropolitan Museum of Art, Uffizi Galleries) that have already tried the new NFT technology create digital replicas with possible amendments of old masterpiece paintings, use them as NFT images and offer these NFTs for sale in limited editions (Valeonti et al., 2021). However, this model raises criticism, namely that it violates the principles of the OpenGLAM "that promotes free and open access to the digitized collections of galleries, libraries, archives and museums initiative" (Valeonti et al., 2021). E.g., Belvedere splits the replica into tiles, Eremitage adds the museum director's signature, and Uffizi sells the digital image as a separate product. The physical artifact is referenced by the NFT, but the buyer does not get license rights on the original. Note that in general you cannot derive rights on a physical object from an NFT (Alpini, 2023): "NFTs are not the artwork, and the artwork is separate from the copyright over the artwork" (Murray, 2023). The coordination workflow is the same as above.

In the fashion business, NFTs either represent garments in the metaverse and/or are linked to physical artifacts (e.g., Prada's "Time Capsule" Rodriguez Sanchez and Garcia-Badell (2023) (see Appendix A) and NIKE's "CryptoKickers" (Marquês et al., 2023; NIKE, 2019; Rodriguez Sanchez & Garcia-Badell, 2023)) to prove their authenticity. When buying a physical clothing item, an NFT is created and transferred to the buyer. Subsequently the buyer can resell NFT and/or physical artifact, however, these NFT models do not provide any rules for this process. CryptoKickers are digital twins (Far et al., 2022), targeting the metaverse (McKinsey, 2022) and reusing the gaming idea of CryptoKitties: NFT owners may "breed" new digital shoe NFTs and claim the corresponding physical ones from the Manufacturer. The coordination workflow consists of selling the physical artifact, generating and minting the NFT, and transferring it to the buyer of the physical artifact. Then the user may autonomously trade the NFT. If no physical artifact exists, the last step of transferring the NFT is omitted. If the user breeds NFTs and requests shoes, the Manufacturer must send them.

Damien Hirst's "The Currency collection" (see Appendix A) model connects NFTs with physical artworks in an unconventional way. It is a collection of paintings, where for each an NFT was created with a foto of the painting as image. These NFTs were sold and then the buyer could decide to keep the NFT or exchange it with the physical artifact. The respective other counterpart was burned, cf. "elimination" (Chandra, 2022) but also for the physical picture. The coordination workflow is: create painting, create NFT, mint and sell NFT, interact with collector, depending on its decision burn either NFT or physical artifact. After this, the collector can autonomously either trade the NFT or sell the painting, depending on the decision.

3. Theoretical foundation

3.1. Technical introduction to NFTs

There are a lot of stories and inaccurate metaphors (Gibson, 2021) being spread about NFTs (Non-Fungible Tokens). Usually, an NFT is equated with the digital image referenced in its metadata. Technically speaking, the NFT 721 standard (Entriken et al., 2018) specifies that an NFT belongs to a smart contract and has a unique tokenID within that smart contract. The smart contract must implement the ERC721 interface that defines functions to transfer the NFT from one owner to another one, to query the owner, to query the balance of the owner, and to enable or disable approval for a third party to manage the NFT. The transfer function is also used to create (mint) and destroy (burn) a token. For this, either the from or the to address of the transaction must be set to null. It is required that the smart contract also implements the ERC165 interface (Reitwießner et al., 2018) for publishing and detecting the smart contract's interfaces. Optionally, the smart contract may implement the ERC721Metadata extension interface (Entriken et al., 2018) to connect the NFT with metadata. This interface specifies functions to retrieve the name and an abbreviated name of the NFT collection, and a URI pointing to the NFT metadata, which are specified as a json file based on ERC721 Metadata JSON Schema (Entriken et al., 2018). It is recommended to specify the name and description of the asset that the NFT represents in the json metadata, as well as to provide a URI to a file of mime type `image/*`. The latter is termed the image of the NFT and used by NFT marketplaces to visualize the NFT. Further data that can be defined in the metadata file are: an external URI of a website, user defined attributes of the NFT, raw SVG image data for on-the-fly image generation, an animation URI, and a URI of a YouTube video. To implement an NFT collection on the Ethereum blockchain, one must deploy the smart contract on the blockchain using a transaction that is sent to the null address. This contract should provide a function to mint an NFT and create a unique tokenID for it. The link to the metadata is termed tokenURI and provided as an argument of the mint function (or set in an extra function). It is up to the token creator where metadata and image are stored. Contracts are stateful and keep record of tokenIDs and tokenURIs, in other words, these data are stored on-chain, whereas metadata and image usually are stored off-chain (e.g., own server, cloud, or a distributed file system like the Interplanetary File System (IPFS) (Daniel & Tschorsch, 2022) (see Appendix A).

3.2. Some caveats of NFTs

Criticism on NFTs comprises: (*) high energy consumption of blockchains (this is true for the proof-of-work protocol, but Ethereum has now switched to proof-of-stake), (*) unclear what you get with the acquisition of an NFT, as license and copyrights often are not defined clearly, (*) where are metadata and image stored and are they immutable, (*) fraud and scams in the crypto world, (*) is an NFT worth its price, and (*) the future of cryptocurrencies and NFT is unclear. However, these issues are out of scope of this paper, and we assume that a collector of an NFT checks carefully licensing issues, metadata immutability and NFT availability (Balduf et al., 2022), e.g., using Etherscan (see Appendix A).

4. Methodology

The proposed research suggests a new model, where NFTs are used for the collaboration between and coordination of stakeholders in different roles. The innovative idea is to couple a physical arts object with a digital Twin in a way that defines an everlasting connection between the Twins. It is for the first time evaluated what kind of evidence about the physical Twin can be derived from the public, temper-proof and permanent trace on the blockchain.

The applied methodology comprises the following steps:

1. A systematic literature review is conducted in order to prove that the raised research objectives and requirements on the model are novel. The results of the literature review are summarized in section 2. The search was on the one hand side carried out by investigating relevant examples from the arts domain which were found in web resources, newspapers and blogs (see section 2). On the other hand side a search strategy was applied in the relevant scientific databases and portals (see Appendix A).
2. The theoretical concepts of NFTs are summarized in section 3 comprising a technical overview of NFTs and the relevant standards in this area (see section 3.1) and possible pitfalls of NFTs (see section 3.2).
3. A new model has been invented and constructed that fulfills all the requirements raised in section 1, of which it has been demonstrated in section 2 that there is no other system that fulfills them all in combination. The conceptual model for combining digital and physical Twin and all the possible steps that might occur when one or both of them are traded, is presented in section 5. These steps comprise: the first sale of artwork and/or NFT (see section 5.4), and follow up sales (see section 5.5).

This model introduces the idea of an inseparable code (see section 5.1) that uniquely identifies the physical art object, and that shall be integrated into the artwork so that it is practically impossible to remove the code or add it later without destroying the artwork. It is not prescribed whether the code is a signature, or if it is woven into, or painted on, or engraved etc. into the art work. For example, the code can be realized with two pearls that are integrated into the artwork – therefore we term the code "pearl-code". This code is the precondition to make it difficult to fake the art object. An image of the snippet of the inseparable code is part of the digital Twin so that the NFT can be used to identify the artwork. Thus the NFT serves as a certificate (see section 5.3) for the physical Twin. Only artworks that possess an NFT of this kind are "real" and not a fake.

Furthermore, the model introduces so-called "trusted agents" which are stakeholders that provide a service that can be used to trade both NFT and artwork together in a reliable way. The supported trusted services are described in section 5.5.

A value network was drawn to show the monetary benefits of each stakeholder (see section 5.7) when a sale is made.

An UML-based formal specification has been developed for the model. Section 5.8 shows a part of this specification, namely the workflow for on-chain and off-chain sale in a trusted way. The current work on an extended formal specification that is based on a coordination language that also provides simulation and verification is sketched in section 5.9. Based on the formal specification, a use case example is shown in section 5.10.

4. As a proof-of-concept a use case study in the fine arts domain has been developed. Its implementation on the Opensea marketplace for NFTs is presented in section 6. In this use case, the artworks are handcrafted crochet accessories like bags and hats. It has been selected, as the idea of the pearl-code stems from this use case, namely two real glass pearls are integrated and crocheted into each physical artifact. The pearls are threaded onto the yarn and thus cannot be removed / added without compromising the crochet piece.
5. The comprehensive evaluation and validation in section 7 of the model comprises: (★) A detailed explanation of the responsibilities of the different stakeholders, on which the model can rely. (★) A summary of the unique features of the model, especially a comprehensive and formal analysis of the traceability of ownership of the physical Twin by tracking the chain of ownerships of the digital Twin on the blockchain. (★) An analysis how this model can contribute to the prevention of fraud. (★) Advantageous properties of the model like scalability and extensibility. (★) A description of the innovative business model including an evaluation of revenue splits for the presented use case, of transaction fees, and speculation strategies for stakeholders.

5. Conceptual model for the new NFT-based coordination

This section proposes a new NFT-based coordination and collaboration model for the trading of fine arts. It uses NFT s as digital twins for physical objects (Crespi et al., 2023) serving as certificates for unique physical artifacts, confirmations of ownership, digital assets and trading tokens.

5.1. Inseparable code

A precondition is that the physical artwork must be uniquely identified during the manufacturing process with an inseparable code.

The model has been motivated by and developed for a crochet Manufacturer, where the physical artifacts are crocheted artworks representing wearable accessories or fashion items like bags, hats and bikinis. Unlike knitware, crochetware must be made by hand, as there exist no robots that can produce them automatically. This makes the pieces rare, special, unique and valuable and motivates the here proposed connection with NFTs. In this use case the inseparable code is realized by means of two glass pearls which are crocheted into the piece. Therefore the model is called the "**PE**arl-**C**ode **I**dentification Model", or " PECI Model " for short. The manufacture's name is "peci.wien" and its website is www.peci.wien, where also the links to social networks and its NFT collection can be found.

However, the PECI Model is applicable also to any other kind of (preferably handcrafted) artwork. The only condition that must be met is that the Manufacturer must (manually) incorporate a unique code into the artwork from the beginning in such a way that it is inseparable and cannot easily be added later on without an expert recognizing that. Depending on how secure it shall be, the Manufacturer can publish rules for its structure, place it always at the same location, or let the code describe its location (like the pearl-code does) etc., so that an expert can verify it and associate it with artworks from this Manufacturer. This code is part of the ID of the NFT. The other describing properties of the NFT can be freely selected anyway; they should only describe the artwork well and be used consistently. E.g., if a Manufacturer produces sculptures, it could carve the code into the sculpture.

The PECI model is explained in general in detail in the following sections.

5.2. Terminology

An account of a crypto wallet that is connected to Opensea is termed *Opensea account*. A physical Artwork with ID K is denoted as $Artwork^K$, and its associated NFT as NFT^K —these two are called $Twins^K$. The Card for $Artwork^K$ is termed $Card^K$. The transfer of NFT^K to stakeholder X's Opensea account is briefly described as a *transfer of* NFT^K *to X*.

