MICHIGAN ROSS

Decentraland NFT (LAND) Market Efficiency & Responsiveness to Events

by

Rachel Schonbaum

Thesis Advisor: Robert Dittmar, PhD

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Abstract

This thesis aims to measure and describe the market characteristics of virtual land NFTs known as LAND. NFTs are a relatively new technology and have gained widespread attention, beginning with their use in the digital art space. In parallel, increased corporate interest in building the metaverse raises questions about what types of digital infrastructure can be used to support this future digital environment. This thesis connects these two trends by considering the case of NFTs being used as digital infrastructure in the metaverse. Specifically, this thesis investigates the market for LAND and adds to the limited body of literature that studies NFTs through an economic lens. By incorporating new data points and events into analysis, the results uniquely describe a section of the NFT ecosystem. Further, the results of this thesis aim to encourage further exploration of this technology and its different markets.

Contents:

Introduction

The internet has become ubiquitous in today's society, but there is an ever-present question of "what's next for our digital future?" One answer to this question is the metaverse. The recent rise in corporate interest in building the metaverse ranges from Facebook's name change to Meta, to millions of dollars being poured into development from companies like Microsoft, Nvidia, Unity, Tencent, and Snap (Culliford, 2021). Though there is no single, standardized definition for the metaverse, there are generally agreed upon concepts and themes. For instance, the metaverse will consist of many platforms and virtual worlds; users should be able to interact and participate "seamlessly" across all of these platforms (Moy, 2022); and the range of user-to-user interactions and experiences will be vast, from social events to financial transactions to artistic creation (Appendix 1). In its current state, our digital environment is not integrated enough to be described as the metaverse – users cannot seamlessly interact and transact across virtual worlds. Contextualized by this developing state of the metaverse, this thesis is motivated by the notion that digital infrastructure should be selected based on its ability to support integration in the metaverse.

We study the case of nonfungible tokens (NFTs) being used as digital infrastructure in Decentraland, a popular virtual world. Each parcel of virtual land in Decentraland is an NFT known as LAND. This thesis aims to characterize the efficiency of the market for LAND using the most recent data. Market efficiency ultimately impacts the adoption of NFTs as digital infrastructure. Therefore, this thesis also incorporates a descriptive study of the factors that affect LAND market efficiency.

Problem Statement

The blockchain-based features of NFTs complement increased integration of platforms, but NFTs are not yet a widely accepted technology (Appendix 2). Even in this case study of Decentraland – a virtual world that functions entirely on NFTs, from the representation of land and assets to the mechanisms of their governing body[1] – the market for LAND demonstrated market inefficiency between 2017 to 2020. One effect of this market inefficiency is that the use of NFTs may be discouraged from use in the metaverse, despite their integration-supporting features. Further, if we assume that the effectiveness of NFTs in supporting platform integration is substantial, then the inhibited adoption of NFTs in the metaverse will also inhibit the growth of the metaverse. Addressing this issue requires an assessment of whether inefficiency can be improved upon and if so, an assessment of possible drivers of efficiency. Specifically, we assess the following two hypotheses:

> **H1**: The minimization of NFT-related transaction costs causes periods of efficiency within LAND markets
>
> **H2**: Increasing integration-related events causes periods of efficiency within LAND markets

These hypotheses are defined by two mechanisms that impact efficiency and are related to two types of integration. Technical inefficiency and transaction costs are traditional inhibitors to market efficiency and are defined the same way in terms of integration-related transaction costs. Integration-related events, however, can be thought of as a back-channel to improving efficiency: events improving social and technical integration can promote participation which directly counteracts the effect of discouraged participation that comes from market inefficiency.

[1] Decentraland's decentralized autonomous organization (DAO).

Integration-related events are defined in this paper as another type of integration that tends to be more social.

Background: NFTs, Decentraland, and Definitions

Non-Fungible Tokens

NFTs are digital representations of asset ownership, where each NFT is completely unique and NFT creators control the scarcity (Appendix 2). As part of the Ethereum (ETH) blockchain, NFTs adopt the characteristics and benefits of smart contracts. The range of ETH-based NFT features is detailed in Appendix 2, but crucially, NFTs are fundamentally trustworthy. Specifically, NFTs are created on ETH's blockchain using smart contracts – ERC-721 or ERC-1155 standards[2] – which allow for safe, immutable transactions of asset ownership. Additionally, the documentation of NFTs and NFT ownership is of public record and verifiable. The trustworthy transactions and documentation of NFTs support digital integration and effectively promotes interaction amongst users. In addition, NFTs benefit from living on the ETH blockchain by adopting any subsequent improvements to the ETH system through Ethereum Improvement Proposals (EIPs). In one case, EIPs have led to increased sustainability in the NFT ecosystem: the ERC-1155 standard started out as an EIP and when implemented, this standard improved the efficiency of transactions. Since Ethereum transactions require gas – the computational energy required to conduct a transaction – the improvement in efficiency directly reduced the impact that NFT transactions have on the environment as well as the cost of gas, known as a gas fee or gas price (Appendix 2).

[2] ERC-721 is the original NFT standard and established the interface for using NFTs on platforms. This enabled core functionality such as transferring tokens, approving transactions, and accessing information. The ERC-1155 standard expands upon ERC-721 by allowing for the handling and transactions of different types of tokens, not just NFTs (Appendix 2).

Generally, NFTs represent digital assets from six categories: Art, Collectibles, Games, Metaverse, Utility, and Other (Nadini et al., 2021). Because of LAND's commodity-like properties, this thesis focuses specifically on the market for LAND, which is in the Metaverse category (Appendix 3). Other NFT markets exist within Decentraland, such as Collectibles, Art, and Games. Finally, there are a few alternatives or direct substitutes for NFTs, especially in the Metaverse category. The main alternative to NFTs is a ledger or database controlled by a centralized entity – typically a single company. Currently, centralized ledgers are most prevalent.

Why Decentraland & LAND

The standardization and uniformity of Decentraland's LAND characteristics are optimal for this thesis' study of NFTs. To allow for better discussion about the value of using NFTs as digital infrastructure in the metaverse, it is important to separate the content that NFTs represent from the features of the technology itself. Unlike other categories of NFTs like Art and Collectibles that welcome subjective valuations, the way Decentraland defines LAND allows this asset to be described as commodity-like. LAND is uniform in size and only differs in objectively-measurable geographical features such as x-y coordinates, distance to roads, distance to districts, and distance to plazas (Appendix 7).

As one of the first movers in the NFT-based virtual world space, Decentraland user adoption is also relatively high. There are nearly 20,000 daily active users on Decentraland and over 12,000 active traders participating across Decentraland's different NFT markets (Farooque, 2022; Dapp, 2022). As is intended in the metaverse, Decentraland users are able to enjoy a variety of activities, from buying and selling virtual real estate to gambling in virtual casinos, socializing at festivals, or creating new avatar skins and artwork. That is to say that Decentraland is already exhibiting instances of integration and increased integration. Finally, Decentraland has enough available time series and event data to be able to study their LAND markets.

Defining Integration & Integration in Decentraland

Integration is used as a defining term for the metaverse, but there are two types of integration to consider. Most commonly, integration is thought of in the sense of technical functionality, such as improved ability for users to transact, communicate, and travel within or between virtual worlds. However, integration is also considered in terms of value created at a social or societal level (i.e. companies in real life collaborating to create social events in a virtual world). These are not mutually exclusive, and both types of integration create value by unlocking positive network effects. Typically, network effects are described as individual platforms increasing in value as the numbers of participating users increases. In the case of the metaverse, both the individual platforms and the whole connected network of platforms increases in value with increased participation.

Decentraland has already demonstrated increased integration of both types. As players in different industries have become more comfortable with the NFT environment, collaborations between metaverse-related companies and other industries have increased. Expanding on the collaborations mentioned in Appendix 1, Decentraland has collaborated with major companies in fashion, entertainment, online gambling, financial services, art, and retail (Gewirtz, 2022; Wilser, 2022). Additionally, Decentraland internally promotes user interaction by running events such as building competitions. Beyond the global improvements to the NFT ecosystem like ERC-1155, Decentraland's governing body (DAO) facilitates a proposal process. Proposals can range in topic but frequently include proposals for features intended to improve the user experience and technical connectivity. For example, the DAO Committee Report (#0018) covering proposals from February 2022 passed a grant request to create the "WeMeta Builder Tag". This tool is an analytics dashboard intended to help users understand engagement (foot traffic, active player time, etc.) in their plots of land (Decentraland.org, 2022).

Defining Transaction Costs & Transaction Costs in Decentraland

Transaction costs are described in this thesis as the barriers that agents face in order to participate within a market. Transaction costs in Decentraland include two primary components: ETH gas fees and switching costs. Transactions in Decentraland occur on ETH and require computational energy known as gas. The amount of gas corresponds with a literal fee that has been historically high but improved upon with updates like the ERC-1155 standard (Appendix 3). The use of cryptocurrencies to transact NFTs has also created a barrier to participation because users are essentially required to create a digital wallet and use cryptocurrency exchanges. Within Decentraland, another step is required due to the platform's use of an internal, fungible cryptocurrency known as MANA (Appendix 3). MANA is only available on certain exchanges, which makes it more difficult to find and use. According to Decentraland's own website, it is "not likely that there [is] an exchange available to convert your USD directly for MANA" (Decentraland, 2021). Typically, one would need to find a cryptocurrency pair like ETH or Bitcoin with which they could then trade for MANA. Though there has been historical evidence of improvements in both of these transaction cost components, technical efficiency improvements are expected to be somewhat infrequent because of the technically difficulty in initiating and successfully implementing them.

Justification & Contributions

This thesis is motivated by the nascency of NFTs. Currently, substantial literature exists on tangential topics like blockchain and market efficiency. The literature on NFTs, however, is extremely limited from an economic perspective and even more so when studying the NFT-Metaverse category. Contributing to the small sample of economic-NFT literature, this thesis analyzes the most recent LAND market data with a new layered methodology. As a descriptive study, there is also a goal of inspiring further research in the NFT-Metaverse space.

Further expanded upon in *Methodology*, this thesis combines stages of analysis from three papers: Dowling's study of LAND market efficiency (2021), Khuntia and Pattanayak's study of Bitcoin market efficiency (2018) and Chu et al.'s (2021) study of cryptocurrency market efficiency**.** Specifically, the same market efficiency tests and settings are pulled from Dowling, but nine months of new data are included; Subsequently and inspired by Khuntia and Pattanayak, a timeline of events are mapped to the market efficiency results. Khuntia & Pattanayak describe policy changes as a possible driver of market efficiency. However, with no known relevant policy developments related to the NFTs in metaverses, this thesis also contributes to the literature by identifying important events and categories of events that could impact NFT markets. Finally, similar to the regression run in Chu et al., this study runs linear regressions to assess the strength of relationships between market efficiency and different types of events.

