THREE ESSAYS ON CRYPTOCURRENCY

by

SHENG-FENG HSIEH

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and approved by

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ABSTRACT OF THE DISSERTATION

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By SHENG-FENG HSIEH

Dissertation Director:
Dr. Miklos A. Vasarhelyi

This dissertation is composed of three essays that explore the fair value measurement for cryptocurrencies and the auditing of the crypto asset ecosystem. The first essay proposes a fair value measurement methodology for actively traded cryptocurrency pairs. The methodology is able to dynamically and automatically identify the principal market for the targeted cryptocurrency pair and determine its fair value, consistently following the accounting standards of fair value measurement under ASC 820 and IFRS 13. The fair value measures derived from the methodology, the unadjusted quoted prices, are classified as level 1 in the fair value hierarchy.

The second essay, following the methodology from the first essay, designs another fair value measurement methodology for thinly traded cryptocurrency pairs. The methodology would dynamically identify the “optimal path” for the targeted cryptocurrency pair with other mainstream cryptocurrencies as intermediaries, supported by prior literature indicated that higher transaction volume would aggregate more private and public market information on equilibrium prices. The empirical demonstration from this methodology is able to generate more frequent and timely fair value measures for thinly traded cryptocurrencies that have few or even no direct trades to the reporting
currencies. The methodology continues to follow ASC 820 and IFRS 13, and the fair value measures from this methodology would be classified as level 2 in the fair value hierarchy.

The third essay proposes a comprehensive framework for auditing crypto asset ecosystem, elaborates on the new challenges and risks for audits of the crypto asset ecosystem, and discusses the auditing issues for entities involving in decentralized finance (DeFi) activities. The vigorously evolving crypto asset ecosystem brings not only challenges and risks but also new assurance opportunities to the auditing practice after completely identifying and addressing those critical issues and challenges.
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CHAPTER 1: INTRODUCTION

After Nakamoto (2008) described the mechanism of a peer-to-peer payment system without going through centralized financial institutes, bitcoin, the first-created cryptocurrency, gradually attracted people’s attention, stimulating the subsequent development of other cryptocurrencies and structuring the cryptocurrency ecosystem in the last decade. The total market capitalization of bitcoins (all cryptocurrencies) has reached the value of approximately 1.184 (2.269) trillion USD on April 15, 2021\(^1\). More and more entities, including general companies, payment companies, hedge funds, etc., are progressively accepting, trading, and investing in cryptocurrencies. Distinct from other typical financial instruments, cryptocurrencies can be transacted on many exchanges worldwide, establishing the unique nature of fragmented markets. Therefore, how to automatically, dynamically, and representatively measure the fair value of cryptocurrencies as the basis for financial reporting becomes a critical issue that should be addressed. Moreover, how to provide financial reporting assurance for entities materially involving with the complex cryptocurrency ecosystem that comprises various centralized and decentralized counterparties should also be discussed. This dissertation, composed of three individual essays, aims to cover the above two issues by proposing two fair value measurement methodologies for actively traded and thinly traded cryptocurrencies and a framework for auditing crypto asset ecosystem.

The first essay aims to propose a fair value measurement methodology for actively traded cryptocurrencies to dynamically determine the principal market of a currency pair

\(^1\) The information about the total market capitalization of bitcoins (all cryptocurrencies) was derived from CoinMarketCap website, available at: https://coinmarketcap.com/currencies/bitcoin/ (https://coinmarketcap.com/charts/).
and its fair value. The static characteristics, the relative long-term (monthly) trading volume, and the real-time trading time decay of cryptocurrency exchanges are considered in the methodology. The methodology provides unadjusted market prices (level 1 inputs) as fair value measures and consistently complies with the accounting standard about fair value measurement under Accounting Standard Codification (ASC) 820 in the U.S. and International Financial Reporting Standard (IFRS) 13 for other countries.

On the basis of the methodology in essay one, the second essay designs another fair value measurement methodology for thinly traded cryptocurrency pairs, which might have few or even no actual trades directly to the reporting currency (which is typically the USD). The theoretical foundation of the methodology is that the higher transaction volume on financial markets, the higher market credibility (Nasiri, Bektas, and Jafari 2018), and the more market information (Bianchi and Dickerson 2020; Brandvold, Molnár, Vagstad, and Valstad 2015; Makarov and Schoar 2019; Park and Chai 2020; Sockin and Xiong 2020) to the equilibrium prices. The methodology translates the targeted cryptocurrency to the reporting currency through the optimal path, which is dynamically selected from different path candidates with intermediary mainstream cryptocurrencies with much higher transaction volume, providing level 2 fair value measures.

The objective of the third essay is to propose a comprehensive framework for auditing the crypto asset ecosystem. Moreover, the complex relationship between the entity and the crypto asset ecosystem comprising centralized and decentralized counterparties is illustrated, which is essential to identify and discuss specific risks and challenges that auditors should pay attention to. This essay also discusses the auditing for entities involving in Decentralized Finance (DeFi) activities, a highly developing and evolving area in recent
years.

This dissertation contributes to the literature and the practice by addressing fair value measurement for cryptocurrencies and proposing a framework for auditing the crypto asset ecosystem. Two proposed methodologies and the framework would be beneficial for different stakeholders, including general companies, hedge funds, stakeholders in the crypto asset ecosystem, service providers, accounting firms, and standard setters.
CHAPTER 2: DYNAMIC PRINCIPAL MARKET DETERMINATION: 
FAIR VALUE MEASUREMENT OF CRYPTOCURRENCY

2.1 Introduction

The market for cryptocurrencies is significant and is expected to expand rapidly over the next few years. In early 2019, the market capitalization of crypto assets was over $90 billion (European Central Bank 2019). Cryptocurrencies are currently measured at fair value, with gains and losses reported in earnings for entities holding such assets as qualified investment companies. The same accounting treatment is afforded to broker-dealers who own cryptocurrencies. Therefore, there is a need to properly measure cryptocurrencies at fair value.