5.3. NFT as certificate

The Manufacturer M creates an artistic image (or video) for each Artwork type and color, termed *type-image*. This needs to be done only once for each combination of type and color. Then for each $Artwork^K$ M creates one single NFT^K according to the following steps:

1. Create a *code-image* showing the snippet of the $Artwork^K$, where the inseparable code is located.
2. Enrich the type-image by M's name, $Artwork^K$'s ID K and code-image (s), resulting in an *nft-image*.
3. Create an NFT^K with nft-image as image.
4. Store the ID properties (type, color, code) as well as other relevant properties like artifact artist and photographer in NFT^K's metadata.
5. Mint the NFT^K as a single at Opensea.

The NFT is initially owned by M, who has one Opensea account. M publishes its Opensea account on its website[1] where you find also M's contact data and postal address.

5.4. First Sale

There exist sales partners for Artworks that run Shops. Let us assume that M, who is trusted and known[1], manages the first sale process on its own, so M has the role of both creator and seller, differentiated in the following as as M^{create} and M^{sell}. Its email address and Opensea account address are the same for all roles. In section 5.5 we will explain how the selling process can be generalized and outsourced to an Agent. M^{sell} decides whether to carry out the first sale *off-chain* by selling $Artwork^K$

[1] Verifying the identity of an Opensea account is not possible per se, because anyone can pretend to be someone else and point to any website. There exist many fake accounts of this kind, including those that pretend to be an important museum, so caution is advised whom you can trust. We suggest checking, if the stakeholder under question has put a link to its Opensea account on its corporate website or social media channel, that is publicly known.

in a Shop (physical or on-line) or *on-chain* by selling NFT^K at Opensea.

Off-chain. Let S be a Shop that M^{sell} commissions with the sale of $Artwork^K$. For this, M^{sell} sends to S: $Artwork^K$ (with $Card^K$), a voucher for NFT^K (including the ID *K*, the link to NFT^K, M^{sell}'s email address and a *voucher-timeout*[2]), a price (for $Artwork^K$ plus NFT^K-voucher), and a *sale-timeout*. S can of course also belong to M^{sell}.

Let User U_1 be a collector who buys $Artwork^K$ at S with fiat money. If U_1 also gets the voucher, U_1 can redeem it by sending (anonymous) email containing a copy of the voucher and U_1's Opensea account address to M^{sell}. The first valid submission within voucher-timeout causes M^{sell} to check the validity of the voucher, if it has not yet been redeemed, and if ok to transfer NFT^K to U_1. Note that M^{sell} does not need to know the real identity of U_1. If U_1 does not timely redeem the voucher, M^{sell} recovers and donates NFT^K for charity purposes. Such a charity organization is here termed *Recovery User RU*. The task of a RU is to sell donated artifacts (in this sense it behaves like a User; but it does not buy any artifacts) and to donate the achieved revenues to a good cause. Finally, S withdraws and keeps its royalties from the achieved sales price, and sends the remaining fiat money to M^{sell}.

If the sale fails, i.e. the sale-timeout expires without a buyer purchasing $Artwork^K$, S returns the $Twins^K$ to M^{sell} by sending $Artwork^K$ per post, and transferring NFT^K on Opensea.

On-chain. M^{sell} lists NFT^K for sale at Opensea with a price and sale-timeout.

Let User U_1 be a collector who buys NFT^K at Opensea with crypto-currency. If U_1 buys the NFT^K directly from a collection of M^{sell}, explaining that the purchase implicitly comes with a voucher for $Artwork^K$, i.e. the right to claim the physical twin, U_1 may request $Artwork^K$ from M^{sell}. However, there is a problem that needs to be solved, namely: How does M^{sell} know who to send $Artwork^K$ to? We cannot assume that U_1 is known, having disclosed its real identity on Opensea. Rather the situation must be supported that U_1 wants to stay anonymous. Sending normal email is not a solution, because the blockchain is public and everybody can track the purchase and see the Opensea account that purchased NFT^K, so anyone could send a postal address to M^{sell}, claiming to have bought NFT^K. The proposed solution is to use a crypto mailer (see Appendix A) and send the claim for $Artwork^K$ and a postal address using the crypto mailer with the same account that was used for buying NFT^K at Opensea. Upon receipt of the first request of this kind within the voucher-timeout defined and published by M^{sell} on its Opensea account, M^{sell} sends $Artwork^K$ to the given postal address. If $Artwork^K$ is not timely claimed, M^{sell} sends it to an RU. Opensea automatically withdraws and keeps its platform royalties from the achieved sales price. If M^{create} has configured creator earnings, these are also automatically subtracted and transferred to M^{create}. Finally the remaining crypto-currency is transferred to M^{sell}.

If the sale-timeout expires without a buyer purchasing NFT^K, no further action is required.

In both cases off-chain and on-chain it is optional, whether U_1 claims the associated Twin. So after the first sale, there are three possibilities what U_1 owns:

(a) both $Twins^K$, or
(b) only $Artwork^K$, or
(c) only NFT^K.

In cases (b) and (c) the ownership of the other $Twin^K$ remains with M^{sell}.

5.5. Follow-up sales

In case (a) U_1 can:

(i) keep both $Twins^K$,
(ii) sell one of them and keep the other one,
(iii) sell both separately, or
(iv) sell both together.

In case (b) U_1 can:

(v) keep $Artwork^K$, or
(vi) sell it.

In case (c) U_1 can:

(vii) keep NFT^K, or
(viii) sell it.

Cases (i)–(iii) and (v)–(viii) can be carried out autonomously by U_1. In cases (ii) and (iii) $Twins^K$ drift apart, and in cases (v)–(viii) they have already different owners. However, the case may arise that after a while U_2 acquires both, NFT^K and associated $Artwork^K$; or that U_1 buys back the counterpart so that it eventually again owns both $Twins^K$. Such a merge opens again all cases (i)–(iv).

Only case (iv) raises issues: Let U_3 be an interested buyer. If U_3 does not know U_1 personally and if U_1 is not a know and trustworthy entity that discloses its real identity, U_3 has the problem, whether it can trust U_1. In the off-chain case, if U_3 receives a voucher for NFT^K, it must rely on the fact that the Shop knows U_1 and can "force" U_1 to transfer NFT^K. But even then, how can anyone trust that meanwhile U_1 did not sell or donate NFT^K to someone else? In the on-chain case, if the purchase is connected with the right to claim the physical twin, the situation is even worse, because on a blockchain there is no responsible entity to blame, if U_1 does not send $Artwork^K$.

To overcome this problem, the PECI Model proposes third parties, called *Agents* who provide *trusted services* as described in section 5.6.

5.6. Trusted services

An Agent A_i must be known, trustworthy[1] and have experience to verify a $Artwork^K$ produced by M^{create} with help of its ID. A_i has a wallet and within that wallet an account for each of its roles A_i^{start}, A_i^{verify} or A_i^{sell}. A_i offers two trusted services termed *trusted sale* and *trusted test*, publishes its terms and conditions, which include a *default-timeout* for the service, a voucher-timeout saying how long owner O_i issuing the trusted service has time to claim the counterpart twin, A_i's royality fee for verification, its postal address, and its Opensea accounts on its web site or social media channel. A_i's roles are in detail:

- A_i^{start} understands a received NFT (transferred on Opensea), or an Artwork (sent per post as described below) as a service request. A_i^{start} waits until both NFT^K and $Artwork^{K'}$ are received from the same owner, claiming that they are Twins. If both are received within given timeouts (see below), it transfers NFT^K to A_i^{verify}.
- A_i^{verify} carries out a verification (see below) and if ok transfers the NFT^K to A_i^{sell}. If the verification fails, it returns the $Twins^K$ to the service requestor.
- A_i^{sell} considers NFTs sent to its account as verified requests that it treats: If the request is a trusted test, it just returns $Twins^K$ to the service requester. This is the indication that the verification was ok, because otherwise the $Twins^K$ would already have been returned by A_i^{verify}. If the request is a trusted sale, it starts the trusted sale process.

So in case (iv), if an owner O_i has NFT^K and $Artwork^{K'}$ that shall be sold together or for which O_i only wants to check if they are Twins, O_i is recommended to select an Agent A_i from the pool of known Agents and do the following:

[2] For all timeouts: If not specified, infinite is assumed.

- transfer NFT^K to A_i^{start}
- send $Artwork^{K'}$ to A_i^{start} (which uses only one post address for all its roles) via post (the sending can be done anonymously) including the following information:
  - the name of the requested trusted service
  - the reference to NFT^K
  - a lump sum for verification (either as fiat money or the link to a transaction where the fee was transferred via cryptocurrency to A_i^{start})
  - O_i's Opensea account address where it holds NFT^K
  - a price and a *service-timeout*
  - if a trusted sale shall be done, the information whether A_i^{start} shall do the sale off-chain or on-chain, and in the former case O_i's bank account
  - a postal address (which can be an anonymous one) to which A_i^{start} shall send back $Artwork^K$, if the trusted test is ok, or if the trusted sale fails.

If A_i^{start} receives an NFT^K from O_i, it waits in its default-timeout until it receives an $Artwork^K$ with the above described information from O_i.

If A_i^{start} receives an $Artwork^{K'}$ with the above described information per post from O_i, it waits in the indicated service-timeout until it receives NFT^K from O_i. In both cases A_i^{start} identifies O_i solely by its Opensea account address. If A_i^{start} runs in a timeout, it returns the received artifact. Note that in the constructed case that O_i sends NFT^K and another O_j sends $Artwork^K$ to A_i^{start}, nevertheless the timeouts will fire, because the condition that both artifacts come from the same owner is not fulfilled.[3] If A_i^{start} has successfully received both artifacts, it transfers NFT^K to A_i^{verify}.

A_i^{verify} verifies if:

1. the above described information sent by O_i is complete
2. NFT^K is valid and really stems from M^{create}
3. $Artwork^{K'}$ is in proper condition
4. K' equals K, i.e., both artifacts have the same ID
5. the code-image matches the snipped with the real inseparable code on $Artwork^N$

If the verification succeeds, A_i^{verify} transfers NFT^K to A_i^{sell}. If the requested service is a trusted test, A_i^{sell} returns $Twins^K$ to O_i. Otherwise A_i^{sell} applies the same sales process as M^{sell} (see section 5.4) for the first sale, but with the following refinements:

- if the sale fails (i.e., the service-timeout expired without a buyer purchasing one $Twin^K$), A_i^{sell} returns $Twins^K$ to O_i
- if the sale succeeds, A_i^{sell} withdraws its royalties from the sales price and keeps them
- if the sale was done off-chain, A_i^{sell} sends the creator earnings as fiat money to M's bank account and the remaining fiat money to O_i's bank account
- if the sale was done on-chain, A_i^{sell} transfers the remaining cryptocurrency to O_i (note that the Opensea platform already took care for the creator earnings of M)

[3] unless in the unlikely event that O_j sends a wrong Opensea account, namely that of O_i; but that is O_j's problem, who may then lose $Artwork^K$ (if the sale is successful and done on-chain) and O_i's risk if sending the wrong $Artwork^{K'}$ not timely, because it may then lose NFT^K (if the sale is successful and done off-chain); otherwise A_i^{start} will receive two Artworks and see that something is wrong and return the Artworks to their respective owner's postal addresses and transfer NFT^K back to its owner; both O_i and O_j also risk to lose the lump sum for verification

A_i^{start} will in any case earn the verification fee, even if the verification fails or if the counterpart Twin is not sent and A_i^{start} did not even start the verification. If the sale is successful, A_i^{start} gets in addition a percentage of the sales price.