Literature Review

Dowling (2021) is one of the few to exclusively study NFT-Metaverse markets, which is why his paper is used as an initial framework. Literature is also sampled from studies on cryptocurrency markets, which are linked to the technical functionality of NFTs through Ethereum. Although cryptocurrency markets are older than NFT markets, they are still considered relatively new, and many of the efficiency tests for cryptocurrency markets can be appropriately applied to NFTs. Similarly, most of the literature sampled for this study – whether about NFTs or cryptocurrencies – rely on the Adaptive Market Hypothesis (AMH) as a theoretical framework. This provides the basis for AMH assumptions similarly being applied in this thesis.

Although his paper is brief, Dowling establishes precedent for observing Decentraland LAND markets due to the uniform size and physical features of the virtual land. His descriptive findings demonstrate a generally inefficient market; however, he does not account for the locational differences of parcels. This is a limitation that is identified by Goldberg et al., (2021), where they find a significant relationship between the price of LAND and its location. Locational differences are associated with different degrees of commercial potential where higher prices are associated with locations close to the city-centers of virtual worlds and locations with easy to remember addresses. This ultimately indicates locational differences should be controlled for. Similar to Dowling, the uniform characteristics of LAND allowed Goldberg et al. to measure the pure effects of locational differences on pricing. In contrast, Nadini et al. (2021) considers the content of NFTs as a contributing factor of NFT prices, and therefore explores a variety of NFT types and marketplaces.

Nadini et al. assesses all categories of NFTs from over 3,000 collections. They ultimately group NFTs by visual features and find that prices are influenced by visual features. The results from Nadini et al. validate the decision to exclude market analysis of other NFT categories in Decentraland, namely wearables, collectibles, and art.While Nadini et al. studies NFTs from multiple platforms, they do not address the level of interaction across these platforms. Ante

(2021) fills this gap by measuring the cointegration[3] of NFT submarkets across the major marketplaces and metaverse platforms.

Ante identifies a reciprocal relationship where the adoption rates of NFT platforms[4] are related to the success of older markets, but newer platforms also impact the direction of success for older platforms. Certain projects might be considered substitutes, which is why Ante studies the relationship across 11 different platforms, which host NFT collections of all categories. Of particular interest to this thesis, Decentraland was the only project out of the 11 that did not seem to be influenced by other NFT projects. However, Decentraland's success is correlated with decreased transactions in CryptoPunks and increased trading volume in SuperRare[5]. Other platforms like Somnium Space – one of Decentraland's competitors and a younger platform – was found to Granger-cause[6] worse sales in other platforms. Overall, Ante's findings demonstrate that the NFT network is made up of connected and integrated platforms. Moreover, the relationships across platforms that he observes continue to support others' findings of NFT market inefficiency.

Thus far, the literature in this review has generally shown that NFT markets are inefficient under both the traditional Efficient Market Hypothesis (EMH) as well as the Adaptive Market Hypothesis (AMH). The literature on crypto-market efficiency, which also uses EMH and AMH assessments, demonstrates a possible trend that NFT markets could exhibit in the future. While crypto-markets are still relatively young, they are older than NFT markets by several years. Khuntia and Pattanayak (2018) and Chu et al. (2021) both study crypto-markets

[3] Cointegration: a statistical technique used to find correlation between several time series (CFI).
[4] Ante defines an NFT project in the same way that this paper defines an NFT platform – i.e. Decentraland would be considered an NFT project.
[5] SuperRare integrated into the Decentraland marketplace in July 2020, allowing users to view and trade art from the SuperRare collection using MANA (Decentraland.org, 2020).
[6] Granger causality: a statistical technique used to find predictive causality across multiple time series; one time series can be used to predict the future values of another time series (Scholarpedia.com).

under AMH and find evidence of increased and sustained periods of efficiency after an initial few years of inefficiency. Importantly, both of these papers study if events and information can be linked to a market response of increased efficiency.

Khuntia and Pattanayak study Bitcoin (BTC) markets from 2011-2017, while Chu et al., studies ETH and BTC from 2017-2018. Both observe that BTC markets experience both periods of inefficiency and efficiency, but they offer different explanations for how events and information impact efficiency. Khuntia and Pattanayak observe a shift in BTC markets towards efficiency in 2015 that lasts through 2017. They offer two reasons as to why the period of efficiency was likely catalyzed and then subsequently stabilized. First, at the macro-level, policy in Europe, Japan, and Russia shifted in favor of cryptocurrency causing the initial shift. Then market efficiency was supported by mechanisms of herd-behavior[7]. Khuntia and Pattanayak do not rigorously prove causality between these events and efficiency. However, they cite studies that have similarly mapped out events that could impact market dynamics to the same timeline where a market exhibits periods of efficiency and inefficiency. They do not expand upon the latter aspect of herd-behavior.

Chu et al. (2019) fills a gap in analysis left by Khuntia and Pattanayak by introducing more rigorous methods to measure the relationship between efficiency and events. They analyze events by running an OLS regression where changes to efficiency are regressed on sentiment analysis from news articles. News is categorized into one of the following eight topics: exchange rates, trading platforms, other cryptocurrencies, regulation, investment, cybersecurity, technology, and politics. Ultimately, they do not find significant results and conclude that events have no "explanatory power" in changes to crypto-market efficiency. These results, however, do

[7] Herding behavior is the tendency to follow the actions of a group.

not discourage using a similar approach in this thesis. Further, certain categories in Chu et al.'s regression are not relevant for this thesis. For example, politics and regulation do not exist quite yet for NFTs, and exchange rates and trading platforms are not as relevant since the scope is limited to Decentraland. Expanded upon in the methodology, this thesis uses categories where events fall into one of two buckets relating to mechanisms of integration (technical or social).

Theoretical Framework: *Adaptive Market Hypothesis*

The three guiding papers of this thesis all utilize Andrew Lo's financial theory, the Adaptive Market Hypothesis (AMH). Lo (2004) created the AMH as a modern adaptation of the traditional Efficient Market Hypothesis (EMH) where he pulls from behavioral economics and evolutionary theory. Specifically, AMH states that the degree of market efficiency varies over time and does not necessarily or likely converge to any state of equilibrium (Lekhal & El Oubani, 2020). In contrast to EMH, Lo's framework allows markets to be characterized dynamically. As is apparent in the literature, AMH assumptions are often appealing to those studying emerging markets. AMH has been used to study a variety of markets, including stock markets, bond markets, cryptocurrency, and foreign exchange markets (Lekhal & Oubani, 2020). While Lo has not developed a formal equation for this theory, his framework is useful in motivating analysis of NFTs because existing literature has demonstrated that overall – and with EMH assumptions – NFT markets are strictly inefficient.

Both AMH and EMH refer to efficiency in terms of pricing efficiency, where prices in efficient markets are defined as always reflecting all possible information. Formally, this can be written as prices being the expectation of the present value of all future cash flows:

$$\text{Price} = E[\sum PV(future\ cash\ flows)]$$

Under this formulation, with traditional EMH assumptions, an agent is assumed to take expectations rationally. Lo challenges rational expectations by using evolutionary theory in AMH and maintaining that agents are often not rational, but are, in fact, fear and greed driven (Lo, 2004). AMH also describes agents as being capable of learning over time. Lo supports the use of evolutionary theory by making parallels to concepts in behavioral economics, such as loss aversion, overconfidence, overreaction, and learning. Even in the cases where EMH allows for the existence of these behavioral biases, EMH asserts that market forces negate the effects of actor irrationality (Lo, 2004). This is a strong assertion that requires that other EMH assumptions are perfectly met, which is unlikely especially in newer markets.

AMH does not negate EMH, nor are all of their mechanisms strictly incompatible. For example, EMH does not disallow for the existence of cycles, but Lo notes that when empirically applied, EMH assumes markets are stationary and in a state of equilibrium (Lo, 2004). Further maintaining his use of evolutionary theory, Lo describes markets as ecosystems that have distinct institutional features, populations, and population preferences. In this living ecosystem, the features and populations are expected to change over time. This dynamic characterization of markets under AMH further attempts to reconcile Grossman & Stiglitz's (1980) challenge to EMH: Grossman & Stiglitz argue that perfectly informationally efficient markets are impossible because without informational inefficiency, there would be no arbitrage opportunities and no one willing to participate in the market. Under AMH, the varying periods of market efficiency demonstrate varying periods of arbitrage opportunity, which ultimately incentives market participation.

EMH allows for some dynamic categorization of markets, though far less than AMH. EMH defines three degrees of market efficiency: weak, semi-strong, and strong. Weak efficiency implies that prices reflect historical price data, semi-strong reflects historical and public information, and strong efficiency reflects public, historical, and private information. A perfectly efficient market under EMH would be described as strong efficient, however, weak-form efficiency is commonly observed across empirical studies (Lekhal & El Oubani, 2020). The prevalence of weak or even semi-strong markets signals how common it is for markets to have sources of inefficiency.

Typically, price inefficiency can be attributed to informational asymmetry, irrational actors, and the presence of technical inefficiency or transaction costs. In NFT markets, informational asymmetry and transaction costs are expected to be prominent due to the technical nature of NFTs. An actor's unfamiliarity with cryptocurrency can be both a technical transaction cost as well as a source informational asymmetry. For instance, an agent participating in an NFT market needs to own a digital wallet[8], learn how to convert currencies, and learn how to set optimal gas prices to complete their transactions (Appendix 2 and 3). For non-crypto natives, much of the technology and related concepts behind NFTs are new and have a steep learning curve; understanding this relatively new technology also requires an understanding of blockchain, decentralized web, and of course, cryptocurrencies. In this regard, AMH remains appropriate for this study. AMH asserts that actors learn over time and from experiences, which influences their expectation function. It is expected that with time, agents will become increasingly familiar with NFT and NFT-related concepts. As agents become more sophisticated, the magnitude of informational asymmetry and transactions costs will decrease. Similarly, as technology improves for NFTs and platforms alike, transaction costs that cause market

[8] In Decentraland, a user can join without a wallet, but most user-to-user transactions still require a wallet. Since user-to-user interactions are closely tied to the value of the platform, wallets are essentially required (Appendix 3). In other platforms, wallets and NFT purchases may even be required in order to create an account.

inefficiency are expected to decrease. Ultimately, the dynamic nature of the Adaptive Market Hypothesis is useful in this assessment of such a nascent market with the potential for many unknowledgeable agents.

Methodology

As noted in the literature review, this methodology is defined by three stages corresponding to each of the following papers: Dowling, Chu et al., and Khuntia & Pattanayak. First, LAND market efficiency is measured using the same standardized tests as Dowling. Subsequently, a timeline of Decentraland events is mapped to the efficiency test results. Finally, to further explore the strength of the relationship between events and market efficiency, two MLR regressions are run. The efficiency tests and regressions both use a time series of weekly returns from 2019 to early 2022. In addition to the methods design, this thesis contributes to the existing body of NFT literature by incorporating nine months of new data. Most LAND market studies begin around February 2019[9] and stop in March 2021. This thesis similarly starts in February 2019 but extends analysis through February 2022.