ASC 820 and IFRS 13 are the most recent guidelines designed to establish a uniform definition of "fair value" and provide a consistent framework for its application. However, with fragmented markets, it may be difficult to determine how existing standards can be used to reflect market realities. In particular, the principal or most advantageous markets may be difficult to establish in fragmented, globally dispersed markets.

The objective of this essay is to develop a methodology to identify the principal market to be used for proper fair value measurement, classification, and disclosure of investments in cryptocurrencies and to ensure that this methodology is aligned with ASC 820 and IFRS 13.

This essay is organized as follows. Following the introduction, we next provide an overview of the relevant standards governing fair value measurement. Then, our proposed methodology is developed, discussed and illustrated in the following sections. Next, we conduct an empirical test that demonstrates the model’s ability to properly discern the
principal market. The final section of this essay provides a brief summary and conclusions.

2.2 Fair Value Measures for Financial Reporting

The definition of fair value for financial reporting is based on an exit price concept. The exit or exchange price is defined as the price that can be obtained on the disposal of an asset or the amount paid for the transfer of an obligation in an orderly transaction between market participants at the measurement date. The concept of an orderly transaction assumes that the hypothetical transaction used to measure fair value will be one in which the seller of an asset or the transferor of an obligation has the usual access to markets would not assume a forced sale as in the case of a liquidation or bankruptcy.

When measuring assets to be used in exchange at fair value, we must identify the principal market (FASB 2011; IASB 2011). Only if a principal market cannot be identified, then the most advantageous market should be used. As in the case of cryptocurrencies, assets may be traded in different active exchanges at different prices. If an entity enters transactions in multiple exchanges and can access prices in those exchanges for the asset at the measurement date, those exchanges can be assessed in terms of volume and level of activity.

According to current accounting standards, the principal market is the market with the greatest volume and level of activity for the asset (FASB 2011; IASB 2011). The fair value of the asset would be measured using the price that would be received in that market. The main objective of our model is to dynamically identify the principal market and once that market is obtained, source all price information employed either as a spot or as a
benchmark from that exchange$^2$.

Specifically, ASC 820 (FASB 2011) indicates that if there is a principal market for the asset or liability, the fair value measurement shall represent the price in that market (whether that price is directly observable or estimated using another valuation technique), even if the price in a different market is potentially more advantageous at the measurement date. Moreover, in order to be relevant, the benchmark price should be at least approximately tradable on an accessible market.

2.3 The Fair Value Model for Financial Reporting: An Application of FASB ASC 820

The fair value model for financial reporting requires that we follow several steps in determining the fair value of an asset or obligation. In the case of cryptocurrency, the unit of account is simply one unit of the digital currency measured as either a single digital coin or a fraction of a digital coin. In addition, because cryptocurrencies cannot be used in production or in conjunction with other assets, the highest and best use is in exchange. The valuation technique used in the case of cryptocurrencies is the market approach.

As a result of employing the market approach, our first valuation issue is to determine the principal or most advantageous market at a specific point in time. When we identify a principal or most advantageous market, we will use a market approach that identifies observed prices. Because the identified price is an observed input, the reliability of the inputs used in our fair value measure should be a Level 1 measure and disclosed as such in the fair value hierarchy.

$^2$ We use a spot price in our illustration found in Section 2.4 of this essay. However, benchmarking or an averaging technique could also be employed after we designate the principal exchange.
2.3.1 Determining the Principal Market and Fair Value

The primary purpose of this essay is to develop a methodology that first, identifies the principal market and second, extracts a fair value for financial reporting purposes from that principal market. As will be discussed, the markets for cryptocurrencies are fragmented and may have limited and/or inaccurate measures of volume. In addition, the reliability of the data extracted from certain exchanges may have to be used with caution. However, we believe that several factors can be considered to improve the reliability of the volume and price information obtained from the cryptocurrency exchanges. These factors include the level of exchange oversight, microstructure efficiency, transparency, and data integrity. Our proposed methodology will take these and other factors into account and allow for the efficient identification of the principal market and the determination of the fair value of the cryptocurrency at the measurement date.\(^3\)

2.3.2 Market Fragmentation and the Challenge of Identifying the Principal Market

As noted earlier, one of the key characteristics of the cryptocurrency market is its high level of fragmentation. The main cryptocurrencies, Bitcoin and Ethereum, are traded on over 100 exchanges worldwide, with a large variety of underlying mechanisms. As such, the possibility exists that there may be no single exchange that is dominant in terms of volume, price discovery, or any other attribute that would make it an obvious principal market.

Moreover, either due to the difference in trading rules and/or to the lack of active arbitrageurs at the current phase of market development for many exchanges, there can be

\(^3\) The same approach to determine a principal market can be used for both financial reporting and tax purposes.
significant differences in the prices between the exchanges, and due to geographic disparity, a constant shift in the volume prominence throughout the day. Some of the less-liquid currencies are traded over one or two exchanges, in particular currencies that are issued by the exchanges themselves. Most of the liquid currencies are likewise traded over several different exchanges with a likelihood that no single exchange can be designated as the principal market.

Several other exchange-traded assets have either a designated principal exchange or a de facto principal exchange that dominates all other exchanges in terms of volume or visibility and serves as a focal point in the price discovery process. The situation is quite different for cryptocurrency, where there may not exist a single dominant exchange in terms of volume.

To illustrate, Table 1 shows the average daily volume over the first quarter of 2019 on four hypothetical exchanges. As we can see, none of these exchanges dominate the market. Assuming that only four exchanges exist, Exchange 1 controls less than 50% of the market, and that percentage level may not be considered significant enough to dominate the entire market. Moreover, volume reporting does not follow any standard, and it has long been suspected that some of the numbers reported by some of the exchanges do not reflect real volume.\footnote{Available at: https://coinmarketcap.com/exchanges/volume/24-hour/. However, as noted by Bitwise in their presentation to the SEC, there are currently 10 reliable exchanges for Bitcoin (Bitwise 2019).}
Table 1: Bitcoin-US Dollar Average Daily Volumes (in millions of US Dollars)

<table>
<thead>
<tr>
<th>Average Daily Bitcoin-USD Volume (Millions of US Dollars) Q1 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchange 1</td>
</tr>
<tr>
<td>Exchange 2</td>
</tr>
<tr>
<td>Exchange 3</td>
</tr>
<tr>
<td>Exchange 4</td>
</tr>
</tbody>
</table>

1. The table reflects the average daily volume of four hypothetical exchanges used in our simulation.
2. We assume that the average daily volume is measured for the first quarter of 2019.