In addition, A_i^{start} may offer a complete off-chain check-Artwork-plagiarism service just to check, if a Artwork is a plagiarism or not (cf. section 7.3).

5.7. Business model representation

We apply the e3-value modeling method to better understand the business values with regard to monetary aspects such as revenues, transaction fees, creator earnings and royalties of the different stakeholders, namely User, Manufacturer, Agent and Shop. The notation is based on the e3-value framework (Bukhsh & Silva, 2016; Gordijn & Akkermans, 2003; Gordijn et al., 2006). It shall contribute "to reach a better understanding of the e-Business model by the stakeholders involved" and "to be able to do an analysis and profitability assessment of the e-Business model for all parties involved" (Gordijn, 2004), and to gain more insights into how blockchain technology and NFTs can influence business models (Marikyan et al., 2022).

The network in Fig. 1 shows the four possible purchase scenarios of a user: (A) buy only an NFT, (B) buy an NFT plus a voucher for the Artwork from a trusted Agent at Opensea, (C) buy an Artwork plus an NFT voucher from a trusted Shop via a trusted Agent, and (D) buy only an Artwork.

In cases (A) and (B), the User carries out the purchase on-chain at Opensea. It pays the required price in cryptocurrency and receives the NFT in return. In case (B), the User also gets a voucher for the associated Artwork Twin. The price to be paid is made up of the revenues for the seller, royalties for the Opensea platform and creator earnings for the Manufacturer. The transaction fees for the blockchain platform are explicitly paid separately and are displayed to the User in its wallet. These costs vary and depend on the time of day at which the purchase is made. In case (B), the price also includes royalties for the Agent.

In cases (C) and (D), the User makes the purchase off-chain in a Shop. It pays the required price in fiat money and receives the physical Artwork in return. In case (C), the User also receives a voucher for the corresponding digital NFT Twin. In case (C), the Shop deducts its royalties from the price and forwards the rest to its trusted Agent – according to the rules of the PECI Model.

Cases (B) and (C) reflect a trusted sales workflow. The price to be paid is made up of revenues for the seller, royalties for the Agent and creator earnings for the Manufacturer. The Agent keeps the royalties for its service, and passes the rest on to the seller, who is either the Manufacturer or the User. In case (B), the creator earnings are automatically passed to the Manufacturer via Opensea, in case (C) it is the Agent's duty – according to the rules of the PECI Model – to forward the "creator earnings" in fiat money to the Manufacturer.

In all cases except (D), the Manufacturer benefits from receiving creator earnings as a permanent "passive" income, even if it is not the seller.

The increased value of owning both Twins and selling them together is not depicted in Fig. 1. It is implicitly assumed that the income a seller can earn in cases (B) and (C) is higher than in cases (A) and (D) respectively.

5.8. Formal specification of the PECI Model

To achieve the correct specification of the model and to avoid disambiguities, a formal specification of the conceptual model presented in section 5 is provided with the Unified Modeling Language UML and

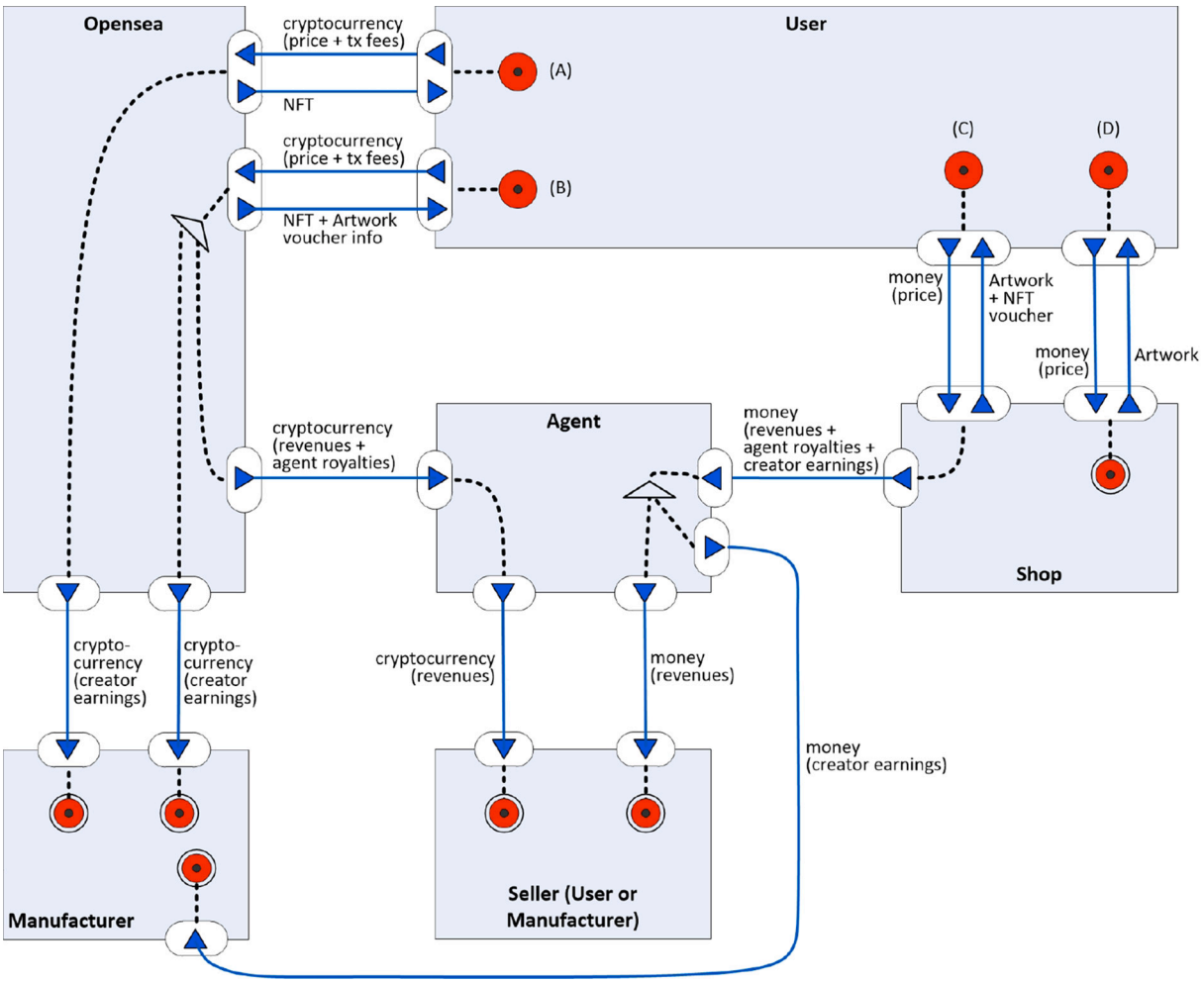

Fig. 1. Value network for a sale to a User.

sequence diagrams.

Fig. 2 shows a part of the specification, namely the successful trusted sale workflow[4] for on-chain or off-chain sale, where the buying User redeems its voucher for the other Twin. The workflow is explained in Table 1.

5.9. More advanced specification considerations

The UML modeling language has the deficiency that it needs a diagram for each possible workflow, which are not all shown here. Also, all failure cases would need separate UML diagrams, e.g., the expiration of sale-timeouts is not depicted.

A more sophisticated approach is to use a coordination language that allows the modeling of concurrent processes and the verification of the model, like the Actors Model Agha (1990) or the Peer Model (Kuehn, 2021, 2022) that allows also the simulation of different scenarios and configurations. A further advantage of the Peer Model is that one specification can capture all features of the PECI Model.

5.10. Example use case

From the UML specification, any use cases can be derived. For example, Fig. 3 depicts the case where a User U1 performs a successful trusted sale, and User U2 buys the NFT and claims the respective Artwork voucher.

6. Use case study and implementation at Opensea

6.1. Use case study

The presented conceptual model was motivated by the use case of a crochet artist. The artist—termed Manufacturer M—integrates two glass pearls into each Artwork, termed Crochet, to make it formally identifiable. These are threaded onto the yarn and cannot be separated from the Crochet or added later: Removing the pearls would destroy either the Crochet or the pearls. A subsequent assembly of pearls can be detected, because then the pearls will not sit on the continuous thread.

Since a Crochet like a bag, hat or bikini is made of many thousand stitches, there are many possibilities to place two pearls. We have developed a *pearl-code* that describes the location of the two pearls: For each pearl this includes the component in which it sits (depending on the Crochet type this is the front, back, left/right side, hat brim, body etc.), the row number within that component, the stitch count within that row, and the orientation of the pearl (inward or outward). M does not produce two Crochets of same type (e.g. City Bag, Shopper Bag, Classic Hat) and same color with the same pearl-code. Thus the full Identification (ID) of a Crochet consists of its type, color and pearl-code. It is extensible by further properties like size and material, if these are necessary to make the ID unique (e.g., material is needed if it is Crochet of the same type and color, but made of a different yarn, e.g., cotton, raffia or macramé). M also creates for each Crochet a handwritten Card

[4] without considering the previously described unlikely event[3]