To characterize market efficiency, the following two tests are run using LAND time series data: a rolling Automatic Portmanteau (AP) test describe serial correlation and rolling Hurst exponent scores describe time series memory. When the data sample is small – as is the case here – the AP test is a better alternative to the traditional Automatic Variance Ratio (AVR) test. As a check, both tests were run and produced similar results and trends. Moreover, only AP test values were included in the *Results* and *Discussion* when measuring efficiency.

[9] Dowling uses data starting in March 2019 due to a change in the LAND characteristics that occurred in February 2019. Similarly, this study excludes data from before March 2019.

Similar to the AP test, the corrected empirical Hurst exponent is used as a variation of the Hurst exponent test due to the small sample size. This test measures time series memory[10], which is a characteristic of markets that can be used to indirectly identify market efficiency. The corrected empirical Hurst test produces exponent values referred to as scores. The Hurst results are used in support of the AP test results, but only the AP tests are graphically combined with the timeline of Decentraland events.

Both efficiency tests are applied over a rolling window of the time series data. Importantly, the results of these tests are sensitive to the window size. For instance, the resulting p-values from the AP test are far more volatile when the window size is below 15 weeks. In order to maintain consistency with Dowling, however, a 40-week window is used.[11]

Ultimately, the combined efficiency and events timeline provides a high-level, descriptive picture of possible relationships between periods of market efficiency and event types. This timeline is further used to specify and define two regressions: an overall regression to see if any event or headline impacted efficiency as well as a regression where information was separated into categories (Figure 8).

***Data Collection*:** LAND Time Series & Event Information

Publicly available LAND data and event information data were used in the market efficiency tests and timeline, respectively.

LAND Time Series Data:

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[10] Time series memory can be categorized into periods where the time series exhibits switching behavior or persistency. Switching behavior is defined as the time series value having a different sign as the next value. Persistency is defined as the time series value exhibiting the same direction as the previous value.

[11] Dowling uses a 40-week window to "balance the need for sufficient data with the limited time period" that is available (Dowling, 2021).

The time series consists of secondary LAND sales, which are transactions after the NFT is minted and sold for the first time. In order to set up the time series, two sets of LAND data were acquired from NonFungible.com: the total number of secondary sale transactions aggregated over time and the total USD value of secondary sales aggregated over time. Additionally, historical pricing of ETH and ETH-gas prices were acquired from YahooFinance, and the number of Decentraland sellers and active unique wallets were acquired from NonFungible.com. ETH, ETH-gas prices, and the number of sellers were used as controls in the regressions (Appendix 4).

Event Information Data:

A list of events was compiled from Decentraland's self-hosted blog because of their clear segmentation of information types. Additionally, Decentraland is incentivized to publish information about both technical efficiency improvements and social integration events; social media forums, other blogs, and major news outlets either post infrequently or include information that is not related to either technical or social types of integration.

The Decentraland blog categorizes information into Technology, Platform, Project Updates, and Announcements. The headlines for each of these categories were web-scraped, as well as their respective publishing dates. For blog headlines that did not provide sufficient information about the post's content, additional information was scraped from within the post. This was primarily the case for Project Updates, which were most commonly DAO Committee Reports, titled *"DAO Committee Report [*report number*]"*. Further, word clouds and term-relevance scores were produced to verify that Decentraland's informational categories can be used as proxies for transaction costs and social integration events. The word clouds and term relevance scores used text from the headlines and posts (Appendix 5).

Data Preparation

The LAND time series was the only dataset that required significant preparation, as detailed in Appendix 6. Additional preparation included merging the LAND efficiency results with the timeline of events from the Decentraland blog. Event categories were further transformed into categorical variables, so as to assess which weeks had announcements and if so, what combination of information types were published. Finally, the control variable datasets – ETH, ETH-gas, and number of sellers – only needed to be converted into weekly averages.

LAND Time Series Data:

To convert the raw data of LAND secondary sales and trade volumes into a time series, the two datasets had to de-aggregated and then divided to get a daily average price (Appendix 6). At the daily level, prices and transaction volumes of NFTs were unsurprisingly volatile. To manage this generally noisy data, the daily percent changes (returns) were then calculated, cleaned, and averaged to find weekly returns (Figure 1, 2).

Data Summary

LAND Average Prices and Returns:

Weekly average prices are consistently below a $5,000 threshold throughout 2020. In the first half of 2021, however, LAND prices start to increase, spiking upwards into the $20,000-30,000 range in the last months of 2021 and into 2022 (Figure 1). The wide range and large standard deviation of weekly returns similarly reflects the volatility of this asset and the inclusion of many outliers (Figure 2, 3). Notably, one of these outliers is a negative return value of -15.452, which was not removed from the dataset because that day represented a local shift in decreased daily transaction volumes.

Information Types:

The four information types were used as proxies for either transaction costs or social integration events: Technology and Platform were used as proxies for minimized transaction costs, and Announcements and Project Updates were used as proxies for increased social integration events. Appendix 5 defines each of the information categories and includes examples of their respective headlines, as well as the headline count. Blog posts from all categories date back as far as January 2018, but only those that fell within the same date range as efficiency test results were included in the timeline and regressions.

Technology and Platform Updates were the least frequent type of announcement, but overall, there was an apparent gap in Technology, Platform, and Project Updates for most of 2020 (Figure 4). Announcements, on the other hand, occurred at a high frequency throughout the whole two-year period. The technical nature of Technology and Platform Updates partially explains their intermittent frequency. More time and money investments are required to successfully change the technology of NFTs or the platform. Similarly, the temporary nature of Announcements and Project Updates partially explains their high posting frequency because these events are relatively easier to organize and implement. For example, terms in Announcement headlines with the highest frequency and relevance score include “games jam”, “treasure hunt”, and “creator contest” – all of which are temporary events that do not directly change the platform or nature of user-interaction (Appendix 5).

Results

Figures 4-6 report the results of the rolling AP test and Hurst exponent scores. Though data from 2019 is used by the tests, the 40-week window means that test results are only observable from 2020 to early 2022. AP test p-values above 0.05 represent periods of market efficiency. Similarly, Hurst exponent scores below 0.5 represent periods where the market exhibits switching behavior, which is a characteristic of efficient markets.

Figure 5: Combined AP Test Results & Information Timeline

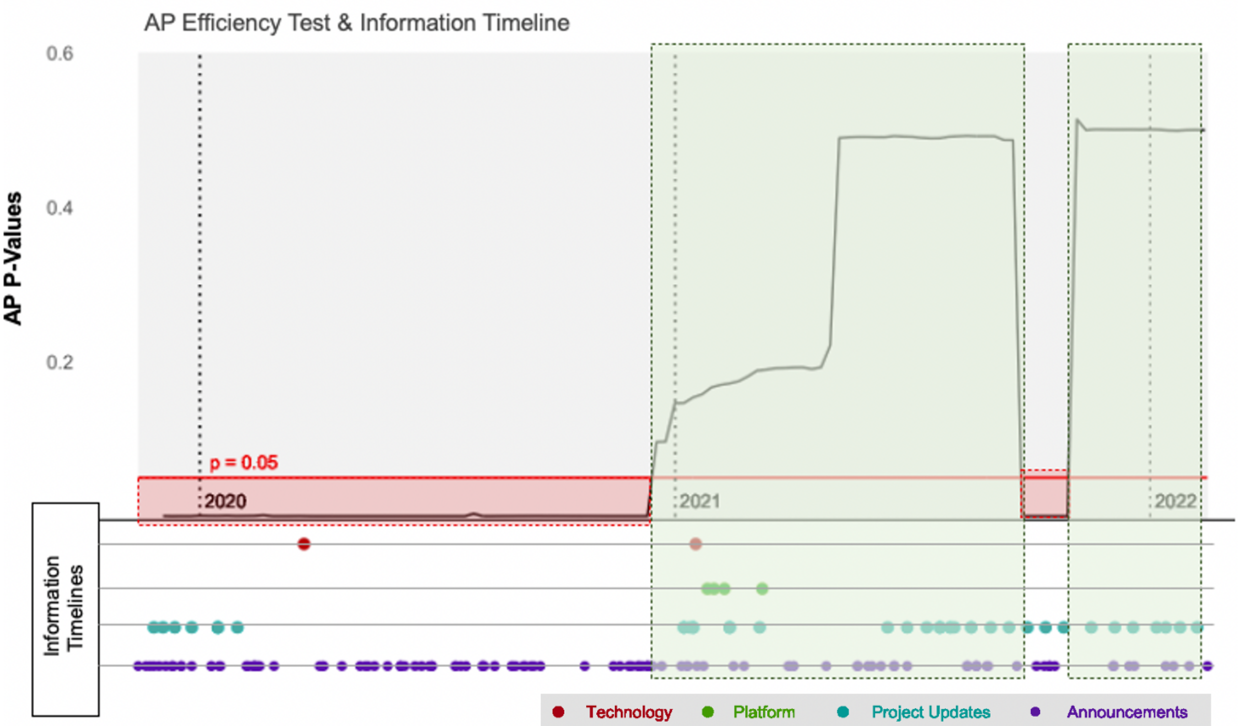


Figure 5: AP test p-values are mapped onto the same x-axis as the four categories of information to create a combined timeline. Periods where the p-value < 0.05 represent periods of market inefficiency.

Efficiency Test & Timeline Results:

For most of 2020, AP p-values remain below the efficiency threshold, which is consistent with the existing literature. Increased efficiency occurs in the last month or so of 2020. This shift towards efficiency was mostly maintained during the nine months of new data where AP p-values increased past the 0.05 threshold throughout 2021. There is a noticeable but temporary drop into inefficiency between the 3rd and 4th quarter of 2021, but efficiency is recovered by the end of the year and into early 2022 (Figure 5). Though the AP test is a more direct test of market efficiency, the AP results were supported by the Hurst exponent scores.

Across the 2020-2022 timeframe, the rolling Hurst scores are predominantly under 0.5 (Figure 4). There are a few periods where Hurst scores exceed 0.5, especially around the 3rd to 4th quarter of 2021. Notably, these periods are around the same brief period of inefficiency exhibited by the AP test results (Figure 7).

In Figure 5, the combined efficiency and events timeline reveals an interesting trend. When the LAND market shifted into efficiency in 2021, Project Updates became frequent. This change in posting frequency is particularly noticeable because there was a year-long lull in blog posts across 2020 for Technology, Platform, and Project Update categories. Other informational categories did not exhibit any changes in posting frequency over the two-year period. To further explore these relationships, the results of the linear regressions were used to measure the strength of how information-types impacted market efficiency (Figure 7).