It is important to note that the time of day over which we measure fair value is also critical in the determination of a principal exchange. Depending on the time of day, some exchanges may dominate certain hours while other exchanges dominate others. Figure 1 shows the average intra-day volume of Bitcoin-US Dollar trades in millions of dollars in trades per hour (time of day). The data presented in Figure 1 indicate that during certain hours Exchange 4 is dominant, while during other times during the day, Exchanges 1 and 2 have more significant trades.
Figure 1 reflects the simulated data for our four exchanges. The volume indicated is the average intra-day volume of Bitcoin-USD trades per hour.

Given the fragmented nature and variability noted on some of the cryptocurrency exchanges, it may be difficult to identify a principal market. So, careful attention must be given to the accounting guidelines for valuation at fair value, and proper interpretations must be made for this setting.

Following both US GAAP and IFRS requirements in such cases, when a principal market cannot be identified, we must consider the most advantageous market from the point of view of the holder of the assets (i.e., the market participant). The most advantageous market is the market where the entity would yield the highest net amount received on sale, after deducting estimated transaction costs. Note that although transaction costs are used to determine the most advantageous market, they are not included in prices...
used in determining fair value.

There are various considerations as to what would be the principal or most advantageous exchange for a particular currency pair and a particular investor, including the jurisdiction under which an exchange operates, the level of regulation and other exchange oversight, as well as liquidity and mechanism details.

As noted earlier, our proposed fair value measurement methodology for cryptocurrencies is a valuation technique that utilizes observable inputs, prices, and other relevant transaction data directly from exchanges. Therefore, a critical step in the valuation process is to identify either the principal or the most advantageous market.

We believe that the use of a principal market is most appropriate because a fair value measurement generally assumes that transactions take place in a principal market. Only in the absence of a principal market should the most advantageous market be used\(^5\).

Determination of a principal market is based on independent analyses performed at the organizational level and can vary among entities and businesses within a single entity. So, the identification of a principal market is entity-specific and can vary among specific entities within a consolidated group.

The standards do not provide specific guidance regarding how an entity should designate a principal market. In addition, the entity is not required to engage in an extensive search of all markets and should incorporate readily available information such as volume.

---

\(^5\) As noted earlier, the use of a principal market is preferred under GAAP and we also believe that a principal market should be identified in the case of the cryptocurrency exchanges. The use of the alternative, the most advantageous market, is questionable given the current stage of development of the cryptocurrency exchanges. Specifically, the exchange that yields the highest net amount on sale of a cryptocurrency could be an exchange that although active, could lack proper oversight or generate data that is uncertain as to quality or integrity. One would tend to question whether an exchange with these characteristics is in fact “most advantageous” from the standpoint of the market participant.
Overall, the principal market is typically presumed to be the market or markets that the entity will normally use to sell an asset or transfer a liability. It is likely, particularly in the case of cryptocurrencies, that an entity will need to reassess its designated principal market as events or activities change, and the information extracted from various markets must be both available and reliable.

Therefore, we must ensure that the data extracted from the designated principal market are as reliable as possible. Due to the rapid shifts in trading volume noted earlier and the fact that some exchanges lack proper oversight or are unregulated, the exchange data reported may not be highly reliable. As a result, we need to develop a systematic methodology that can be used to score and rank the exchanges and ultimately identify the principal market. Specifically, we propose a methodology to designate a principal market by considering characteristics such as exchange oversight, microstructure efficiency, transparency, data integrity, frequency of trades, and overall volume. By taking these characteristics into account, the fair value extracted from the designated principal market will be more reliable.

The proposed methodology for determining a principal market is presented in the next section of this essay.

2.3.3 Proposed Methodology to Determine a Principal Market and Measure the Spot Fair Value

Our proposed methodology to designate a principal market for fair value measurement uses a ranking approach that considers several exchange characteristics,

---

6 We are using the spot price for illustrative purposes, but other benchmarks or averaging techniques can be used to determine the price or fair value at the reporting date.
including oversight, transaction volume, and frequency of trades. Specifically, to rank the credibility and quality of each exchange, we dynamically assign a score to the key characteristics for each exchange by employing a five-step process. The five-step weighting process for identifying a principal exchange and the last price on that exchange is presented below.

**Step 1:** Assign each exchange for each pair of currencies a *Base Exchange Score (BES)* reflecting static exchange characteristics such as oversight, microstructure, and technology.

**Step 2:** Adjust the BES based on the relative monthly volume of each exchange. This new score is the *Volume Adjusted Score (VAS).*

**Step 3:** Decay the adjusted score based on the time passed since the last trade on the exchange. Here, we are assessing the level of activity in the market by considering the frequency of trades. The decay factor reflects the time since the last trade on the exchange. This is the final *Decayed Volume Adjusted Score (DVAS).*

**Step 4:** Rank the exchanges by the DVAS score and designate the highest-ranking exchange as the *Principal Market* for that point in time.

**Step 5:** Designate the price of the last transaction on the principal market as the primary spot price at that point of time.

That is, after we designate the principal market, the spot fair value assigned to the cryptocurrency is measured at the time and date of the financial report. The mathematical specification of this process, along with illustrations, are presented in the following sections.