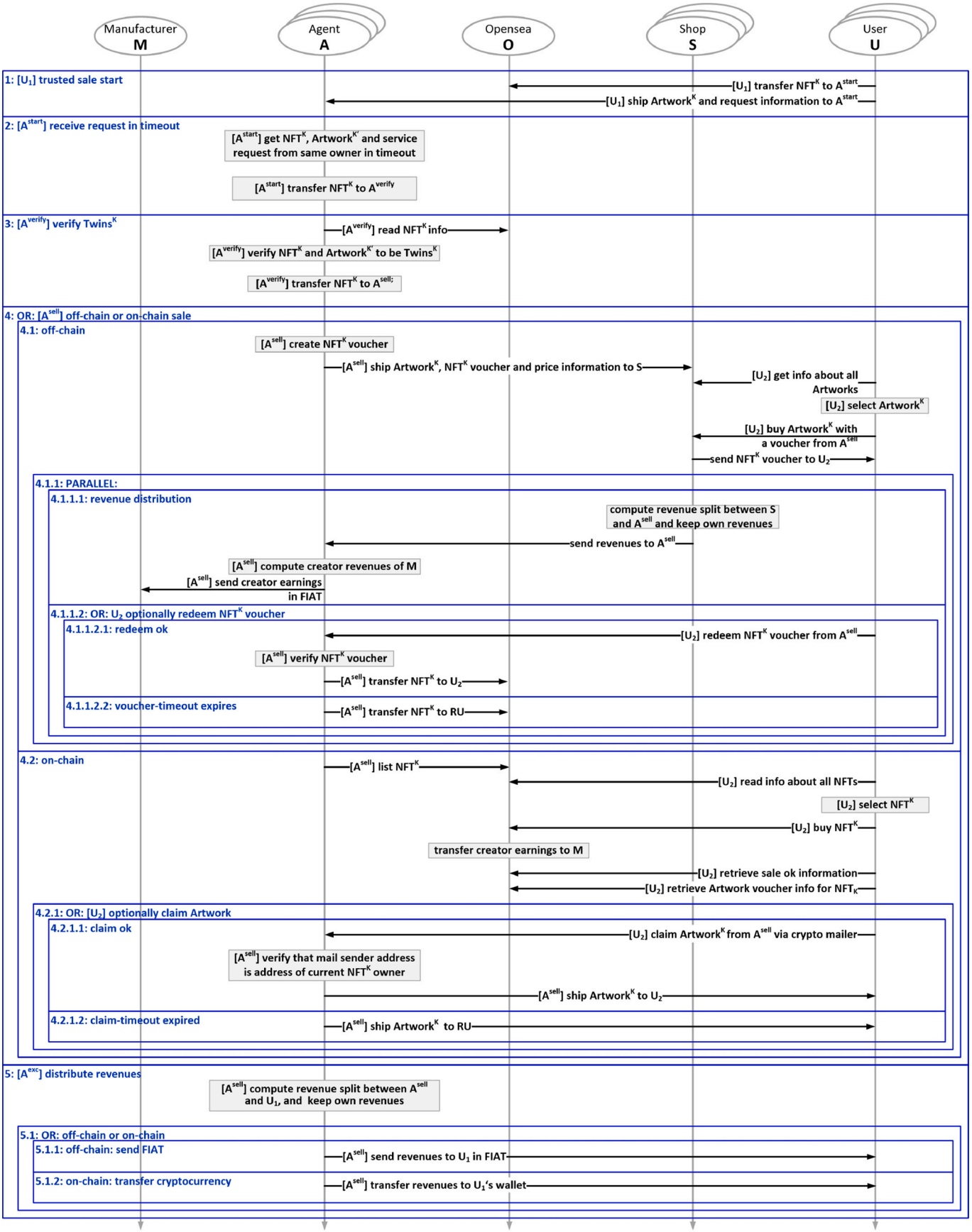

Fig. 2. Part of the UML specification.

Table 1
Explanation of the steps of the UML specification in Fig. 2.

Step	Explanation
1	The trusted sale is started by U_1 who issues the transfer of NFT^K to A^{sell}, ships $Artwork^K$ to A^{sell}, and requests A^{sell} to execute the trusted sale.
2	Next, A^{start} waits for a service request. If it receives NFT^K, and $Artwork^{K'}$ with the service request information from the same owner, it starts its next phase by transferring NFT^K to A^{verify}.
3	Next, A^{verify} reads the information about NFT^K on Opensea, performs the verification of $Twins^K$ (see section 5.5) and transfers NFT^K to A^{sell}. Note that Opensea never replies: Stakeholders must pull information from Opensea.
4	The sale is either carried out off-chain (4.1) or on-chain (4.2). Both scenarios are shown in the specification using an OR block.
4.1	In the off-chain case, A^{sell} creates an NFT^K voucher, ships $Artwork^K$, voucher and price information to S for selling. The voucher contains A^{sell}'s email address. U_2 retrieves information about all Artworks available at S, selects $Artwork^K$, buys it with fiat money and gets the voucher for NFT^K.
4.1.1	Revenue distribution (4.1.1.1) and redeeming of the voucher (4.1.1.2) can be done in parallel:
4.1.1.1	S calculates the revenue split between S and A^{sell}, keeps its own revenues, informs A^{sell} about the successful sale by sending A^{sell} its revenue proportion. A^{sell} computes creator revenues of M^{create} and sends them to M^{create} in fiat money.
4.1.1.2	U_2 decides whether to claim NFT^K-voucher or not. Both cases are shown:
4.1.1.2.1	For claiming it, U_2 sends email with a copy of the voucher and its Opensea account address to A^{sell}. A^{sell} verifies the voucher and issues the transfer of NFT^K to U_2 at Opensea.
4.1.1.2.2	If U_2 does not redeem the voucher within the voucher-timeout, A^{sell} donates NFT^K to a Recovery User RU. Note that an RU is subsumed in the specification by the U stakeholder role, as it may sell artifacts.
4.2	In the on-chain case, A^{sell} lists NFT^K at Opensea for sale with the desired price. U_2 retrieves information about available NFTs at Opensea, selects NFT^K out of these, and buys it with cryptocurrency. The smart contract that executes the sales transaction automatically transfers the configured creator earnings to M^{create}. U_2 sees that the transaction was successful, and checks that a voucher for $Artwork^K$ is implicitly included in the purchase.
4.2.1	U_2 optionally can claim $Artwork^K$. Both cases are specified with an OR block.
4.2.1.1	If U_2 claims $Artwork^K$, it sends A^{sell} an email with a crypto mailer. A^{sell} verifies that U_2's Opensea account address equals the one with which NFT^K was bought, and ships $Artwork^K$ to the postal address indicated in the email.
4.2.1.2	If U_2 does not claim $Artwork^K$, i.e., the voucher-timeout expires, A ships $Artwork^K$ to an RU.
5	The successful trusted sale is finished by A^{sell} by computing the split of the remaining revenues into those for A^{sell} and U_1. A^{sell} keeps the own revenues and sends the other ones to U_1 as fiat money or transfers cryptocurrency to U_1's wallet account, depending on whether the sales was carried out off-chain (5.1.1) or on-chain (5.1.2).

with M's contact data and Crochet's ID, so that the pearls can be more easily found. M delivers the Card with the Crochet; the same does an Agent and a Shop (see below), if Crochet's Card still exists.

6.1.1. Implementation at Opensea

Many blockchain implementations and NFT marketplaces exist. Opensea is currently the largest NFT marketplaces, it is open to everybody, does not apply curation and requires royalties only if you sell an NFT. There exist many other blockchain implementations and (curated) NFT marketplaces as well like Binance NFT, Coinbase, Crypto.com, LaCollection, NFT LaunchPad and SuperRare, and galleries like Unit London that provide NFT trading platforms. In the following we selected Opensea (see Appendix A) on Polygon or Ethereum blockchain (Buterin, 2014) as it is the largest marketplace and implements the required NFT standards (see section 3.1), providing respective user interfaces. For the Ethereum blockchain analysis tools exist out-of-the-box that can be used to track NFTs there. For sure, the PECI Model can also be realized with any other marketplace, or even with self-implemented smart contracts, provided that the NFT standards are implemented correctly. The essential point is that the NFT is stored on a blockchain, where it can be analyzed and observed with respective tools in order to track its full history as will be explained in section 7.2. In addition, it is possible to implement different NFTs on different marketplaces. The migration of one NFT to another marketplace depends on the capabilities of the marketplace, i.e. if it can access and represent the respective data found on the blockchain.

The objective was not to develop new smart contracts, but to use existing ones. The author has therefore developed the on-chain coordination parts of the PECI Model at Opensea, using its native interfaces and without implementing new applications or smart contracts. The crochet bags collection is termed "peci-bags" and the crochet hats collection "peci-hats" (see Appendix A) The project was presented at the Vienna Design Week. The crochet masterpieces created by the artist are marked with glass pearls. The first NFT minted was the "City Bag Red" (see Appendix A). Its pearl-code can be found in the description of the NFT, it is termed crochet-nft-id and has the value of `B-48-M2-OI-M3-OI`. This stands for body row number 48, stitch number 2, orientation inwards, stitch number 3 (in the same row), orientation inwards.[5] Its type is "City Bag", the color is red, and other properties comprise the artist, fotographer, history, and the Manufacturer PECI.wien (see Appendix A). Another NFT from this collection is "Micro Classic Bag Neon" (see Appendix A) the first sale of which was off-chain, i.e. the crochet bag was sold in a Shop and afterwards the collector claimed the NFT.

Fig. 4 shows the nft-images and Fig. 5 the pearl-images. As these are fotos of the respective snippet of the physical artifact, it is a further contribution for verifying whether the Crochet at hand is a forgery or the real thing, as it is practically impossible to crochet two artifacts with exactly the same twist of the thread. This is especially true, if e.g. two or more yarns are crocheted at the same time, as is the case in the selected crochet bag examples.

7. Discussion and evaluation of the PECI Model

The PECI Model is a new approach that uses NFTs for the coordination of on-chain and off-chain trading transactions: It defines how the trading of unique physical artifacts (handcrafted Artworks) and their associated digital Twins (digital Artworks) can be linked. NFTs serve for certification, provenance tracking, and communication tokens in order to make the interactions of stakeholders safe and accountable.

The discussion is carried out by referring to the use case of the Crochet Manufacturer, i.e. where the Artworks are Crochets and the inseparable code is realized with two pearls.

7.1. Prereqisites

7.1.1. Responsibility of stakeholders

As a precondition of the model, certain stakeholders must obey the following responsibilities:

- The Manufacturer promises not to produce two Crochets with the same ID *K*, and to mint only one NFT^K per $Crochet^K$.
- An Agent promises not sell NFT^K and $Crochet^K$ concurrently. Also, it must provide a voucher for the Twin existing in the other world. The same holds for the Manufacturer, if it carries out the first sale on its own, i.e. without an Agent.

7.1.2. Implementation using existing platforms and smart contracts

The requirement was not to write new applications and smart contracts but to rely on existing features of Opensea for NFT management and trading. Therefore the implementation requires no costs and can be done straightaway. There are no requirements on the blockchain used by Opensea, but it is advantageous, if its transaction fees are low.

[5] "M" stands for "Masche" in German which means stitch.

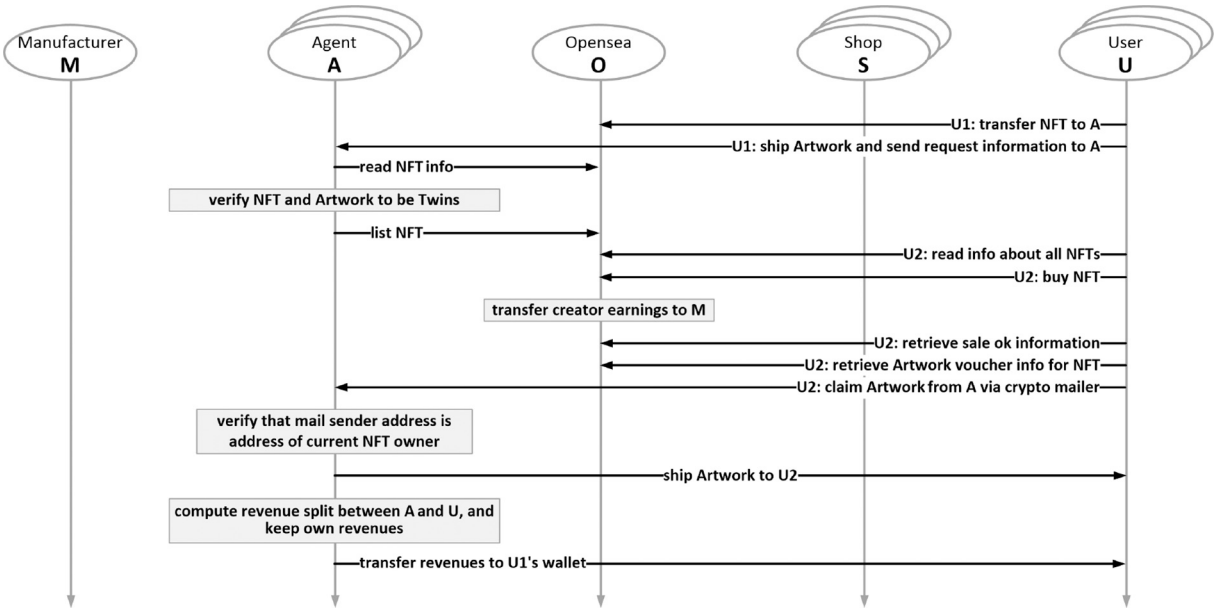

Fig. 3. Example use case diagram: successful on-chain sale of an NFT.