Regression Results:

The results of R1 show that there is no statistically significant relationship between all categories of information and efficiency **(**Figure 8). Separating the information into its four types, however, showed a significant relationship between efficiency and the proxies for social integration events – Announcements and Project Updates. Technology and Platform – the proxies for transaction costs – did not have a statistically significant impact on efficiency. Though Announcements and Project Updates both correlated to changes in market efficiency, they impacted efficiency differently. Project Updates were found to positively affect efficiency by increasing AP test p-values (0.093). Announcements, however, decreased p-values (-0.043). The magnitudes of both coefficients are sizeable, considering the threshold for efficiency is 0.05.

Discussion

When the market for LAND shifted towards efficiency in early 2021, two trends in blog posts and users were observed. The initial shift towards market efficiency followed a period of high activity in Announcement posts that revolved around increased user interaction and platform collaborations (Figure 5). These events included updates on a Builder Contest, Game Jam, End of Year virtual party, and the Decentralized Economy Global Summit (Decentraland.org, 2022). These events were intended to catalyze user engagement, but leading up to this period, the number of sellers and wallets had stagnated below 500 and 1,000 respectively (Appendix 4, Table 1). This eventually changes in parallel with changing market efficiency.

Though there was an unusual increase in blog posts during the first two months of 2021, only Project Updates and Announcements were sustained through the rest of the year and into 2022. Whereas Announcements are consistently frequent, the increased Project Updates is an evident change from the previous year and warranting further exploration.

The majority of Project Updates consists of DAO committee reports. These reports describe community-driven decisions, and they typically include polling results about improving all aspects of the Decentraland platform. While there was a small cluster of Project Updates around the end of 2019 and into early 2020, there were also fewer and less engaged participants – as indicated by the stagnated number unique of wallets.[12] This potentially explains why those DAO reports may have had less of an impact on early market efficiency. In contrast, the revitalization of DAO reports in 2021 is paralleled by an increase in sellers and wallets: after a slow increase in the first half of 2021, sellers tripled, and the number of unique wallets increased

[12] A single user can have multiple unique wallets, so this metric is not a direct equivalent to the number of Decentraland users but still indicates some level of engagement with the platform.

five times (Appendix 4). With more Decentraland users being invested in the platform, the effect of DAO reports could be weighted more.

Exploring the importance of DAO Committee Reports also helps to investigate the temporary period of inefficiency that occurred in the 3rd quarter of 2021. Leading up to this period of inefficiency was a series of Project Updates, including two posts that diverge from the typical DAO committee report format. The first post on August 3rd described a technical protocol improvement, and the second post on August 18th was an update on 10 community grant projects worth $35,000 USD. Importantly, these posts may have created informational asymmetry – a common source of market inefficiency. Informational asymmetry can be caused by a lag in when the information is released and when it is consumed by market participants. Due to these posts being updates, another type of lag may have occurred: the lag between when information is released and when the content is actually implemented in Decentraland. For instance, the August 3rd post describes events that would be implemented on August 16th, and the grant updates were all on-going projects.

Another related aspect that may have caused this temporary period of market inefficiency is the level of sophistication of the market participant. The highly technical nature of the protocol improvement post could have been challenging for market participants to interpret. Therefore, it would have been difficult for participants to appropriately adjust their pricing expectations, causing the temporary period of inefficiency. When the market rebounded a few months later and became efficient again, expectations would be readjusted, and the lags resolved.

The descriptive picture of the combined efficiency-events timeline can be coupled with the regression outputs to assess the two proposed hypotheses. Hypothesis 1 is neither supported by the combined timeline, nor the regression outputs. Meanwhile, Hypothesis 2 is supported by both the timeline and regression outputs.

As noted above, Project Updates describe platform improving events, which aligns with their positive impact on AP test p-values. Interestingly, Announcements have a negative impact on AP p-values even though they are used as a proxy for events that are meant to increase user interaction. One possible reason for this effect is market participants may be negatively perceiving the content of Announcement events. Negative user perception could create frictions and deter platform participation. Alternatively, Announcement headlines could be more prone to hyperbole, which could cause market participants to misadjust their pricing expectations.

The lack of support for Hypothesis 1 does not explicitly rule out the possibility of transaction cost events impacting efficiency. The issue persists that the timeline and regression do not capture the lag between a headline's publication and its implementation in Decentraland. Further, compared to social integration events, transaction cost events are more prone to longer lags. For example, the addition of ERC-1155 involved a lengthy process of development, testing, and implementation. Before the process was complete, notice of this improvement proposal was already published and publicly accessible. Finally, a higher amount of user skepticism may be associated with transaction cost events because they are higher-stakes and require larger investments of time, energy, and money.

Limitations

The two major limitations of this thesis are data availability and the choice of proxies for events. Data access is a fundamental and unavoidable limitation of this study. NFT markets are relatively new with only a few years of data available. The small sample of initial data points was further reduced by the set-up of the rolling efficiency tests, which required a large window.

Additionally, data availability proved to be an issue in the regression set-up. Goldberg et al. (2021) finds that geographical features have a significant impact on LAND prices. These features should have been controlled for in the regressions, but only a few weeks of data incorporating geographical features were available (Appendix 7).

While Decentraland's blog was useful in sorting information into categories of either transaction costs or integration events, using additional publication sources is encouraged. For example, one of the limitations of using Decentraland's blog is they did not post as frequently about the total NFT environment, even though these events influence the platform and market participants. Using additional sources to capture the total NFT environment would specifically address the issue of the small number of transaction cost events; there were only 32 transaction cost events compared to 103 social integration events. Additionally, Decentraland's definitions of the informational categories were not well-defined. Though the word clouds and term-relevance scores verified Decentraland's definitions, the content across categories was not mutually exclusive. It is possible then, that transaction cost events were incorporated into Project Updates while this category was being used as a proxy for only social integration events.

Finally, this paper produced descriptive and suggestive results. To prove causality, future research should use a different methodology. Specifically, future methodology would need to account for the lag between publication of information and its implementation. One partial solution to accounting for lag is to use a source that most market participants actively monitor. It is unknown to what extent market participants viewed Decentraland's blog. Other social forums like Discord, Reddit, and Twitter, however, are well-established amongst many users, and Decentraland hosts accounts on each of these platforms.

Conclusions & Areas of Future Research

The possibility of improved market efficiency in Decentraland's LAND market has positive implications for NFT usage in the metaverse. While this paper's results do not prove causality between events and market efficiency, NFTs should not be ruled out as digital infrastructure simply because of periods of market inefficiency. Cryto-markets were inefficient for a few years before shifting towards efficiency, but NFT markets are already demonstrating periods of sustained efficiency. The technology is also still relatively new, and future improvements are expected. Similarly, the entire NFT ecosystem is expected to change significantly over the next decade.

In addition to expanding this analysis to non-LAND categories, a different theoretical framework can be used to describe changes to the NFT environment. The Fractal Market Hypothesis, for instance, changes the previously described expectation function to vary depending on the participants' level of understanding (Liu & Chen, 2020). This approach is particularly relevant to the NFT space since there is a wide range of familiarity with NFT as a technology itself and related topics of cryptocurrencies, blockchain, and decentralization.

Finally, one category of information was not captured by either Hypothesis 1 or Hypothesis 2: the presence of government policy and regulation. Significant improvements to crypto-market efficiency corresponded with policy changes, but there has been no such equivalent for NFTs yet. As the political, social, and financial environment evolves in relation to the NFT ecosystem, many areas of further research will open up.

Figures

Figure 1: Daily and Weekly Average Prices

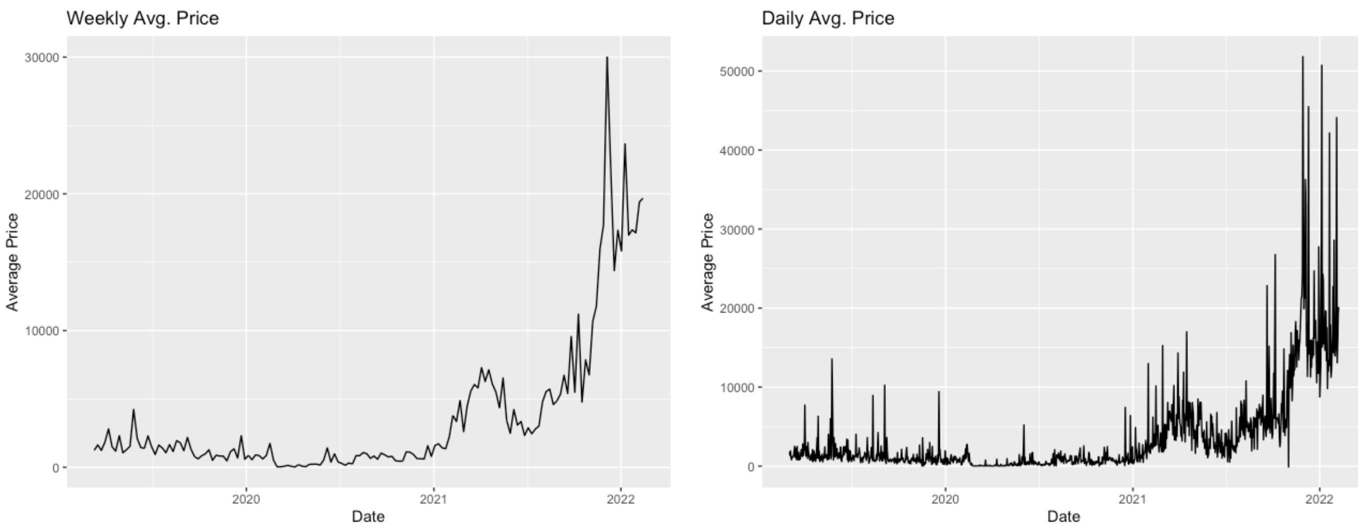


Figure 2a: Boxplot of Outliers from Daily Returns & Weekly Average Returns over 2019-2022