---

7 We call this the “freshness” of the data.
base exchange score (BES).

The Base Exchange Score (BES) reflects the fundamentals of an exchange, given equal volume and equal decay. The BES will determine which exchange should be designated as the principal market at a given point of time. This score is determined by computing a weighted average of the values assigned to four different exchange characteristics. These characteristics are:

1. Exchange Oversight
2. Microstructure Efficiency
3. Data Transparency
4. Data Integrity

exchange oversight.

This score reflects the rules in place to protect and to give access to the investor. The score assigned for exchange oversight will depend on parameters such as jurisdiction, regulation, “Know Your Customer and Anti-Money Laundering Compliance” (KYC/AML), etc. For example, we account for “jurisdiction” by using a basic hierarchy. Here, a Level 1 jurisdiction is assigned a score of 100, and that score is reduced by 20 points for each subsequent level\(^8\). A sample jurisdiction hierarchy is presented in Table 2.

---

\(^8\) The hierarchy is based on the S&P Sovereign Foreign-Currency Ratings, S&P Institutional and Economic assessment and whether the local currency is restricted.
Table 2: Exchange Oversight-Jurisdiction Hierarchy

<table>
<thead>
<tr>
<th>Level</th>
<th>Jurisdiction</th>
<th>Oversight Score [$s^{ov}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>US, EU, Japan, Switzerland, Australia, New Zealand, Singapore</td>
<td>100</td>
</tr>
<tr>
<td>Level 2</td>
<td>UK, Israel, South Korea, Hong Kong</td>
<td>80</td>
</tr>
<tr>
<td>Level 3</td>
<td>Latam, China, India, Russia, Eastern Europe</td>
<td>60</td>
</tr>
<tr>
<td>Level 4</td>
<td>South Africa, South East Asia</td>
<td>40</td>
</tr>
<tr>
<td>Level 5</td>
<td>Africa, Middle East</td>
<td>20</td>
</tr>
</tbody>
</table>

1. The oversight scores are developed from our simulation using factors such as location and regulation.

2. In addition, the levels were developed by referring to S&P Sovereign Foreign-Currency Ratings, S&P Institutional and Economic assessment, and if the local currency is restricted.

**Microstructure efficiency.**

The second exchange characteristic is microstructure efficiency. Based on prior research (Roll 1984), we take the effective bid-ask spread as a proxy for efficiency. For each exchange and currency pair, we take an estimate of the “effective spread”\(^9\) relative to the price in “pips.”\(^10\) The score for exchange \(i = 0, \ldots, n\) is computed as:

\[
S_{i}^{eff} = 100 \times \frac{\max_j (sp_j) - sp_i}{\max_j (sp_j) - \min_j (sp_j)}
\]  (1)

\(^9\) As the ticker size is very small for most cryptocurrencies on most exchanges, the gap between best bid and best ask can also be very small. However, as is often the case, there are extremely low volumes on these quotes and, as such, the spreads do not reflect actual transactions costs or efficiency. A better measure would be the price obtained if you run the book in both directions on a reasonable size order (say 1 XBT for a XBT-USD transaction). We refer to this spread as the *effective spread*.

\(^{10}\) Pip is the “percentage in points” and represents the smallest move possible based on exchange conventions.
Where $sp_0, sp_1, ..., sp_n$ are the spreads of the relevant exchanges measured as pips (1/10,000) of the asset price.

**data transparency.**

Transparency is the term used for a quality score that is determined by the level of detail of the data offered by exchange and is based on the hierarchy provided in Table 3.

<table>
<thead>
<tr>
<th>Level</th>
<th>Data Detail</th>
<th>Score $[s_{\text{tran}}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Orders</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Order Book / TAQ$^{11}$</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>Trades</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>Candles</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>None</td>
<td>20</td>
</tr>
</tbody>
</table>

1. The transparency hierarchy is developed based on the data detail available and the integrity of the data extracted. The integrity score is simulated by including the impact of order reconstruction, minute volume matching, and daily volume matching.
2. The data integrity score included in this simulation is a weighted average of order reconstruction and the time scales. The weights are based on the relative importance of each factor assigned by the entity.

Similar to the jurisdiction hierarchy, Level 1, the highest level in the transparency hierarchy, is assigned 100 points and is reduced by 20 points for each subsequent lower level. Exchanges considered within the transparency hierarchy are also evaluated in terms of data integrity by computing a data integrity score that includes the impact of order reconstruction and the time scales. The weights are based on the relative importance of each factor assigned by the entity.

---

$^{11}$ This is a limit order book or the aggregate inside quote for each exchange.
reconstruction, minute volume matching, and daily volume matching. The data integrity score is discussed below.

**data integrity.**

Integrity is evaluated on three-time scales, on tick level, short-term (minutes), and daily, with the following scores:

\[ s_{ord} \] - order reconstruction

\[ s_{minute} \] - minute volume matching

\[ s_{day} \] - daily volume matching

A weighted average of these scores will give the data integrity score. The weights are based on the *relative importance* of each factor at a point in time as assessed by the entity. Relative importance is a subjective term, which may be weighted differently by different practitioners and valuation specialists. ASC 820 does not provide guidance regarding the use a specific approach but only requires the consistent use of the methodology selected. The weights used in this essay are based on extensive discussions with practitioners, valuation specialists, and crypto asset portfolio managers as to the relative importance they may attribute to each factor. Determination of weights merit an informed discussion once the structure and regulation of this market become clearer and further experience with the methodology is gained.

\[ s_{int} = \omega_{ord} \cdot s_{ord} + \omega_{minute} \cdot s_{minute} + \omega_{day} \cdot s_{day} \] (2)
These scores, $s_{ord}$, $s_{minute}$, and $s_{day}$, are defined in the same way in the following sections.