Fig. 4. NFT image of City Bag Red and Micro Classic Bag Neon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Permissoned-ness of blockchains—as generally demanded for the coupling of NFTs with real physical objects in the literature (Sheldon, 2022)—is not required. Any other NFT marketplace that supports functions for minting, selling, and transferring of NFTs, and the configuration of creator earnings and revenues for sales, can be used as well. The detailed tracking of transactions is done by means of Etherscan. Because Opensea is constantly being developed, we hope that the following desirable features will also be added in the future: more fine-grained revenue configuration possibilities—i.e., not only on entire collections, but also on single NFTs—and better search functions.

If the model is enhanced by self-developed smart contracts (Ante, 2021), this will cleary open further innovation possibilities.

7.2. Unique features

The unique features of the PECI Model are discussed in the following.

7.2.1. Connecting physical and digital artworks

The PECI Model must deal with two kinds of not synchronized transactions: those performed on-chain on Opensea to exchange NFTs, and those performed off-chain in the real world namely shipping Crochets (off-chain). Since they are performed in different worlds (virtual and real), and Users are untrusted, it may happen that a buyer pays for both Crochet^K and NFT^K, but a dishonest seller does not send the counterpart, or sells it to someone else. The PECI Model ensures a

Fig. 5. Pearl-code image of City Bag Red and Micro Classic Bag Neon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

consistent trade of a Crochet^K and its associated NFT^K by introducing Agents, who guarantee that these two worlds spanning transactions are carried out atomically, or a rollback is performed. If the User does not claim the counterpart, it is returned to a Recovery User. The model defines an everlasting connection between the Twins in both worlds. Even if an Crochet is damaged and cannot be resold anymore, the connection to its certificate (i.e., NFT) remains, but the Crochet will not be traded any more via an Agent. Note that if an NFT is burned or deleted, the certificate remains visible on the blockchain—only that it cannot be traded any more.

7.2.2. *Traceability of ownership*

The ownership of an NFT is evident: All transactions at Opensea are transparent and can be tracked with Etherscan. The history of transactions $TX_1,\ldots,TX_N$ shows when NFT^K was minted, listed, transferred, or sold. Looking at the transactions everyone can check the sequence of NFT^K's owners. TX_1 is the minting transaction of M^{create}, who is the first owner. One can research (via websites and social media channels) if an owner is trustworthy[1] and if it is an Agent, Manufacturer, or Recovery User; otherwise it is any User (anonymous or not anonymous).

The challenge is, how much can be read out with the help of the TXs about Crochet ownership, which is not reported explicitly on the blockchain. Table 2 and Table 3 evaluate which information can be derived from TX_N, if NFT^K is either sold or transferred according to the rules of the PECI Model which has been designed with a special focus on this aspect. Other TXs like to start a listing are not relevant for Crochet ownership changes. In both tables M acts in its role as M^{sell}, but the roles M^{create} and M^{sell} are collapsed into M, because M has only one Opensea account; " n/a " stands for "not applicable", i.e., this situation cannot occur.

Table 2 reveals that a purchase of NFT^K does not trigger any conclusion about Crochet^K yet. Note that a User is the only stakeholder who may buy an NFT. The stakeholders that may sell are: Manufacturer, Agent, User and Recovery User. The rating of probabilities is out of scope of this paper, but the likelihood that U_j owns also Crochet^K, if it buys NFT^K from M or A^{sell} is quite high, because both are reliable stakeholders who offer U_j the opportunity to claim Crochet^K. The chances to own Crochet^K are quite lower, if U_j buys NFT^K from U_i, especially if U_i is anonymous. In order to estimate the chances, one can check: ★) U_i's identity, ★) if there exists any conclusion (see Table 3) or probability that U_i owns Twins^K, ★) if U_i promises to ship Crochet^K and if so ★) how trustworthy the mechanism that U_i suggests for that is (cf. usage of crypto mailer). The least chances to own Crochet^K are, if U_j buys NFT^K from RU_i, because it is very unlikely that RU_i owns Twins^K, because RU_i is not allowed to buy artifacts—it only gets single artifacts for which the voucher was not claimed. Only if subsequently U_j starts a trusted sale that successfully passes the verification phase, we can conclude retrospectively that U_j owns Crochet^K.

Table 3 shows the conclusions we can draw from transfer TXs:

The ownership of Crochet^K is confirmed in the following cases: M owns Twin^K s after minting. A^{start} owns Twin^{K}s, after M starts a trusted sale at A^{start}. A_i^{sell} owns Twin^K s on behalf of U_k who issed a trusted service at A_i^{sell}, after A_i^{verify}'s verification succeeded (i.e., A_i^{verify}'s transferred NFT^K to A_i^{sell}). U_k owns (or owned) Crochet^K, after an A_i^{sell} transferred NFT^K to U_j. Such proven ownerships of Twins^K constitute *checkpoints*, with the first checkpoint being TX_1.

Some explanatory remarks:

M can manage the first sale on its own, or do it via the trusted sale service of A_i^{start}. The verification that M owns both Twins^K must always succeed, because M is trustworthy. Nothing is ever transferred or sold to M.

Each U_i is autonomous and not trustworthy per se. Therefore, it cannot be assumed that U_i follows any rules and we must consider all possible cases what U_i might do in any situation.

RU must be trustworthy and its identity must be known; therefore it is differentiated as an own stakeholder. But in fact, RU behaves like a restricted User who may only sell the artifacts donated to it, but is not allowed to buy. If it wants to buy something, it must act as a U and create a separate U account on Opensea.

If Twins^K have drifted apart, the separation can be repaired by a *merge*, when a U_k eventually gets both Twins^K, possibly from different owners, and then successfully executes either a trusted test or trusted sale at an Agent.

Over the time you may even figure out *reliable Users* from the transaction history. These are Users who have sold NFT^K and demonstrably also shipped Crochet^K to the buyer—which can be verified in a delayed way as described above.

Table 2
Conclusion about Crochet^K ownership, if TX_N is a sale of NFT^K from U_i to U_j.

	M_j	A_j^{start}	A_j^{verify}	A_j^{sell}	U_j	RU_j
M_i	n/a	n/a	n/a	n/a	U_j bought NFT^K from M_i. *No conclusion yet.*[1]	n/a
A_i^{start}	n/a	n/a	n/a	n/a	n/a	n/a
A_i^{verify}	n/a	n/a	n/a	n/a	n/a	n/a
A_i^{sell}	n/a	n/a	n/a	n/a	U_j bought NFT^K from A_i^{sell}. *No conclusion yet.*[1]	n/a
U_i	n/a	n/a	n/a	n/a	U_j bought NFT^K from U_j. *No conclusion yet.*[1]	n/a
RU_i	n/a	n/a	n/a	n/a	U_j bought NFT^K from RU_i. *No conclusion yet.*[1]	n/a

[1] We need to wait, if there is a transfer TX_M ($M > N$) of NFT^K in the future. If so, U_j owned Twins^K at the time of TX_N.

Table 3
Conclusion about Crochet^K ownership, if TX_N is a transfer of NFT^K from U_i to U_j.

	$\mathbf{M}_j$	A_j^{start}	A_j^{verify}	A_j^{sell}	$\mathbf{U}_j$	$\mathbf{RU}_j$
$\mathbf{M}_i$	n/a	M_i, who created Twins^K, issues a trusted sale of them at A_i^{start}. *Conclusion:* **M_i owns Twins^K.**	n/a	n/a	U_j bought Crochet^K at a Shop with a voucher for NFT^K, and redeemed it at M_i; therefore M_i transfers NFT^K to U_j. *Conclusion:* **U_j owns (or just owned) Crochet^K.**	A User bought Crochet^K at a Shop with a voucher for NFT^K, but did not redeemed the voucher; therefore M_i transfers NFT^K to RU_j. *Conclusion:* **Twins^K have drifted apart.**[1]
A_i^{start}	n/a	n/a	A_i^{start} received NFT^K and Crochet$^{K'}$ from a User for verification. *No conclusion yet.*	n/a	A_i^{start} received NFT^K from U_j for verification, but did not receive Crochet$^{K'}$ within the default-timeout, therefore A_i^{start} transfers NFT^K back to U_j. *No conclusion.*	n/a
A_i^{verify}	n/a	n/a	n/a	A_i^{verify}'s verification of Twins^K is ok, so it starts the selling phase at A_i^{sell}. *Conclusion:* **A_i^{sell} owns Twins^K on behalf of owner O_i, who transferred NFT^K in TX_{N-2} to A_j^{start}.**	A_i^{verify}'s verification of NFT^N and Crochet$^{K'}$ and failed, so it returns them to their owner U_j, who transferred NFT^K in TX_{N-2} to A_j^{start}. *Conclusion:* **U_j does not own Crochet^K.**[2]	n/a
A_i^{sell}	n/a	n/a	n/a	n/a	If TX_{N-3} was a transfer from U_j to A_{start}, it was a successful trusted test; otherwise U_j bought Crochet^K with NFT^K -voucher and redeems it, so A_i^{sell} transfers NFT^K to U_j. *Conclusion:* **U_j owns (or just owned) Crochet^K.**[3]	The sale of Crochet^K with NFT^K -voucher to U_j was successful, but U did not redeem it, so A_i^{sell} transfers NFT^K to RU_j. *Conclusion:* **Twins^K have drifted apart**[2].
$\mathbf{U}_i$	U_i gifts NFT^K to M. *No conclusion.*	U_i issues a trusted service at A_j^{start}. *No conclusion yet.*[4]	U_i gifts NFT^K to A_j^{verify}. *No conclusion.*	U_i gifts NFT^K to A_j^{sell}. *No conclusion.*	U_i gifts NFT^K to U_j. *No conclusion.*	U_i gifts NFT^K to RU_j. *No conclusion.*
$\mathbf{RU}_i$	n/a	RU_i issues a trusted service at A_j^{start}. *No conclusion yet.*[2]	n/a	n/a	n/a	n/a

[1] But a User may donate Crochet^K to RU_j.
[2] But U_j could acquire Crochet^K.
[3] U_j can sell Crochet^K at any time. E.g., it could have bought Crochet^K, then sold it and only afterwards have redeemed NFT^K-voucher.
[4] One needs to wait for TX_{N+2}.