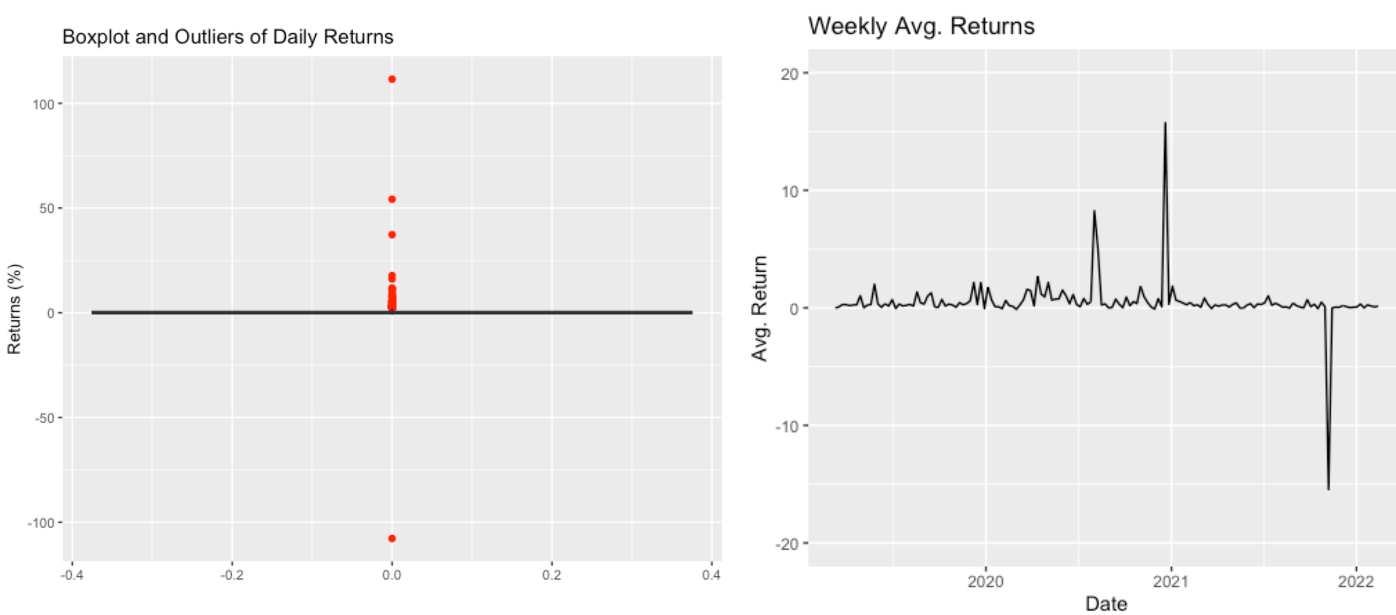


Figure 2a: The boxplot (left) excludes the biggest outlier, which was removed due to its irrelevance (detailed below). There are still are large number of outliers, especially in the positive direction. Average weekly returns (right) are stable for most of 2019, less so in 2020, and stable again for most of 2021.

Figure 2b: Table of Daily Returns Outliers

Date	Return	Date	Return	Date	Return	Date	Return
4/27/19	5.165145	12/31/19	8.34317	5/24/20	7.085616	12/2/20	3.824078
5/17/19	2.429067	1/4/20	5.237525	5/28/20	3.031817	12/17/20	111.552
5/24/19	9.545575	1/6/20	3.044296	6/4/20	4.363685	12/25/20	2.469895
5/28/19	3.61934	1/11/20	3.509442	6/14/20	3.986188	12/27/20	11.73771
6/24/19	3.067455	2/3/20	3.086637	6/18/20	5.987999	12/31/20	2.530857
6/26/19	2.800909	3/8/20	4.606598	6/22/20	2.569485	1/6/21	4.511056
7/10/19	2.291068	3/18/20	6.589565	7/8/20	6.045394	1/12/21	2.472349
8/1/19	2.304157	3/19/20	5.968992	7/15/20	2.36476	1/22/21	2.146251
8/12/19	11.2354	3/22/20	7.968443	7/23/20	3.918501	1/31/21	3.218522
9/4/19	8.732816	3/28/20	2.478643	7/26/20	2.472324	2/28/21	5.529315
9/8/19	9.930662	4/3/20	2.380886	7/29/20	3.334621	4/27/21	3.049377
9/29/19	4.844271	4/10/20	17.76866	8/1/20	54.20589	5/8/21	2.510753
10/26/19	2.229778	4/14/20	2.849624	8/5/20	37.28036	5/25/21	2.788416
11/6/19	3.29431	4/18/20	5.550233	9/12/20	2.396484	6/30/21	2.678816
11/11/19	2.861331	4/25/20	7.563397	10/3/20	5.338377	7/6/21	2.664799
11/20/19	2.317647	4/30/20	16.1178	10/14/20	2.441347	7/10/21	5.353301
11/24/19	3.473795	5/6/20	3.973551	10/18/20	2.332704	7/22/21	3.416054
12/1/19	4.248141	5/11/20	2.250252	10/28/20	11.64406	9/20/21	3.314833
12/6/19	11.23326	5/13/20	2.272333	11/2/20	3.363668	10/23/21	2.434014
12/16/19	7.818606	5/14/20	3.057699	11/4/20	2.686269	11/2/21	−107.751
12/19/19	7.492138	5/21/20	4.196529	11/12/20	2.368302		

Figure 2b: only 83 of the 84 total outliers are shown here since one outlier was cleaned from the dataset

Additional Discussion on Outliers:

November 17, 2019 was the only removed outlier. This day had a return of 119,555 (11,955,500%) due to the previous day having a contribution of $0.0299 from one trade and the subsequent day jumping back up to a daily sales contribution of $10,760.04 across three transactions. The nearly $0.00 contribution mimicked the data that was filtered out at the beginning, thus warranting its removal. Other interesting outliers include the biggest negative outlier (-107.75).

Some volatility is to be expected with NFT purchases given their nascency. Removing the other outliers that did not show signs of unusual behavior would therefore inappropriately alter the efficiency outcomes. Further, comparing this raw data to Dowling's, there are evident differences in summary statistics at both daily and weekly levels.

Figure 3: LAND Time Series Summary Statistics

Table 1: Daily

Statistic	N	Mean	St. Dev.	Min	Max
Avg. Price	1,066	3,632.925	5,896.681	−106.048	51,822.190
Returns	1,066	0.511	5.405	−107.751	111.552

Table 2: Weekly

Statistic	N	Mean	St. Dev.	Min	Max
Avg. Price	154	3,692.914	5,345.910	21.633	30,034.860
Returns	154	0.511	1.995	−15.452	15.750

Figure 4: AP Test & Hurst Score Results

Table 1: Rolling Efficiency Test P-Values, Hurst Scores

Rolling	N	Mean	Median	St. Dev.	Min	Max
AP	115	0.180	0.001	0.218	0.000	0.514
Hurst	115	0.327	0.355	0.152	−0.146	0.639

Figure 5: Combined AP Test (rolling) Results & Information Timeline

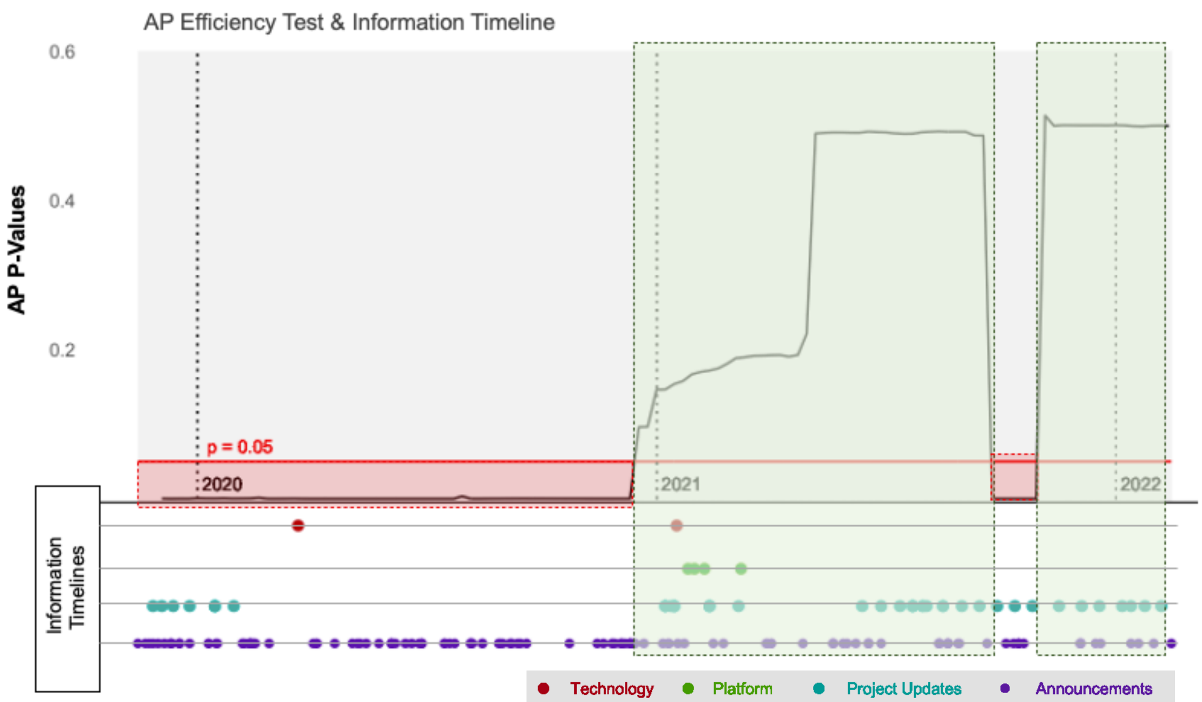


Figure 5: AP test p-values are mapped onto the same x-axis as the four categories of information to create a combined timeline. Periods where the p-value < 0.05 represent periods of market inefficiency.

Figure 6: Corrected empirical Hurst scores (rolling)

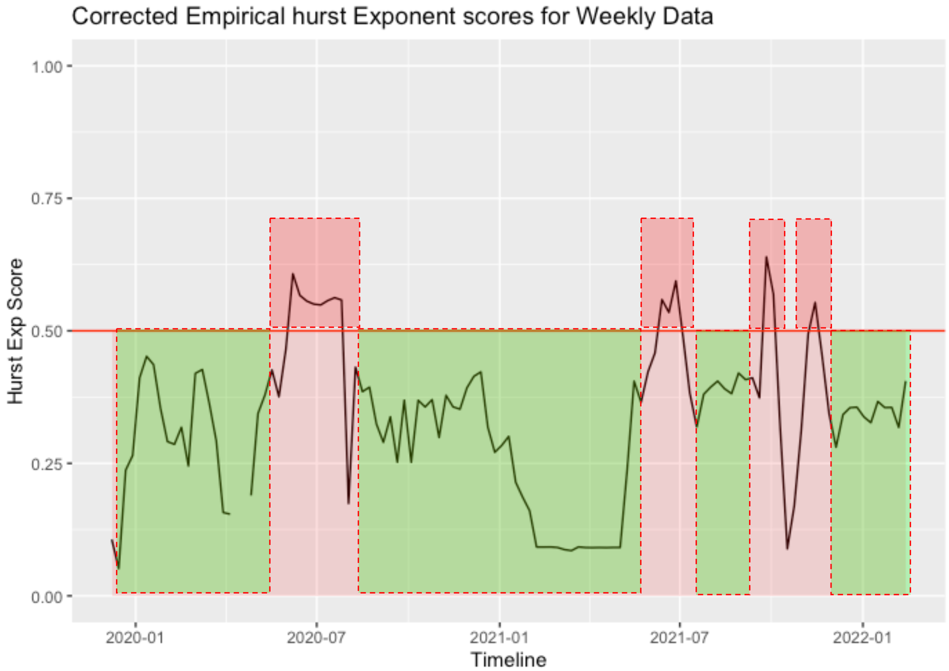


Figure 6: A rolling corrected empirical Hurst score test is applied to the weekly returns data (window of 40-weeks). Exponents that are greater than 0.5 represent periods where the market exhibits dependence or persistence, whereas values below 0.5 represent time series switching behaviors.