**order reconstruction.**

Exchanges with Level 1 transparency will provide for each transaction a corresponding “Order ID” with size information on the order. An order for which we can identify all transactions that were completed as part of the order (including cancelation) is considered a “reconstructed order”. Let the volume-weighted fraction of reconstructed orders be $p_{ord} > 0$ then the corresponding score is:

$$s_{ord} = 100 \times (1 - e^{-\nu p_{ord}}) \text{ for } \nu > 0. \quad (3)$$

**minute volume matching.**

Level 3 transparency will provide tick by tick data for trades, level 4 transparency will provide candle data. Let $p_{min} > 0$ be the fraction of the volume on the time bar accounted by individual trades, then the corresponding score is:

$$s_{minute} = 100 \times (1 - e^{-\nu p_{min}}) \text{ for } \nu > 0. \quad (4)$$

**daily volume matching.**

Daily volume matching is the same as the minute volume matching except that it is determined for daily volume.
2.3.4 Mathematical Specification of the Principal Market Designation Process

The computations below are all done per currency, and as a result, even the BES could vary from one currency to another. Although top exchanges generally tend to be ranked high on all the currencies they serve.

The mathematical specification of the principal market designation process is presented below.

**Step 1:** The BES for exchange $ex_1, ..., ex_n$ is computed as follows:

$$s_{ex_i}^{BES} = \omega_{ov} \cdot s_{ex_i}^{ov} + \omega_{eff} \cdot s_{ex_i}^{eff} + \omega_{tran} \cdot s_{ex_i}^{tran} + \omega_{int} \cdot s_{ex_i}^{int}$$  \(5\)

Again, the weights are based on the relative importance of each factor and their direct impact on the overall quality of the exchange based on managements’ assessment. For example, it is likely that oversight and efficiency would typically have more weight than transparency and data integrity.

**Step 2:** For computing the VAS let $vol_0, ..., vol_n$ be the monthly volumes of these exchanges, the VAS is then calculated as:

$$s_{ex_i}^{VAS} = \frac{vol_{ex_i}}{\sum_j vol_{ex_j}} \cdot s_{ex_i}^{BES}$$  \(6\)

**Step 3:** For computing the DVAS at time $T$, let $\{ p_t^{ex_i} : t > 0 \}$ the time series of prices provided by exchange $ex_i$, and let $t_{ex_i}$ the time stamp on the most recent trade observed
on the exchange, namely \( t_{ex_i} = \max \{ 0 < t < T : \{ p_{t}^{ex_i} : t < \tau < T \} \neq \emptyset \} \), then the decayed weight is given by:

\[
S_{T,ex_j}^{DVAS} = e^{-|T-t_{ex}|} \cdot S_{ex_i}^{VAS}
\] (7)

**Step 4**: The principal market is the exchange with the highest DVAS,

\[
exprincipal = \arg\max\{S_{T,ex_j}^{DVAS} : ex_1, ..., ex_n\}
\] (8)

**Step 5**: Prime spot price is the last price as of time \( T \) on the principal exchange:

\[
p_T = p_{exprincipal}^{exprincipal}
\] (9)

### 2.4 Illustration: Identification of the Principal Market and Assigning a Fair Value

In this section, we demonstrate how to identify a principal exchange and assign a fair value for financial reporting by using our methodology.

We assume the market is made up of four exchanges operating in different locations worldwide. The numbers and scores attributed to these exchanges are for illustrative purposes only\(^{12}\). We also assume that we will measure a spot price of a cryptocurrency at the end of the first quarter. The following illustration will follow our five-step methodology using data created for the four hypothetical exchanges. The methodology will be used to determine the principal market and designate the spot price on the measurement date for

---

\(^{12}\) Any resemblance to existing exchanges is by coincidence.
financial reporting.

Step 1: Assign each exchange for each pair of currencies a BES reflecting static exchange characteristics such as oversight, microstructure, and technology.

The BES measures for our hypothetical exchanges are presented in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Base Exchange Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchange</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Exchange 1</td>
</tr>
<tr>
<td>Exchange 2</td>
</tr>
<tr>
<td>Exchange 3</td>
</tr>
<tr>
<td>Exchange 4</td>
</tr>
</tbody>
</table>

1. “Oversight” reflects the exchange rules in place to protect and give access to the investor. The score includes factors such as jurisdiction, regulation and KYC/AML requirements.

2. “Effective Spread” on any exchange is defined as pips (1/10,000) of the asset price.

3. “Order Reconstruction” or a reconstructed order is defined as an order for which we can identify all transactions that were completed as part of the order (including cancelation). Reconstruction is based on the level of orders and minute and daily volumes.

4. “Integrity” is the weighted average of order reconstruction and the time scales. The weights are based on the relative importance of each factor assigned by the entity.

“Transparency” is the term we use for the quality score that is determined by the level of detail of the data offered by an exchange.

5. The percentage weights included below the variable titles are determined by management.

As noted in Table 4, the exchange with the highest BES is Exchange 3. The BES is
the weighted average of the four key exchange characteristics: Oversight, Efficiency, Data Integrity, and Transparency. The weights used in this computation are noted below the exchange characteristic column on the table. In our example, the BES for Exchange 1 would be computed as follows:

\[ \text{BES}_{\text{Exchange 1}} = (35\% \times 100) + (30\% \times 0) + (25\% \times 84.19) + (10\% \times 100) = 66.05 \]

This score must now be adjusted for volume. This is done in Step 2.

**Step 2**: Adjust the BES based on the relative monthly volume of each exchange. This new score is the VAS.

The volume adjusted BES amounts for sample exchanges are presented in Table 5.