7.2.3. Anonymity of stakeholders

Users can stay anonymous: At Opensea they need not disclose their identity. To be precise, Users on a blockchain are pseudonymous, because one can track all their TXs and possibly draw conclusions about them based on their behavior. If a User buys an NFT^K and claims the Crochet^K, too, it uses the crypto mailer and can send an anonymous post box address to the Agent. If the User buys a Crochet at a Shop, it does not have to provide its name or address; for redeeming the voucher, it just needs to create an (anonymous) Opensea account and send email to the Agent (from a anonymous email account) with the NFT voucher info and its account address.

All other stakeholders—Manufacturer, Agent, Shop and Recovery Users—must be known and trustworthy entities. Except of the Shop, they have to run known Opensea accounts.

7.3. Dealing with plagiarism and fraud

7.3.1. NFT plagiarism

The creator M of NFT is documented in TX_1. It is not possible to fake the origin of an NFT.

7.3.2. Crochet plagiarism

Let us assume a User U_1, who wants to know if a precious Crochet^K that it wants to buy from owner O_2 is a plagiarism or a valuable work of art from a recognized Manufacturer M_i, who applies the PECI Model. In the worst case, O_2 does not even know M_i and does not have Card^K. In the best case, O_2 offers Card^K and NFT^K as well. U_1 shall now do the following:

1. Verify, if Crochet^K has two pearls, and if the two pearls were not mounted afterwards. If this verification fails, Crochet^K is not the real artifact, or the pearls were removed, so Crochet^K is no Twin any more.
2. Verify, if Card$^{K'}$ is co-sold with Crochet^K, and if so validate the pearl-code written on Card$^{K'}$ (i.e., it must match the pearls situated on Crochet^N). If this verification fails, nevertheless Crochet^K could be the real one, because Card$^{K'}$ could be false.
3. Figure out M_i and NFT^K and verify the pearl-code:

3.a) If NFT^K is also offered, U_1 can verify *everything*, namely:

- NFT^K (i.e., the pearl-code must match Crochet^K's pearls; the pearl-image(s) must match Crochet^K's pearl place(s); and all other properties in the metadata must also fit to Crochet^K)
- M_i (i.e., it must be the issuer of NFT^K's TX_1 and be trustworthy),

If this verification fails, Crochet^K is a plagiarism. Otherwise only the improbable case could occur, that Crochet^K is a *perfect fake*, i.e., it is an indistinguishable replica of the real Crochet^K. In order to minimize even that risk, U_1 can use the check-crochet-plagiarism-service of an Agent (5.) or demand that O_2 also demonstrably owns NFT^K.

3.b) If Card^K exists, then M_i and ID *K* are found there. So U_1 can can find M_i on Opensea (via a reference to M_i's Opensea account on its website or social media channel) and can try to locate NFT^K in M_i's "Created" collection on Opensea by manually comparing *K* with each NFT's ID). Note that as current state-of-the-art Opensea search mechanisms are very limited and a search for properties (namely the pearl-code) is not possible, but only for terms contained in an NFT name, collection name or Manufacturer name. If found, U_1 can verify everything (see 3.a).

3.c) Otherwise O_2 might tell U_1 the reference to NFT. If found, U_1 can verify everything (see 3.a).

3.d) Otherwise O_2 might know M_i; or U_1 anticipates M_i. Next, U_1 must investigate all NFTs in the "Created" collection of supposed M_i as explained above. If found, U_1 can verify everything (see 3.a).

3. e) Otherwise U_1 might know Crochet^K's type name and can search for NFT^K on Opensea via Crochet^K's type name, or in the Internet via Crochet^K's image and/or type name. The NFT^K is recognized via the pearl-code that must match Crochet^K's pearls. If found, U_1 can verify everything (see 3.a).

4. Verify that NFT^K is not owned by a M_i or a A_i^{sell}, because then the Twins^K are either with M_i or A^{sell} and the Crochet^K at hand is a plagiarism—even if everything else was successfully verified (see 3.a). This fact can easily be "double checked" by writing M_i or A_i^{sell} an email.

5. If M_i or NFT^K could not be found by the above approaches, or if U_1 is not able to compare the pearl-code with the pearls found on the Crochet, it can consult an Agent, who offers a check-crochet-plagiarism service and who has experience which Manufacturers are following the PECI Model. However, the Agent will need to get access to Crochet^K for this check. Also, an Agent is skilled in checking twist of threads and the montage of pearls against the pearl-foto, and in reading pearl-codes, i.e., it can "extract" the pearl-code from the Crochet^K and thus more easily search for NFT^K.

6. If O_2 claims to own NFT^K, U_1 should verify that this is the case: This is only possible, if O_2 shows U_1 that it is connected to Opensea with the account that currently owns NFT^K according to NFT^K's TX history.

7. If O_2 also offers NFT^K together with Crochet^K, U_1 should verify that O_2 owns NFT^K (see 6.) and somehow ensure that O_2 will transfer NFT^K to U_i.

For the plagiarism check it is irrelevant who owns NFT^K.

Only for the improbable case that Crochet^K is a perfect fake, U_1 has more security, if O_2 is the current owner (especially if it acquired it from an Agent or from a Manufacturer), or if O_2 determines a checkpoint (see section 7.2).

In any case U_1 should also check if Crochet^K is damaged or not. However, this has no impact on the plagiarism check but probably on the price.

7.4. Flexibility

7.4.1. Scalability

Any number of stakeholders of any kind are possible, because they do not have to synchronize with each other. Also other NFT marketplaces can be added and run in parallel, if they offer the required functionality.

7.4.2. Extensibility

Through the introduction of additional NFTs that are created by trustworthy parties, the PECI Model can be further improved. E.g., more information can be derived on Crochet ownership, by means of a "Crochet shipping certificate". This is a new NFT, created by an Agent (or Manufacturer) when a Crochet is shipped to a User, and that could also contain a photo of the Crochet, so that the tracking of the current state of the Crochet becomes possible. This NFT can of course be traded; but it is independent of the associated Twins.

7.4.3. Combinability of roles

Each participant can have more than one role. To do this, they only need to create the required Opensea accounts for each role and act with these accounts so that the roles can be differentiated from the outside. E.g., if a RU_i also wants to buy, it must create a User account U_{RU^i} on Opensea. E.g., if a M_i also wants to offer trusted services, it must create respective Agent accounts on Opensea: $A_{M^i}^{start}$, $A_{M^i}^{verify}$ and $A_{M^i}^{sell}$.

7.5. Innovative business model

7.5.1. Revenue opportunities

New revenues streams arise for stakeholders, e.g., a Manufacturer gets revenues with each sale of an NFT, and an Agent gets revenues for offering innovative trusted services. The PECI Model provides the configuration of royalties for Agents and Shops, as well as of creator earnings for Manufacturers.

An example for configuring the revenues as percentage of the sales price would be: 5% for Agents, 10% for Manufacturers (i.e., creator earnings at Opensea), 2,5% for Opensea (this is the current state-of-the-art), and 20% for Shops.

This means that a selling U (or RU) earns the most in the following order:

1. direct sale off-chain via Shop (100%),
2. direct sale on-chain (87,5%),
3. trusted sale on-chain via Agent (82,5%),
4. direct sale off-chain via Shop (80%),
5. trusted sale off-chain via Agent (75%).

M^{sell}, who also gets creator earnings as M^{create}, earns the most in the following order:

1. direct sale on-chain (98%),
2. trusted sale on-chain via Agent (92,5%),
3. trusted sale off-chain via Shop (80%),
4. trusted sale off-chain via Shop & via Agent (75%).

7.5.2. Economy of transaction fees

For each transaction TX on a blockchain, the respective blockchain platform demands TX fees. These depend on various factors, like traffic, time of the day, the platform itself etc. and are hardly to predict. As state-of-the-art, TX fees on Ethereum are high and on Polygon negligibly low. The rule is that the issuer of a TX has to pay the fees. The PECI Model foresees an economically reasonable distribution of these costs according to the following main principles:

For the trusted sale service: The seller U shall pay all TX fees that occur, because if the sale is successful the seller will earn money (note that the seller could also be a RU or M). In detail: the issuing transfer of the NFT to A^{start} is payed by U. In addition U must send A^{start} a lump fee that should cover overhead transactions that A will need (these comprise TX fees for all intra transfers of A; in the off-chain case also the transfer of the NFT to U if it redeems its voucher (or to RU otherwise)). If the sale service fails, U must nevertheless pay all TX fees incurred up to that point. The argumentation is: If the Twins do not match, it is U's fault; if no buyer can be found, this is the risk of the seller, because it may have selected a wrong sale price or sale timeout.

The donator of an NFT takes over the TX fees, too.

In case of a direct sale, the buyer pays for the TX fees. It sees the fees on Opensea and can decide whether it is worth it to him/her to carry out the purchase.

If a M manages the first sale on its own, in the on-chain case, the buyer pays directly the TX fees; in the off-chain case M must pay for the TX fees of transferring the NFT to the buyer U if it redeems the NFT voucher (or to RU otherwise); but M can include these costs to the Crochet sale price in the Shop.

7.5.3. Scarcity

Scarcity can be a determining factor for the value of an Artwork (Roux, Goldsmith, & Cannon, 2023). Each Crochet is fabricated manually and is therefore slow fashion. Also the creation of the NFT according to the PECI Model involves several steps that cannot be automatized, like the creation of the individual and artistic images. Even if several Crochets of same type are produced, they are nevertheless unique and in addition are identified by means of the pearls. This explains why the artifacts are rare and valuable. Price and quality of crochetware reveal, if it comes from a sweat factory or from a recognized craft Manufacturer.

7.5.4. Speculation strategies

Of course, the market will show over time, how Users act. But an obvious strategy is to assume that owning both Twins is more valuable and secure than owning only one. It is therefore preferable to buy an NFT from a Manufacturer or an Agent. If U_i buys a Crochet at a Shop, there should exist an accompanying NFT^K voucher containing the Opensea account address of the Manufacturer or an Agent. If nevertheless U_i buys an artifact with ID K directly from another U_j, U_j should check that it is not a plagiarism (see section 7.3) Also, U_i can try to get also the associated $Twin^K$. If U_i has NFT^K, it can investigate the provenance chain (see section 7.2) to see it it can draw any conclusion about the owner of $Crochet^K$; if not it, U_i can start asking the owner involved in the last checkpoint. If U_i has $Crochet^K$, it can figure out NFT^K by applying the mechanisms described in section 7.3 and find the owner of NFT^K. If the respective (or assumed) owner is not anonymous, then U_i can use normal email; otherwise it must use a crypto mailer to send the requesting email.