Figure 7: Matching the results of AP test p-values and Hurst exponent scores

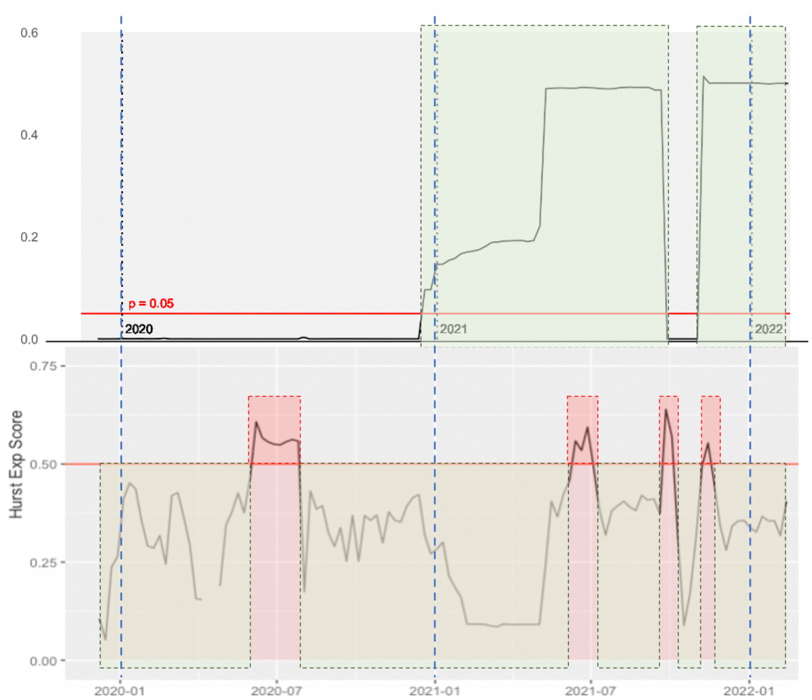


Figure 7: Figure 7 aligns the results from both efficiency tests based on year (indicated by the blue dotted lines). Each y-axis is separate and is slightly different in scale, representing the different tests

Figure 8: Regression Design & Regression Results

Table 1: LINEAR REGRESSIONS OF INFORMATION TYPES ON EFFICIENCY (AP TEST P-VALUES)	
R1. Any Information Type	$P\text{–}Value = \boldsymbol{\beta_1 * Any\ Information} + \beta_2 * ETH + \beta_3 * ETH\text{–}Gas + \beta_4 * \#\ of\ Unique\ Sellers$
R2. Each Information Type	$P\text{–}Value = \boldsymbol{\beta_1 * Technology + \beta_2 * Project\ Updates + \beta_3 * Platform\ Updates + \beta_4 * Announcements} + \beta_5 * ETH + \beta_6 * ETH\text{–}Gas + \beta_7 * \#\ of\ Unique\ Sellers$

Table 2: AP P-Values: R2, R3

	Dependent variable:	
	AP_p	
	(1)	(2)
Any Announcements	0.012 (0.017)	
Platform		−0.089 (0.058)
Technology		−0.020 (0.041)
Project Updates		0.093*** (0.026)
Announcement		−0.043** (0.021)
ETH Open	0.0001** (0.0001)	0.0001** (0.0001)
ETH High	0.0002** (0.0001)	0.0001* (0.0001)
ETH Low	−0.0003*** (0.0001)	−0.0002*** (0.0001)
ETH Volume	0.000* (0.000)	0.000* (0.000)
Gas Open	−30.557 (19.289)	−11.390 (21.449)
Gas High	1.496 (12.919)	6.764 (13.963)
Gas Low	40.381 (28.196)	13.408 (30.977)
Gas Close	−12.988 (24.584)	−16.246 (25.379)
Sellers	0.0001*** (0.00003) 2	0.0001*** (0.00003)
Constant	−0.045 (0.042)	−0.008 (0.048)
Observations	224	224
R^2	0.724	0.745
Adjusted R^2	0.711	0.729
Residual Std. Error	0.117 (df = 213)	0.114 (df = 210)
F Statistic	55.880*** (df = 10; 213)	47.238*** (df = 13; 210)
Note:		*p<0.1; **p<0.05; ***p<0.01

Appendices

Appendix 1: Metaverse Background

Definitions of the Metaverse	
Moy, 2022 JPM	"The metaverse is a **seamless convergence of our physical and digital lives**, creating a unified, virtual community where we can work, play, relax, transact and socialize. The metaverse is still early in its evolution, and there is no singular, all-encompassing definition to which people can turn… **there is no one virtual world but many worlds**, which are taking shape to enable people to deepen and extend social interactions digitally. This is done by adding an immersive, three-dimensional layer to the web, creating more authentic and natural experiences. The metaverse even has the promise of facilitating accessibility from the comfort of the home, breaking down boundaries and democratizing access to key goods, services and experiences."
Joshi, 2021 Vice	*"*A shared virtual space that is interactive, immersive and hyper-realistic" "It's not real at this stage, and won't become real until people have a single location they can go to to get into in a virtual world they could live in," *– Ibrahim Baggili, a cybersecurity expert and the founding director of the Connecticut Institute of Technology at the University of New Haven"*
MatthewBall.vc	"The Metaverse, like the internet, mobile internet, and process of electrification, is a network of interconnected experiences and applications, devices and products, tools and infrastructure"
Associated Press, 2021	"Zuckerberg has described it as a "virtual environment" you can go inside of — instead of just looking at on a screen. Essentially, it's a world of endless, interconnected virtual communities where people can meet, work and play, using virtual reality headsets, augmented reality glasses, smartphone apps or other devices" "It's the **next evolution of connectivity** where all of those things start to come together in a seamless, doppelganger universe, so **you're living your virtual life the same way you're living your physical life**" – Victoria Petrock

In the context of a developing digital environment, it is important to scrutinize the progress being made to develop the metaverse, such as investment into different digital infrastructure. The ultimate and desired state of the metaverse integrates platforms and systems that are not only at the digital level but also extend into the "real-life" world. For example, companies are investing in the development of AR and VR technologies to enable a three-dimensional user experience.

Who are the main players currently leading the development of the metaverse?

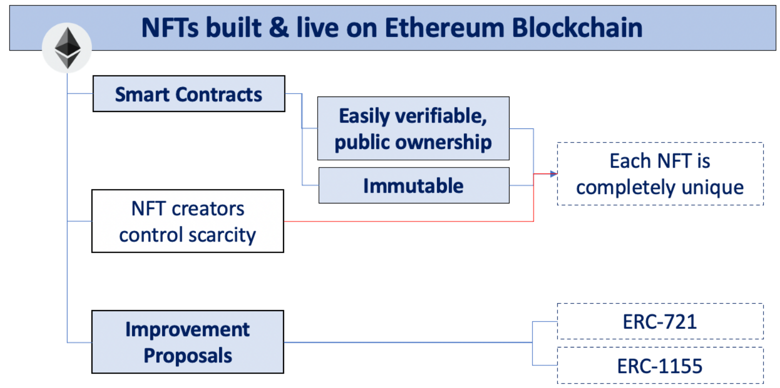
Gaming and online game companies represent nearly 95% of the $10.4B funds that were raised in 2021 by metaverse-related companies (Kunthara, 2021). These companies include industry leaders such as Epic Games, Unity, and Roblox. The other 5% is split between companies developing aspects of augmented reality and virtual worlds, however, there is also demonstrated interest by consumer brands and other industries: Gucci-Roblox (Associated Press, 2021), Chipotle-Roblox (Kunthara, 2021), Warner Music Group-The Sandbox (WMG, 2022), Adidas-The Sandbox (Waterworth, 2022), PwC-The Sandbox (Waterworth, 2022), and Miller-Lite-Decentraland (Molson Coors, 2022). Other major virtual worlds that are comparable to Decentraland and promote the use of NFTs as infrastructure include Somnium Space, The Sandbox, and Cryptovoxels.

Appendix 2: NFTs, Blockchain & Ethereum Background

<table>
<tr><th colspan="2">Non-Fungible Token Background</th></tr>
<tr><td>What does non-fungible mean?</td><td>Non-fungible = “Not interchangeable” because of the object’s “unique properties”

Fungible = “can be exchanged because their value defines them rather than their unique properties”
Unlike currencies, NFTs are not traded as a 1:1 object – while $1 USD is perfectly equivalent to $1 USD, no single NFT is equal to any other NFT. Further, as completely unique assets with different metadata*, NFTs cannot be replicated.
What is Metadata? Information or data that is used to describe other data. For example, the citation of academic sources can be considered metadata: the listing of titles, authors, dates, and publication allow individuals to sort, identify, and access the content of the published material. Similarly, NFTs have properties like an identification system (Cofield, 2022).
Source: Ethereum.org, 2022</td></tr>
<tr><td>What is a non-fungible token (NFT)?</td><td>An NFT is a unique digital token that represents ownership of digital or non-digital assets:
Each NFT is completely unique (non-fungible) and has an owner
NFTs are built off of and live in the Ethereum (ETH) blockchain. Each NFT must be minted, essentially adding the digital asset to the ETH blockchain as an NFT. The ETH blockchain acts “as a public ledger”, allowing for easy and public access of NFT information such as proof of ownership.
The NFT creator controls the scarcity of the NFT</td></tr>
<tr><td>What are smart contracts?