<table>
<thead>
<tr>
<th>Exchange</th>
<th>Monthly Volume (Millions of US Dollars)</th>
<th>Percent Volume Represented by Each Exchange</th>
<th>Base Exchange Scores (BES)</th>
<th>Volume Adjusted Score (VAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchange 1</td>
<td>48.6</td>
<td>26.9</td>
<td>66.05</td>
<td>17.77</td>
</tr>
<tr>
<td>Exchange 2</td>
<td>48.3</td>
<td>26.7</td>
<td>79.46</td>
<td>21.25</td>
</tr>
<tr>
<td>Exchange 3</td>
<td>36.5</td>
<td>20.2</td>
<td>89.32</td>
<td>18.08</td>
</tr>
<tr>
<td>Exchange 4</td>
<td>47.1</td>
<td>26.1</td>
<td>83.21</td>
<td><strong>21.70</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>180.5</strong></td>
<td><strong>100.0</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. The VAS is computed by weighting the BES by the percent of the total volume generated on each exchange.
2. The monthly volume of each exchange was determined in our simulation.
In our illustration, the VAS for Exchange 1 would be determined as follows:

\[
\text{VAS} = (\% \text{ Volume} \times \text{BES}) = (26.9\% \times 66.05) = 17.77
\]

At this point in implementing our methodology, Exchange 4 has the highest VAS at 21.70. This illustrates the fact that an exchange with a high BES can be less dominant due to lower volume. In this case, the principal exchange shifted from Exchange 3 to Exchange 4. However, that score is to be adjusted for the potential decay or time lag between trades. The decayed volume adjusted scores or DVAS are computed in Step 3.

**Step 3**: Decay the adjusted score based on the time passed since the last trade on the exchange. Here, we are assessing the level of activity in the market by considering the frequency of trades. The decay factor reflects the time since the last trade on the exchange. This is the final DVAS.

We track the freshness of the data by tracking the most recent trades. An example is presented in Table 6.

<table>
<thead>
<tr>
<th>Time</th>
<th>Exchange 1</th>
<th>Exchange 2</th>
<th>Exchange 3</th>
<th>Exchange 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:34:26.370</td>
<td>00:34:26.370</td>
<td>00:34:08.183</td>
<td>00:33:11.000</td>
<td>00:31:25.701</td>
</tr>
<tr>
<td>00:34:29.184</td>
<td>00:34:29.184</td>
<td>00:34:08.183</td>
<td>00:33:11.000</td>
<td>00:31:25.701</td>
</tr>
<tr>
<td>00:34:30.410</td>
<td>00:34:30.410</td>
<td>00:34:08.183</td>
<td>00:33:11.000</td>
<td>00:31:25.701</td>
</tr>
<tr>
<td>00:34:32.167</td>
<td>00:34:32.167</td>
<td>00:34:08.183</td>
<td>00:33:11.000</td>
<td>00:31:25.701</td>
</tr>
<tr>
<td>00:34:32.382</td>
<td>00:34:32.167</td>
<td>00:34:08.183</td>
<td>00:33:11.000</td>
<td><strong>00:34:32.382</strong></td>
</tr>
<tr>
<td>00:34:33.510</td>
<td>00:34:33.510</td>
<td>00:34:08.183</td>
<td>00:33:11.000</td>
<td><strong>00:34:32.382</strong></td>
</tr>
</tbody>
</table>
1. The times presented in Table 6 are simulated and reflect the time when a new trade (“fresh” data) arrives.

2. The times noted in bold indicate a new trade or the exchange with the “freshest” data.

We assume that we are measuring the spot price at a point in time, which could be the financial reporting date. In this example, we observe the arrival of new trades from approximately 30 minutes after midnight. Therefore, at 00:34.32.167 minutes after midnight, Exchange 1 had the most recent trade on line 4. Then, at 00:34.32.382, Exchange 4 had the most recent trade and therefore decayed less than the other exchanges at that point.

This is also seen in Figure 2 below. It shows a partial measurement period for the last minute considered from 34:00 minutes after midnight through 35:00 minutes after midnight.
1. Figure shows the partial results of simulating the arrival of new trades over a period of approximately 30 minutes after midnight on the reporting date.

2. The figure captures the time starting with 34 minutes after midnight and ending at 36 minutes after midnight. However, we assume that the standard designated “closing” time adopted in practice will be 35 minutes after midnight.

3. Vertical discontinuity indicates arrival of new data (i.e., a fresh trade) and resets the DVAS for that exchange. When there are no trades, the DVAS decays.

4. Exchange 4 shows the highest DVAS (between 20.0 and 22.5) at 34:33 and the least decay relative to the other exchanges at that point which was the freshest piece of data. This is because no other trades arrived between that point and the “closing” time of 35:00 minutes after midnight.

Vertical discontinuity indicates the arrival of new data (i.e., a fresh trade) and resets
the DVAS for that exchange. When there are no trades, the DVAS decays\textsuperscript{13}. Exchange 4 shows the highest DVAS (between 20.0 and 22.5) at 34:33 and the least decay relative to the other exchanges at that point which was the freshest piece of data. This is because no other trades arrived between that point and the “closing” time of 35:00 minutes after midnight.

\textbf{Step 4}: Rank the exchanges by the DVAS score and designate the highest-ranking exchange as the \textit{Principal Market} for that point in time. Table 7 provides the final rankings and the identification of the principal exchange.

\begin{table}
\centering
\caption{Principal Market Determination Based on Ranking of Decayed Volume Adjusted Scores}
\begin{tabular}{|c|c|c|}
\hline
\textbf{Time: Minutes after Midnight} & \textbf{Decayed Volume Adjusted Score} & \textbf{Ranking: Principal Market} \\
\hline
00:34:26.370 & 17.80 & Exchange 1 \\
00:34:29.184 & 17.80 & Exchange 1 \\
00:34:30.410 & 17.80 & Exchange 1 \\
00:34:32.167 & 17.80 & Exchange 1 \\
00:34:32.382 & 21.25 & Exchange 4 \\
00:34:33.510 & 21.25 & Exchange 4 \\
\hline
\end{tabular}
\end{table}

1. The DVAS scores reported in Table 7 are the approximate DVAS amounts extracted from the graph presented in Figure 2.

2. These scores are also confirmed by our simulation results.

\textsuperscript{13} These data were selected to illustrate changes in the principal exchange and therefore, we used high decay levels in our computations. The decay levels would not be as extreme in an actual setting.
Exchange 4 is designated as the principal exchange based on the ranking of the DVAS amounts at the fair value measurement point. That is, at 34.33:510 minutes after midnight, Exchange 4 is the principal exchange as it has the “freshest” data or the exchange with the least decay at the time. Note that higher volume at that time of day could be due to activity in the Asian markets at that time.