In contrast to current approaches for real-world-based NFTs (Far et al., 2022), NFTs in the PECI Model have still value as standalone digital artworks, even if the physical artifact gets lost or damaged. If it can be proven that a very important person was in possession of an NFT or a Crochet, its value could increase.

8. Conclusion

The contribution of the paper is a new and comprehensive coordination model, termed PECI Model, in the field of fine arts, for more secure trading of artworks. It introduces several roles, where a few participants must be trustworthy, but the vast majority, namely the Users buying, collecting and selling artworks need not be trustworthy and can stay anonymous. A major technical advantage is that it can be implemented with out-of-the-box features of existing NFT marketplace platforms. As proof-of-concept a real use case has been implemented for a Crochet Manufacturer on Opensea.

The innovative features of the PECI Model are: Physical artworks are permanently linked with NFTs that serve as certification, tracking and communication tokens in the trading workflow. The linkage is accomplished by introducing a unique code, termed pearl-code, that must be integrated into the physical artifact as well as into the NFT. Two artifacts connected in this way are termed Twins. Clearly, the provenance of an NFT is known, immutable and secure. But due to the introduction of so-called trusted Agents and splitting their phases into several roles that report their results on the blockchain via NFTs, also the ownership of the physical artifact is widely traceable via the chain of transactions of its NFT. The paper analyses the many possible states in the chain of transactions and what we can conclude from them about the current (or recent) ownership of the physical Twin, despite Users may remain anonymous. The PECI Model also supports a widely recognition of fraud. Also here, the chain of transactions plays an important role, and also here a systematic analysis is provided, which can serve as a guidance for buyers. The model is scalable towards any number of participants and extensible towards new stakeholder roles and services.

The PECI Model opens new business opportunities for the different stakeholders: The newly introduced *Agents* may offer trusted services, guaranteeing that Twins can be bought together. *Manufacturers* can sell their products as always. But in parallel, as an extension, they can market them with the shown digital Twin concept. The big innovative advantage here is that the manufacturer now also has ongoing income, namely every time an on-chain sale takes place, regardless of whether it is trusted or not. The "white space" growth opportunity for the manufacturer can be seen in the area of "innovation and diversification", because the manufacturer diversifies its existing physical product by creating new, innovative offerings in form of digital Twins. There it will grow in untapped market segments, namely the crypto market which has high growth forecasts. *Users* will speculate with artworks in a much more reliable way than today—several strategies are discussed. Even if the physical Twin gets lost, the NFT still is a valuable asset that can be traded.

Finally, also a value network, a formal specification and a complete and systematic analysis of the model are provided. This is of particular importance, as there exist much more aspects as one would assume at first glance (cf. conclusions about the ownership of the physical Twin, and plagiarism detection) that only this way can all be precisely and consistently defined and reviewed.

The PECI Model can be generalized to other kinds of physical artworks into which a unique code is crafted. It makes sense for new artworks that are created with the knowledge that they are linked to NFTs and where from the beginning a tight integration with a product code is considered. This will open completely new business models and roles for Manufacturers (i.e., creators of fine arts), Agents (e.g., museums, galleries, auction houses), and Users (art collectors).

The proposed model is easy to apply, as it does not cause development costs, beyond creating an NFT via out-of-the-box interfaces on existing platforms. This idea of a digital Twin is a first step towards business models in the metaverse, which will certainly represent the future of the internet. It is therefore to be expected that companies will take a close look at this model to consider how they can map the digital Twin concept onto their products.

The blockchain and NFT philosophy is that everything is transparent and open source. This means that proprietary or patented NFT models are a contradiction to this and would hinder the breakthrough of NFTs. Therefore, the contribution of the paper is to make an innovative NFT -based coordination model available to the community and to discuss its advantages and disadvantages with the community.

CRediT authorship contribution statement

Eva Maria Kuehn: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

Acknowledgments

The photos of "City Bag Red" and "Micro Classic Bag Neon" in figure 4 were taken by Susanna Hofer.

Appendix A. Glossary of web resources

Name	Description	URL (last visited: 25.4.2024)
Bored Ape Yacht Club	NFT collection featuring profile pictures of cartoon apes	boredapeyachtclub.com
City Bag Red	NFT by PECI.wien	opensea.io/assets/ethereum/0x495f947276749ce646f68ac8c248420045cb7b5e/43506412417015865344645373979169304999142817222430322070644856726628455153665
Cryptokitties	Blockchain game based on NFTs	cryptokitties.co
Cryptopunks	NFT collection featuring unique punky characters	larvalabs.com/cryptopunks
IPFS	Interplanetary File System	ipfs.tech
ETHMail	Email hosting service using an Ethereum wallet	ethmail.cc
Etherscan	Blockchain explorer for the Ethereum blockchain	etherscan.io
Micro Classic Bag Neon	NFT by PECI.wien	opensea.io/assets/ethereum/0x495f947276749ce646f68ac8c248420045cb7b5e/43506412417015865344645373979169304999142817222430322070644856745320152825857
Opensea	Marketplace for NFTs and crypto collectibles	opensea.io
peci-bags	Crochet bags NFT collection on Opensea	opensea.io/collection/peci-bags
peci-hats	Crochet hats NFT collection on Opensea	opensea.io/collection/peci-hats
PECI.wien	Crochet manufacturer	peci.wien
The Currency collection	NFT project of Damien Hirst	heni.com/nft/more-info/the-currency
Time Capsule	NFT project of Prada	www.prada.com/at/en/pradasphere/special-projects/2022/prada-timecapsule

Appendix B. Search strategy

This section investigates the usage of NFTs together with physical objects, with a focus on fine arts. A systematic literature review of related approaches was performed, that establish a permanent link between an NFT and a physical craft object and where this sustained connection is completely and clearly specified. The search strategy used is explained in the following.

A methodology that relates to systematic literature research as described in (Ven et al., 2023) (page 9) and that is based on the PRISMA Statement (Moher et al., 2009) was applied: identification through search in selected databases; elimination of duplicate records; screening of title, abstract and keywords; reviewing of the full text and if eligible, extraction of the results.

B.1. Identification

The following on-line databases were used for the search:

ACM Digital Library (Association for Computing Machinery),[6] arXiv,[7] Elsevier's Science Direct,[8] Google Scholar,[9] DBLP (Digital Bibliography & Library Project),[10] IEEE Xplore (Institute of Electrical and Electronics Engineers),[11] ResearchGate (RG),[12] Scopus[13]), SpringerLink,[14] Web of Science (WoS),[15] and Wiley's InterScience.[16]

The search was conducted using combinations of AND and OR keywords, following the explanations below. Some databases support wildcards, while others impose restrictions on connecting keywords, necessitating either multiple queries or simplified ones. For example, with Elsevier, only 8 operators are allowed, leading to the need to split the query into two parts, with the need to manually merge the results. ResearchGate, on the other hand, has limited research capabilities, making it challenging to create useful combinations of keywords that comply with the specified criteria. A notable limitation is the lack of strict results; databases may include records that only approximately fulfill the query, resulting in a large number of records that require manual filtering.

The search encompassed all fields of the article, with no date restrictions. It is important to note that DBLP allows searches only in the title. Collections and editorials, where the articles themselves can be found through the search, were excluded already during the identification phase. Duplicates within each database were also eliminated right away, as were papers not in English or those not published and, consequently, unavailable for download. So if K out of N records remained after the initial elimination of records, this is referred to as "K/N". During the identification process, we discovered that in databases with substantial record counts that do not support wildcards, explicitly using plural forms in queries could yield additional results. Therefore, these were later incorporated for those databases.

The applied queries and resulting numbers of records are:

[6] dl.acm.org
[7] arxiv.org
[8] www.sciencedirect.com
[9] scholar.google.at
[10] dblp.uni-trier.de
[11] ieeexplore.ieee.org
[12] www.researchgate.net
[13] www.scopus.com
[14] link.springer.com
[15] www.webofscience.com
[16] onlinelibrary.wiley.com

B.2. ACM

Query (“NFT” AND (“business model*” OR “business process*”) AND (“Art” OR “valuable asset*” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **1/16 Records**

B.3. arXiv

Query (“NFT” AND “business model” AND “art” AND “phygital”) $\Longrightarrow$ **0 Records.**
Query (“NFT” AND “business model” AND “art” AND “digital twin”) $\Longrightarrow$ **0 Records.**
Query (“NFT” AND “business model*”) $\Longrightarrow$ **1 Records.**
Query (“NFT” AND “business process*”) $\Longrightarrow$ **0 Records.**

B.4. DBLP

Query (NFT business) $\Longrightarrow$ **0 Records.**
Query (NFT art$) $\Longrightarrow$ **7/11 Records.**
Query (NFT digital) $\Longrightarrow$ **2 Records.**

B.5. Elsevier

Query (“NFT” AND (“business model” OR “business process”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **26 Records.**
Query (“NFT” AND (“business models” OR “business processes”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **27 Records.**

B.6. Google Scholar

Query (“NFT” AND (“business model” OR “business models” OR “business process” OR “business processes”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **464/ca. 562 Records.**

B.7. IEEE

Query (“NFT” AND (“business model” OR “business models” OR “business process” OR “business processes”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **20/27 Records.**

B.8. ResearchGate

Query (“NFT” AND “business model” AND “art” AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **29/40+ Records.**

B.9. Scopus

Query (“NFT” AND (“business model” OR “business process”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **42/42 Records.**

B.10. Springer

Query (“NFT” AND (“business model” OR “business process”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **89/304 Records.**

B.11. Web of Science

Query (“NFT” AND “business model” AND “art” AND “phygital”) $\Longrightarrow$ **0 Records.**
Query (“NFT” AND “business model” AND “art” AND “digital twin”)) $\Longrightarrow$ **0 Records.**
Query (“NFT” AND “business model” AND “art”) $\Longrightarrow$ **3 Records.**
Query (“NFT” AND (“business model” OR business process”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **3 Records.**

B.12. Wiley

Query (“NFT” AND (“business model” OR “business process”) AND (“art” OR “valuable asset” OR “valuable assets” OR “luxury”) AND (“phygital” OR “digital twin”)) $\Longrightarrow$ **1/3 Records.**

B.13. Remove duplicates

In summary 698 Records were identified. The elimination of all duplicates across all databases resulted in 566 Records.

B.14. Screening of title, abstract and keywords

The criteria for exclusion in this phase were: wrong domain (e.g. gaming, healthcare, crypto currency, industry 4.0, supply chain), collections or editorials, or primarily application of the NFT concept for the metaverse. The result of this phase were 35 eligible Records.

B.15. Eligibility

The criteria for exclusion after reading the full paper were: not fulfillment of the required keyword combinations (this had to be checked manually, because some search engines delivered unreliable results), wrong domain (see above), or primarily application of the NFT concept for the metaverse.