How do NFTs use and benefit from smart contracts?</td><td>The NFT minting process requires the use of ETH smart contracts:
Smart contracts are programs that are stored on Ethereum’s blockchain.
Each contract has a set of specifications written into its code. The contract will be executed automatically, but only upon the specifications of the contract being met.
Smart contracts use “if/when…then…” statements.
Smart Contract Benefits: IBM has identified benefits associated with the use of smart contracts falling into categories of trust and transparency, security, and efficiency. For the sake of this thesis, trustworthy storage and transactions are emphasized as the most important benefits.
Smart contracts uniquely address the issue of uncertainty that comes with traditional contracts
After a transaction is completed, the result cannot be changed
Smart contracts remove the need for intermediaries and transaction enforcement, which can save money and time for all parties involved
There is an aspect of privacy:
“Transactions are tied publicly to a unique cryptographic address” but not your identity
Only parties involved in the contract can see the results.
“Transaction records are encrypted”</td></tr>
</table>

	NFT-Ethereum Features:  Sources: *Ethereum.org, 2022; IBM*
What is ERC-721? ERC-1155?	There are different smart contract standards. NFTs use an ERC-721 or ERC-1155 standard. • The ERC-721 standard is the original standard used for NFTs and initially enabled key functionality like being able to transfer tokens from one account to another, approve transactions, and track and access certain information. • ERC-1155 can be thought of as an updated version of the ERC-721 standard. ERC-1155 manages multiple token types – both fungible and non-fungible tokens. ERC-1155 is thought to improve functionality and efficiency of transactions; transfers, balances, and approvals can occur at a batch-level. Sources: *Ethereum.org, 2022*
What is ETH-Gas? Gas fees?	Gas is the energy of powering a transaction or Ethereum contract. There is an associated gas fee that corresponds with amount of energy needed per transaction and the speed of said transaction. Gas is the main transaction cost of the Ethereum blockchain. The gas price or fee is the amount of Ethereum coin (ETH) paid to the miners, in order to process your transaction. A **gas limit** also exists. This is the limit of the number of operations that are run before the transaction is dropped (i.e the miner runs out of gas).
Categories of NFT classifications: **Art, Collectibles, Games, Metaverse, Utility, and Other**	NFTs can range from standard visuals like JPEGs or GIFs to in-game wearables like user avatar skins, as well as audio, usernames, tickets, and much more. NFTs can also be used for non-digital assets like real-world artwork, real estate, and property rights. Art and Collectible are the most common types of NFTs.

Category	Description
Art	NFTs of digital artworks, such as images, videos, or GIFs
Collectible	NFTs of interest to a collector
Games	NFTs used n competitive games
Utility	NFTs for specific purposes (e.g. secure and decentralized name service)
Metaverse	Piece of virtual worlds
Other	NFTs of small collections that are not included in the other categories

Source*: Nadini et al., 2021 & NonFungible.com*

Appendix 3: Decentraland Background

Decentraland Background:	
What is decentralization? How is the decentralized web defined?	Decentralization generally means distributed control over multiple parties. In the context of the web, decentralization refers to different mechanisms and decisions being distributed over the users or multiple governing bodies. There is a range of rhetoric about decentralizing the web, with a number of these voices describing scenarios of reducing the control that a single or few companies currently have. “The term ‘Decentralized Web’ is being used to refer to a series of technologies that replace or augment current communication protocols, networks, and services and distribute them in a way that is robust against single-actor control or censorship.” – Jason Griffey, Harvard University “The Decentralized Web is like the World Wide Web we have today[…]the only difference is that the underlying architecture is decentralized, so that it becomes much harder for der for any one entity (whether through malicious censorship or accidental failure) to take down any single Web page, website, or service.” – Dr. Jeremy Gillula “The changes will be almost completely transparent to the end user. This is not a bad thing – you don’t want to make users re-learn how to use The Web. The main changes [users] will see is that content will load much, much faster, and access to it will be more reliable (both in terms of speed/latency and in terms of availability). For example, they may never see a 404 page ever again because as long as at least one computer in the world somewhere has the page, it will be possible to view it.” – Kyle Drake, Neocities Source: *Syracuse University*
Basics: 	Decentraland is a virtual world that uses NFTs to make up nearly every aspect of their world. As the name implies, this virtual world is decentralized and is managed by the DAO. The world is made up of a variety of land and districts (see map left). To enter Decentraland, you do not need a digital wallet, but you are limited in your actions, and your progress is not tracked. This is known as the Decentraland Explorer mode, where information is locally stored. Wallets are “a bridge between blockchain and decentralized applications”; each wallet has a public and private key where you respectively can access your assets and sign each transaction. Without a wallet, users cannot participate in events and allows you to hold assets. There are a number of building tools that users and LAND owners can use to create in-world items. Decentraland and the DAO help to add new tools. Decentraland’s native currency is known as MANA, and it is a cryptocurrency. There are only a few ways in which MANA can be purchased:

	1) Buy with USD ($) on most of the popular crypto exchanges, such as Bittrex or Binance 2) Buy with Ethereum on the official Decentraland Marketplace 3) Buy with Ethereum at Uniswap 4) Buy with USD ($) from a CoinCloud ATM (USA only) Source*: NFTplazas.com* Within Decentraland, a user can be represented by a customized avatar, though it is not necessary (i.e. users that do not have a wallet). Avatars can be customized with wearables and skins that can be purchased. Avatars and usernames are NFTs. There are some that are free, but they can be purchased and traded.
LAND, Estates, Scenes, Plazas, and Districts	LAND makes up the virtual land of Decentraland. Each parcel has its own x,y coordinate. LAND parcels are 16m x 16m. LAND can make up larger "neighborhoods" called Estates. Formally, Estates are defined as the "association of two or more directly adjacent parcels of LAND" and cannot be separated by features like roads, plazas, or other parcels. A scene is an "experience" or a little world with its own "entities, components, and systems". Users can build scenes. Districts are themed community spaces but are not publicly owned. Plazas, however, are public and not for sale. Plazas are also where players respawn.
What is the DAO?	DAO = Decentralized Autonomous Organization; As a decentralized body, users are able to determine the policies of Decentraland. These are publicly published in a variety of forums, including Decentraland's own blog. The DAO "owns the most important smart contracts and assets that make up Decentraland – the LAND Contract, the Estates Contract, Wearables, Content Servers and the Marketplace. It also owns a substantial purse of MANA which allows it to be truly autonomous as well as subsidize various operations and initiatives throughout Decentraland"
Who are Decentraland's competitors?	Currently, the major virtual worlds promoting use of NFTs as metaverse infrastructure include Decentraland, Somnium Space, Sandbox, and Cryptovoxels.

Appendix 4: ETH, ETH-Gas Price, Decentraland Sellers, and Decentraland Wallets Data

Figure 4.1: Total Number of Weekly Average Sellers and Unique Market Wallets

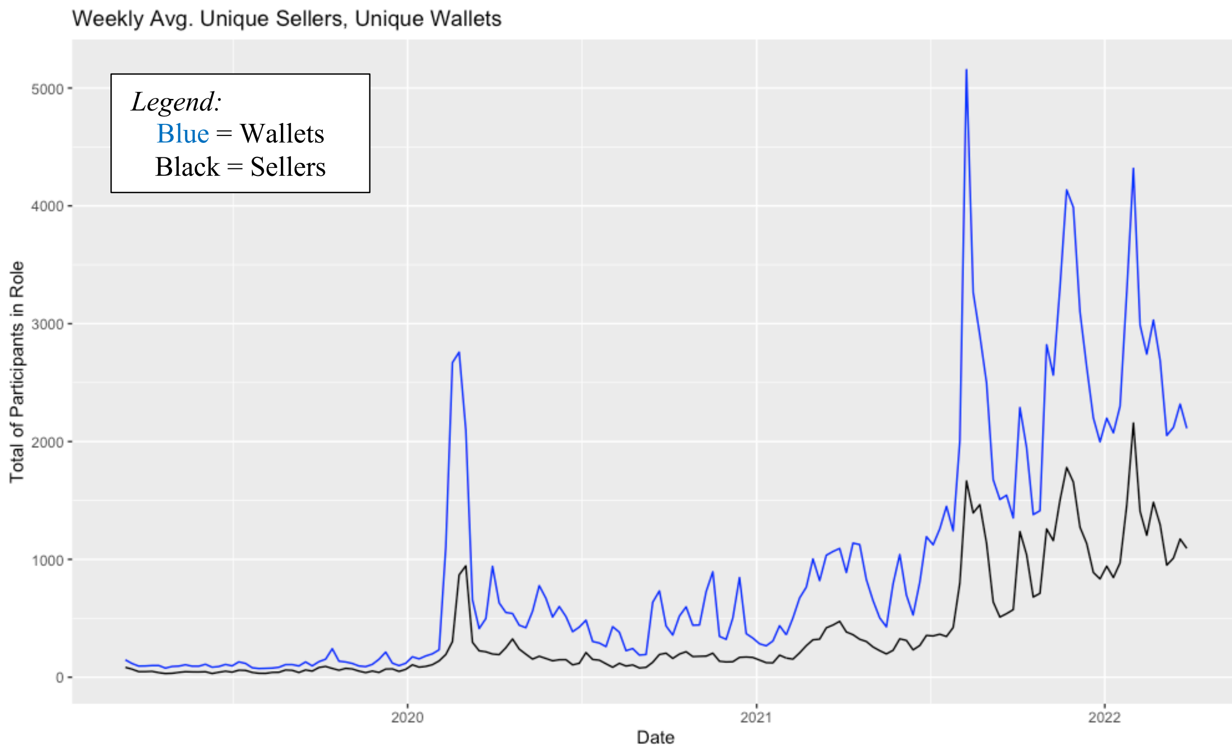


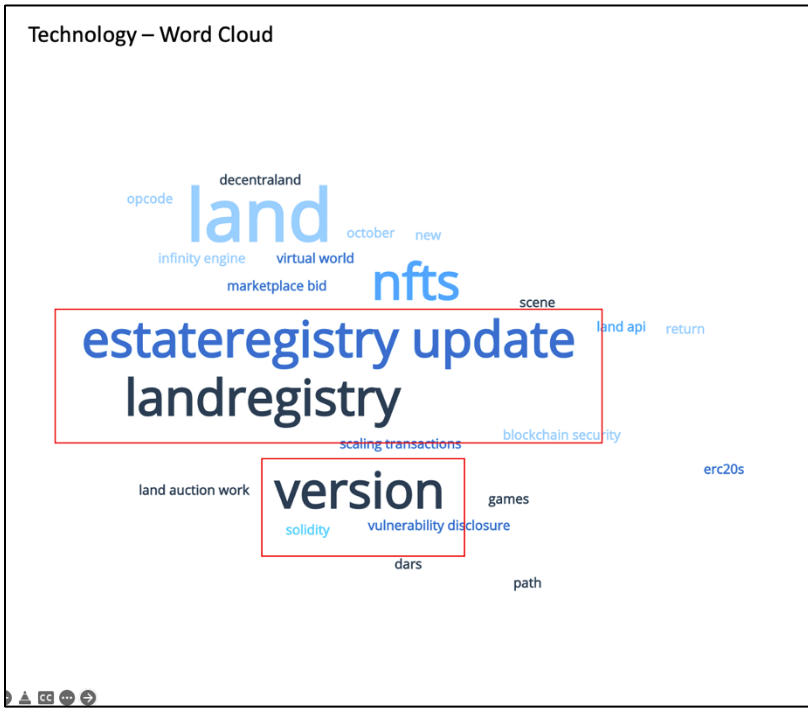
Figure 4.2: Summary Statistics of Decentraland Sellers and Unique Wallets