**Step 5:** Designate the price of the last transaction on the principal market as the prime spot price at that point of time.

<table>
<thead>
<tr>
<th>Time</th>
<th>Designated Spot Price</th>
<th>Exchange 1</th>
<th>Exchange 2</th>
<th>Exchange 3</th>
<th>Exchange 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:34:26.370</td>
<td>3,811.47</td>
<td>3,811.47</td>
<td>3,809.5</td>
<td>3,808.52</td>
<td>3,808.21</td>
</tr>
<tr>
<td>00:34:29.184</td>
<td>3,811.47</td>
<td>3,811.47</td>
<td>3,809.5</td>
<td>3,808.52</td>
<td>3,808.21</td>
</tr>
<tr>
<td>00:34:30.410</td>
<td>3,811.47</td>
<td>3,811.47</td>
<td>3,809.5</td>
<td>3,808.52</td>
<td>3,808.21</td>
</tr>
<tr>
<td>00:34:32.167</td>
<td>3,811.47</td>
<td>3,811.47</td>
<td>3,809.5</td>
<td>3,808.52</td>
<td>3,808.21</td>
</tr>
<tr>
<td>00:34:32.382</td>
<td>3,810.00</td>
<td>3,811.47</td>
<td>3,809.5</td>
<td>3,808.52</td>
<td>3,810.00</td>
</tr>
<tr>
<td>00:34:33.510</td>
<td>3,810.00</td>
<td>3,811.46</td>
<td>3,809.5</td>
<td>3,808.52</td>
<td>3,810.00</td>
</tr>
</tbody>
</table>

1. “Designated Spot Price” is the spot price extracted from the exchange with the freshest data on the measurement date and time.
2. In this case, the spot price extracted from Exchange 4 at 34:33:510 minutes after midnight is used for tax and financial reporting purposes.
3. This assumes that 34:33:510 minutes after midnight is the point in time predetermined as the “closing” date and time for the tax or financial report.

The prime spot price is $3,810 and represents the fair value of the cryptocurrency
extracted from Exchange 4 at 34:33.510 minutes after midnight at the end of the first quarter. This valuation is used to measure the investment in cryptocurrencies on the quarterly report for the first quarter\footnote{After the valuation and reporting the investment in cryptocurrencies in the financial statements at fair value, the accountant will need to disclose the level of reliability of the inputs used to measure the fair value in the hierarchy. We understand that this can be debated. One could argue that if the observed, quoted spot price is extracted from the principal market (as we define it in this essay), then the fair value could be disclosed at Level 1. Conversely, if position is taken that this fair value is determined in a market that is less active, then a Level 2 disclosure could be used. It should be noted that management assumptions are used in determining the principal market and not the final fair value measurement. It is also important to recall that the standards do not provide strict guidance as to how the principal market is to be determined and also indicate that the entity does not need to engage in an extensive search to identify the principal market but should incorporate all available information.}.\footnote{The actual names of the exchanges were removed in order to anonymize the data. This was necessary to comply with requests from certain exchanges included in this study.}

\section{2.5 Determining the Principal Market: An Empirical Demonstration}

In this section, we illustrate the ability of the proposed methodology (the “Model”) to determine a principal market and extract the price of the last market transaction for financial reporting purposes. The methodology is consistent with the guidance found in both ASC 820 (FASB 2011) and IFRS 13 (IASB 2011).

To run our empirical demonstration, we collected real-time price quotes for the Bitcoin and U.S. dollar (XBT-USD) pairs traded on six major exchanges (anonymized as Exchange A to F)\footnote{The actual names of the exchanges were removed in order to anonymize the data. This was necessary to comply with requests from certain exchanges included in this study.}. We then ran a demonstration designed to illustrate the Model’s ability to select the principal market using actual trade data. Finally, we determine the fair value derived by the Model from the last transactions for each minute from the exchanges used in our sample.

The results are reported in Figures 3 and 4. Figure 3 presents the tick price patterns
of XBT-USD on the selected exchanges, while Figure 4 shows the prices of the last transaction of XBT-USD on each minute on each exchange between 8:30 and 8:45 AM on June 26, 2019. In addition to the actual exchange prices for XBT-USD, we include the fair value measures derived from the Model in Figures 3 and 4. Six exchanges are split into two groups, Exchange A to C in Panel A and Exchange D to F in Panel B of Figures 3 and 4, according to their clustering characteristics.

In Panel A of Figure 3, the actual tick price patterns on Exchange A to C were clustered together, and the Model also appropriately followed this pattern in the 15-minute time interval between 8:30 and 8:45 AM on June 26, 2019. The patterns from the remaining Exchange D to F were separately clustered, shown in Panel B of Figure 3. In addition, the Model often selected Exchange A as the principal market for XBT-USD during the time intervals included except for 8:35 and 8:41 AM. Here, Exchange C was determined as the principal market (Panel A of Figure 4). The change in principal market designation based on varied market conditions demonstrates the ability of the Model to objectively and dynamically determine the principal market of a currency pair using real-time trade behavior on exchanges.
Figure 3: The Actual Tick Prices of XBT-USD on the Selected Exchange with the Fair Value Measures Derived from the Proposed Methodology (the Model) from 8:30 to 8:45 AM, June 26, 2019.