The result were the following eligible Records: (Akahyaoglu, 2021) is a study and analysis of new services for museums involving NFTs, and the development of a collaborative platform termed "CultureChain". A phygital experience is motivated where digital touchpoints within the museum environment are integrated. (Alnuaimi et al., 2022) proposes a comprehensive system that uses NFTs to track precious jewelry, whereby fraud can be avoided. Trusted parties are needed for delivery services. Smart contracts and off-chain services are implemented. A detailed formal description of the system is provided. (Herinckx & Ghislain, 2022) analyzes NFTs and blockchain to fight counterfeiting in the second-hand luxury fashion market. The study provides good insights into the fashion industry strategies and provides recommendations for different scenarios. (Li & Chen, 2023) is an analysis of using NFTs for managing digital property rights, thus creating value for creators and collectors. The physical product is paired with a digital twin. A detailed analysis of how NFTs empower business model innovation is carried out (Udokwu et al., 2023) deals with the problem of counterfeiting luxury products and proposes a digital verification for them by means of NFTs. A formal model and an implementation of a prototypical blockchain-based authentication and verification system across the lifecycle of ownership of luxury accessories are presented.

Note that some noteworthy papers that present interesting approaches, albeit in other domains or not dealing with digital twins, are two papers that were not identified by the search: (Westerkamp et al., 2018) presents a solution for supply chains based on new smart contracts, where interaction rules and stakeholder roles are well defined. (Solouki & Bamakan, 2022) introduces smart contracts for a concept they term "dynamic NFTs", where the NFT's metadata are dynamically updated to reflect changes in the real world. Moreover, three further interesting papers, albeit from other domains, that were identified by the search, are: (Hamledari & Fischer, 2021) in the area of building construction, gives insights on blockchains' and smart contracts' impact on improved accuracy, completeness and latency of information in the construction information flow. (Hasan et al., 2023) and (Elmay et al., 2023) propose, implement, and evaluate solutions to manage the ownership transfer and traceability of NFTs that represent digital twins, also considering the delivery of the associated physical assets; however not related to arts. Comprehensive system architectures are specified, that include new algorithms and the development of secure smart contracts.

Appendix C. Results

The eligible papers were classified according to the following criteria:

(A) There is a new proposal for an everlasting linkage between a physical artifact and an NFT that represents a kind of digital twin of it. (B) No extra software like smart contracts or off-chain services needs to be developed – out-of-the-box platforms and services suffice. (C) A complete formal specification and formal analysis of the model and its coordination workflow is provided in order to prove the correctness of the approach in all situations. (D) The model is applied in the fine arts area and contributes to avoid fraud. (E) There exist "white space" growth opportunities for the manufacturer.

From this we can conclude that the proposed PECI Model can claim to be the first approach to fulfill all criteria and might become a pioneer for further, similar innovative business models or extensions, variants and adaptations of the one presented.

References

Agha, G. A. (1990). *ACTORS: A model of concurrent computation in distributed systems*. MIT Press.

Akahyaoglu, N. (2021). *Bridging past & future: Harnessing NFTs as a storytelling medium for audience engagement and revenue growth in museums*. Ph.D. thesis.

Alnuaimi, N., Almemari, A., Madine, M., Salah, K., Al Breiki, H., & Jayaraman, R. (2022). Nft certificates and proof of delivery for fine jewelry and gemstones. *IEEE Access, 10*, 101263–101275.

Alpini, A. (2023). *NFT and NFTed artworks between property and copyrightability*. Universita di Macerata.

Ante, L. (2021). Smart contracts on the blockchain – A bibliometric analysis and review. *Telematics and Informatics, 57*, Article 101519.

Balduf, L., Florian, M., & Scheuermann, B. (2022). *Dude, Where's my NFT: Distributed infrastructures for digital art* (pp. 1–6). New York, NY, USA: Association for Computing Machinery.

Bukhsh, F. A., & Silva, P. D. A. (2016). Modeling e-business customization with e3value modeling. In *International Conference on Frontiers of Information Technology (FIT)* (pp. 187–192).

Buterin, V. (2014). *Ethereum: A next-generation smart contract and decentralized application platform*.

Chandra, Y. (2022). Non-fungible token-enabled entrepreneurship: A conceptual framework. *Journal of Business Venturing Insights, 18*.

Crespi, N., Drobot, A. T., & Minerva, R. (Eds.). (2023). *The digital twin*. Springer.

Daniel, E., & Tschorsch, F. (2022). IPFS and friends: A qualitative comparison of next generation peer-to-peer data networks. In *, 24*. *IEEE Communications Surveys and Tutorials* (p. 3152).

Du, L., Kim, M., & Lee, J. (2022). *The art NFTs and their marketplaces. CoRR abs/2210.14942*.

Elmay, F. K., Madine, M. M., Salah, K., & Jayaraman, R. (2023). Nfts for trusted traceability and management of digital twins for shipping containers. In *IEEE international conference on pervasive computing and communications workshops and other affiliated events, PerCom workshops 2023, Atlanta, GA, USA, March 13-17, 2023* (pp. 433–438). IEEE.

Entriken, W., Shirley, D., Evans, J., & Sachs, N. (2018). *ERC-721: Non-Fungible Token Standard*. URL:.

Far, S. B., Bamakan, S. M. H., Qu, Q., & Jiang, Q. (2022). A review of non-fungible tokens applications in the real-world and Metaverse. In *, 214*. *Procedia Computer Science* (pp. 755–762), 9th international conference on information technology and quantitative management.

Gibson, J. (2021). The thousand-and-second tale of NFTs, as foretold by Edgar Allan Poe. *Queen Mary Journal of Intellectual Property, 11*, 249–269.

Gordijn, J. (2004). 5 – E-business value modelling using the e3-value ontology. In W. L. Currie (Ed.), *Value creation from E-business models* (pp. 98–127). Oxford: Butterworth-Heinemann.

Gordijn, J., & Akkermans, J. (2003). Value-based requirements engineering: Exploring innovative e-commerce ideas. *Requirements Engineering, 8*, 114–134.

Gordijn, J., Petit, M., & Wieringa, R. (2006). Understanding business strategies of networked value constellations using goal- and value modeling. In *14th IEEE international requirements engineering conference (RE'06)* (pp. 129–138).

Hamledari, H., & Fischer, M. (2021). Measuring the impact of blockchain and smart contracts on construction supply chain visibility. *Advanced Engineering Informatics, 50*.

Hasan, H. R., Madine, M. M., Yaqoob, I., Salah, K., Jayaraman, R., & Boscovic, D. (2023). Using nfts for ownership management of digital twins and for proof of delivery of their physical assets. *Future Generation Computer Systems, 146*, 1–17.

Herinckx, J., & Ghislain, R. (2022). *The use of Blockchain to fight counterfeiting in the second-hand luxury fashion market*. Master's thesis. Louvain School of Management

Howell, J. (2022). *Phygital NFTs: Bridging the gap from physical to digital*, 101blockchains.com.

Kuehn, E. (2021). A practical tool-chain for the development of coordination scenarios – Graphical modeler, DSL, code generators and automaton-based simulator. In *23rd*

Int. conference on coordination models and languages (COORDINATION 2021) (pp. 239–254). Springer.
Kuehn, E. (2022). *The Peer Model tool-chain. Science of computer programming 223*. URL:.
Li, S., & Chen, Y. (2023). How nonfungible tokens empower business model innovation. *Business Horizons, 66*, 543–554.
Lyubchenko, I. (2022). What is art? NFTs, Beeple, and art connoisseurship in the 21st century. *Interactive Film & Media Journal, 2*, 174–190.
Marikyan, D., Papagiannidis, S., Rana, O. F., & Ranjan, R. (2022). *Blockchain: A business model innovation analysis. 2*. Digital Business.
Marquês, C., Ferreira, A. M., & Oliveira, F. (2023). Modular design and technology for diversity and a more sustainable fashion. The rtfkt x nike and clo case studies. In N. Martins, & D. Brandão (Eds.), *Advances in design and digital communication III* (pp. 94–103). Cham: Springer Nature Switzerland.
McKinsey. (2022). *Value creation in the metaverse*.
Mele, C., Spena, T. R., Marzullo, M., & Di Bernardo, I. (2023). The phygital transformation: A systematic review and a research agenda. *Italian Journal of Marketing*.
Moher, D., Liberati, A., Tetzlaff, J., & G., A.D. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine, 6*(7), Article e1000097.
Murray, M. D. (2023). *Transfers and licensing of copyrights to NFT purchasers*. SSRN.
NIKE. (2019). *System and method for providing cryptographically secured digital assets. US Patent, US 10,505,726 B1*.
Reitwießner, C., Johnson, N., Vogelsteller, B. F., Baylina, J., Feldmeier, K., & Entriken, W. (2018). *ERC-165: Standard Interface detection*.
Rodriguez Sanchez, M., & Garcia-Badell, G. (2023). Dressing the metaverse. The digital strategies of fashion brands in the virtual universe. In A. C. Broega, J. Cunha, H. Carvalho, & B. Providência (Eds.), *Advances in fashion and design research* (pp. 387–397). Springer International Publishing.
Roux, C., Goldsmith, K., & Cannon, C. (2023). On the role of scarcity in marketing: Identifying research opportunities across the 5ps. *Journal of the Academy of Marketing Science, 1197–1202*.
Sheldon, M. D. (2022). Tracking tangible asset ownership and provenance with Blockchain. *Journal of Information Systems, 36*, 153–175.
Solouki, M., & Bamakan, S. M. H. (2022). An in-depth insight at digital ownership through dynamic nfts. *Procedia Computer Science, 214*, 875–882, 9th international conference on information technology and quantitative management.
Udokwu, C., Zimmermann, R., Norta, A., Brandtner, P., Kormiltsyn, A., & Aroh, S. M. (2023). Exerting qualitative analytics and blockchain requirement-engineering in designing and implementing a luxury products authentication system. *Inventions, 8*, 49.
Umashankar, P. (2023). *Exploring phygital nfts: The fusion of real & digital worlds. Nerd for tech (medium.com)*.
Valeonti, F., Bikakis, A., Terras, M., Speed, C., Hudson-Smith, A., & Chalkias, K. (2021). Crypto collectibles, museum funding and OpenGLAM: Challenges, opportunities and the potential of non-fungible tokens (NFTs). *Applied Sciences, 11*.
Ven, M., Machado, P. L., Athanasopoulou, A., Aysolmaz, B., & Turetken, O. (2023). Key performance indicators for business models: A systematic review and catalog. *Information Systems and e-Business Management, 21*, 753–794.
Westerkamp, M., Victor, F., & Köpper, A. (2018). Blockchain-based supply chain traceability: Token recipes model manufacturing processes. In *2018 IEEE international conference on internet of things (iThings) and IEEE green computing and communications (GreenCom) and IEEE cyber, physical and social computing (CPSCom) and IEEE smart data (SmartData)* (pp. 1595–1602).
Wilson, K. B., Karg, A., Ghaderi, H., Wilson, K. B., Karg, A., & Ghaderi, H. (2022). Prospecting non-fungible tokens in the digital economy: Stakeholders and ecosystem, risk and opportunity. *Business Horizons, 65*, 657–670.
Zalan, T., & Barbesino, P. (2023). Making the metaverse real. Digital. *Business, 3*, Article 100059.