Table 3: Unique Decentraland Sellers, Wallets

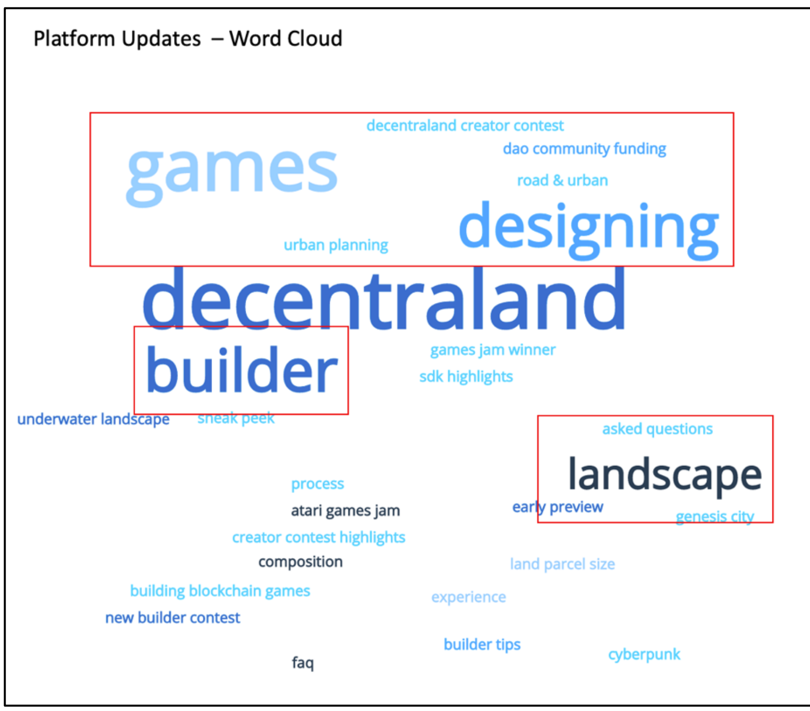
Statistic	N	Mean	St. Dev.	Min	Max
Sellers	160	379.837	457.163	31.000	2,157.286
Wallet	160	934.829	1,043.087	73.571	5,155.857

Appendix 5: Categorization of information with word clouds and relevance scores.

Word clouds and headline term relevance scores were automatically calculated by MonkeyLearn.com – a machine learning platform with text analysis.



Top 13 Word / Phrase	count	relevance
estateregistry update	2	0.976
land auction work	1	0.732
marketplace bid	1	0.488
landregistry	2	0.488
scaling transactions	1	0.488
infinity engine	1	0.488
blockchain security	1	0.488
virtual world	1	0.488
nfts	2	0.488
vulnerability disclosure	1	0.488
version	2	0.488
land api	1	0.488
solidity	1	0.244



Top 12 Word / Phrase (most relevance)	count	relevance
decentraland	**5**	**0.976**
decentraland creator contest	**1**	**0.732**
creator contest highlights	**1**	**0.732**
land parcel size	**1**	**0.732**
dao community funding	**1**	**0.732**
building blockchain games	**1**	**0.732**
games jam winner	**1**	**0.732**
new builder contest	**1**	**0.732**
road & urban	**1**	**0.732**
atari games jam	**1**	**0.732**
early preview	**1**	**0.488**
urban planning	**1**	**0.488**

Project Updates – Word Cloud

Top 19 Word / Phrase (most relevance)	count	relevance
point of interest	49	0.999
dao	176	0.722
last report.\cell	27	0.719
dao committee	53	0.613
vp	125	0.580
dao committee report	11	0.439
last dao committee	11	0.439
catalyst node	11	0.293
wearable publications fees	8	0.280
next steps:\cell	9	0.240
features request	11	0.240
proposal	82	0.239
contract here.\cell	8	0.213
decentraland\'92s map	12	0.213
dao agent	10	0.213
dao facilitator	9	0.213
grant	80	0.188
decentraland foundation	21	0.186
voting power	12	0.186

Announcements – Word Cloud

Top 15 Word / Phrase (most relevance)	count	relevance
decentraland treasure hunt	4	0.992
creator contest	12	0.992
decentraland marketplace	6	0.826
games jam	12	0.826
decentraland	73	0.744
decentraland wearable initiative	3	0.744
land auction	6	0.661
creator contest part	2	0.496
fresh new look	2	0.496
wearable initiative	6	0.496
decentraland public launch	2	0.496
technical update	2	0.331
art week	4	0.331
decentraland partners	4	0.331
decentraland dao	3	0.331
next step	2	0.331

Table 5.1: Information/Headline Types & Definitions

Information Types & Decentraland Definitions	Definitions & Examples	Count
Technology: "The technology behind Decentraland's platform"	Technology headlines as specific to the infrastructure behind Decentraland and NFTs. **Examples:** • *Version 2.0 of the LAND API* • *Decentraland's Path To Toward Scaling transactions* • *Safely Using ERC20s*	**Total:** 14 **Included in Efficiency Tests[13]:** 2
Project Updates: "Releases, developments, and updates"	Project Update headlines are predominantly DAO committee reports, which can range in specific topics but critically impacts the Decentraland platform and LAND usage. • *Guest Post: DAO Committee Report #0018* • *Communication Protocol Improvements* • *Technical Updates – 10 March, 2021*	**Total: 58** **Included:** 30
Platform: "Explore the philosophy and practice of building virtual experiences for Decentraland"	Platform headlines involve the overlap between the social aspects of Announcement headlines but are more specifically about integration-related events of Decentraland, such as the contests and games, which have high relevance rankings (Appendix B). • *Game Jam returns for 2021* • *New Builder Contest: Cyberpunk 2021* • *DAO Community Funding*	**Total: 16** **Included:** 4
Announcements: "The latest news from Decentraland"	Announcement headlines have the greatest range of content from event highlights to new platform features and technical updates. There is no documentation on how Decentraland categorizes information in Announcements from others. Given the timeline and frequency of posts of *Announcements* but blatant gap in Technology and Platform updates, it is possible that content is shared between *Announcement* and other categories. • *Metaverse Fashion Week is here!* • *The In-World Builder is Now Open to Everyone!* • *Animoca Brands Partner with Decentraland*	**Total: 176** **Included:** 99

Source: Decentraland.org

[13] "Included" represents the number of headlines of this information type that were included in the timeframe of the efficiency tests. The efficiency tests are run on weekly data, so if multiple posts occur in one week, only one dot will show up on the timeline.

Appendix 6: LAND Time Series Data Preparation

Given the aggregated nature of the exported LAND data, average daily prices are calculated by:

1. Taking the day-to-day difference in both total sale ($) value and daily total transaction volumes
2. Dividing daily sale ($) contribution by daily transaction volume

$$\text{Avg. Daily Price (ADP)} = \frac{\Delta \text{ Daily Aggregated Total Sale Value (\$)}}{\Delta \text{ Daily Aggregated Total Transaction Volume}}$$

3. Daily percent change, also referred to as "returns" throughout this paper, are then calculated as:

$$\text{Daily Return} = \frac{\text{ADP}_{\text{n+1}} \text{ - } \text{ADP}_{\text{n}}}{\text{ADP}_{\text{n}}}$$

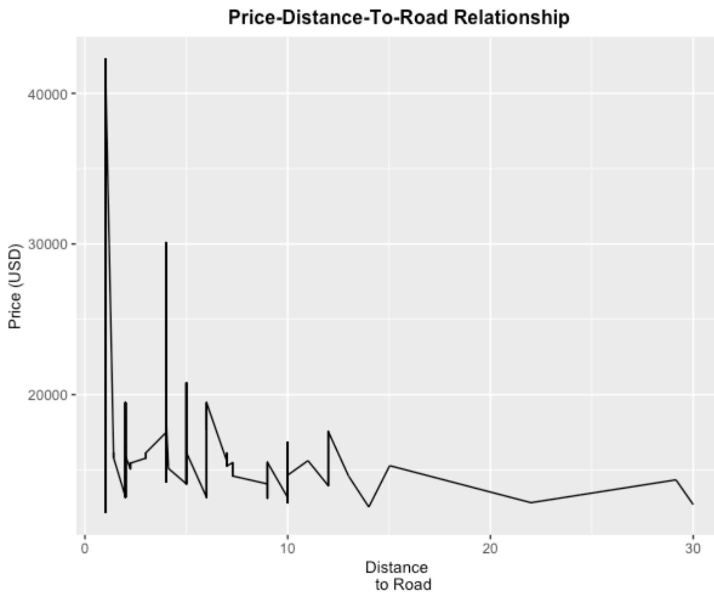
4. Finally, daily returns are averaged to get a dataset of weekly returns

Appendix 7: Geographical LAND Features

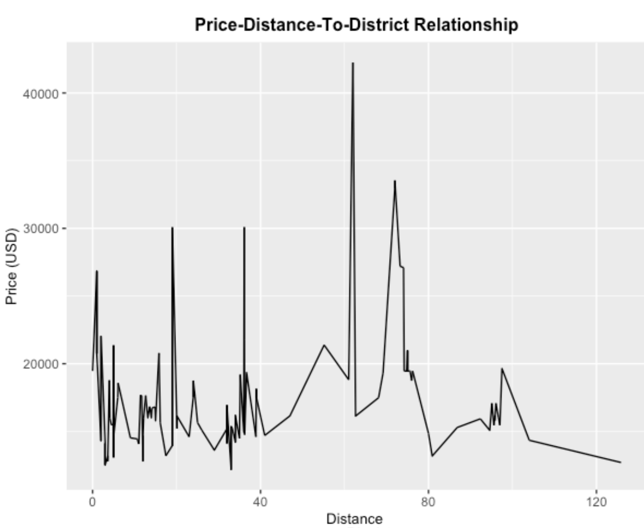
The geographical features of interest include distance to roads, distance to district, distance to plaza, closest plaza, and closest district. These features can be described as measures of a parcel's accessibility and visibility. Higher accessibility and visibility are considered to correspond with higher value because these areas allow for easier interaction with other users.

Though not substantial enough to run a full regression, a couple weeks' worth of sale data was scraped from NonFungible.com, including prices, times, and geographical features of the LAND sales. Corroborating Goldberg et al. (2021), there is an apparent relationship between price and LAND geographical features.

Price to Distance-to-Road: The shorter the distance to a road, the higher the price.



Price to Distance-to-District: There is a less apparent relationship between price and distance to district because distance to district does not incorporate the relative importance of different districts. The list of districts and their average prices provides a better metric for how different districts are priced.



District	Avg. Price	Avg. Distance to District
Fluffy DC	26820.00	1.00000
The Crypto Valley	22245.44	41.50333
District X	22015.27	2.00000
Festival Land	20788.32	15.81000
Yoga Center	19462.74	0.00000
Dragon City	18061.69	46.72900
Mother Russia Land	17502.04	16.23000
Star Kingdom	17482.36	55.45906
Fashion Street	17235.65	39.25200
Voltaire	16125.00	8.83000
Design Quarter	15981.04	4.12000
Dragon Kingdom	15160.02	4.80500
Aetherian City	15104.49	12.66667
The Forest	14522.15	9.00000
Star City	14081.69	3.00000
Vegas City	13449.81	11.50000
Engineering Park	12540.40	3.00000

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