Panel A Exchange A to C
Panel B Exchange D to F

Figure 4 shows that the prices of the last transaction from the selected exchanges and the fair value measures from the Model (the dots on the graph are the last prices and the fair value measures) for the end of each minute over the 15-minute interval (8:30 to 8:45 AM) are consistent. If the lines representing the Model and the exchange overlap, it indicates that the exchange was determined as the principal market at that specific minute. Consistent with the patterns exhibited in Figure 3, Exchange A was often determined as the principal market in the interval. However, the Model did not select Exchange A as the principal market from the six exchanges at 8:35 and 8:41 because the trading behavior on Exchange A real-time became more volatile and less reliable. Therefore, a different principal market, Exchange C, was selected.
Figure 4 The Prices of the Last Transaction of XBT-USD on Each Minute on the Selected Exchanges with the Fair Value Measures Derived from the Proposed Methodology (the Model) from 8:30 to 8:45 AM, June 26, 2019

Panel A Exchange A to C
Panel B Exchange D to F

Finally, Table 9 indicates that the fair value measures generated by the Model highly correlate with the prices of the last transaction of XBT-USD on the selected exchanges. The highest correlations were found between the model and Exchange A (corr. coef. = 1.000000), Exchange B (corr. coef. = 0.998900), and Exchange C (corr. coef. = 0.998723). This confirms the ability of the Model to discern the most reliable exchanges as the principal market in the determination of the fair value for financial reporting.
Table 9 The Pearson Correlations among the Price of the Last Transaction of XBT-USD on Each Minute on the Selected Exchanges with the Fair Value Measures Derived from the Proposed Methodology (the Model) on June 26, 2019

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Price_Exchange A</td>
<td>1.000000</td>
<td>0.998000</td>
<td>0.998723</td>
<td>0.990858</td>
<td>0.996870</td>
<td>0.994050</td>
</tr>
<tr>
<td>Price_Exchange B</td>
<td>0.998000</td>
<td>1.000000</td>
<td>0.998754</td>
<td>0.990951</td>
<td>0.998649</td>
<td>0.995882</td>
</tr>
<tr>
<td>Price_Exchange C</td>
<td>0.998723</td>
<td>0.998754</td>
<td>1.000000</td>
<td>0.990221</td>
<td>0.997061</td>
<td>0.994196</td>
</tr>
<tr>
<td>Price_Exchange D</td>
<td>0.990858</td>
<td>0.998951</td>
<td>0.990221</td>
<td>1.000000</td>
<td>0.987679</td>
<td>0.982408</td>
</tr>
<tr>
<td>Price_Exchange E</td>
<td>0.996870</td>
<td>0.998649</td>
<td>0.997061</td>
<td>0.987679</td>
<td>1.000000</td>
<td>0.996443</td>
</tr>
<tr>
<td>Price_Exchange F</td>
<td>0.994050</td>
<td>0.995882</td>
<td>0.994196</td>
<td>0.982408</td>
<td>0.996443</td>
<td>1.000000</td>
</tr>
<tr>
<td>The Model</td>
<td>1.000000</td>
<td>0.998900</td>
<td>0.998724</td>
<td>0.990857</td>
<td>0.996869</td>
<td>0.994050</td>
</tr>
</tbody>
</table>

2.6 Conclusion

This essay presents a theoretical model to implement the use of fair value accounting for measuring and reporting cryptocurrencies for qualified investment companies and broker-dealer-owned holdings of cryptocurrency. Based on the theoretical model, we develop a methodology to assess the quality of digital currency exchanges and determine a principal market. With a principal market identified, a fair value is obtained to price the investment in cryptocurrencies.

Under the fair value model, cryptocurrencies are carried on the balance sheet at fair value with all unrealized gains and losses reported in current earnings. However, we acknowledge the difficulty of determining a principal exchange needed to extract a “true” price in a fragmented market. In response, we develop a dynamic system to assess the credibility of the exchange by considering characteristics such as jurisdiction, regulation, oversight, volume, and frequency of trades. The methodology is structured as a balance between the ability to obtain data from reliable sources, typically the more highly credited
exchanges, and the timeliness of the data.

We begin our assessment of the exchanges by assigning a base exchange score that includes values for the characteristics such as regulation, exchange microstructure, data quality, transparency, coverage, volatility, and other mechanisms, such as trading rules. Then, we weigh the base score for volume and, finally, reduce the score for infrequent trades or decay.

Our weighting methodology operates on two-time scales. On the longer monthly time scale, we adjust a set of initial weights by the volume each exchange traded over the previous month, and on the shorter time scale, we decay the initial weight based on the time passed since the last trade.

With a final or “decay-weighted” score, the principal exchange is selected. The point in time price needed for financial reporting and tax can then be extracted from the principal exchange. We provide empirical evidence to demonstrate the practicality of the model by demonstrating the model’s ability to select the principal market and extract a fair value or price. Given that the price is observable and quoted on an exchange, the fair value will not only be relevant but will faithfully represent the asset's economic value. Because our fair value measurement approach uses quoted prices, the valuation should be classified as a Level 1 measure in the fair value hierarchy.
CHAPTER 3 FAIR VALUE MEASUREMENT IN INACTIVE CRYPTO ASSET MARKETS

3.1 Introduction

The total market capitalization of crypto assets, including cryptocurrencies, reached a market capitalization of more than 2.269 trillion USD on April 15, 2021\textsuperscript{16}, and this amount is expected to grow. Crypto assets are held by many types of investors and entities, and some holders of crypto assets (e.g., qualified investment companies) are permitted under U.S. GAAP to carry these investments at fair value with unrealized gains and losses recognized in current earnings. Other investors typically classify crypto assets as indefinite-lived intangible assets which require financial statement valuation at cost with downward revaluation to fair value if impaired. In either case, it is necessary to measure the fair value of crypto assets at a point in time for financial reporting purposes.

The current accounting guidance for fair value measurement and disclosure under ASC 820 (FASB 2011) and IFRS 13 (IASB 2011) define a three-level fair value hierarchy used to rank the reliability of the inputs used in the fair value measurement. The levels, from high to low, are as follows:

Level 1: Quoted prices in active markets for identical assets or liabilities that the entity can access at the measurement date

Level 2: Observable inputs other than level 1 inputs

\textsuperscript{16} The information about the total market capitalization of all cryptocurrencies was derived from the CoinMarketCap website, available at: \url{https://coinmarketcap.com/charts/}. 
Level 3: Unobservable inputs

The classification in the hierarchy is driven by the lowest level of input reliability. If a crypto asset pair\(^{17}\) is actively traded on exchanges, the valuation process is fairly straightforward because the fair value at a point in time can be extracted from the principal market. Here, the valuation is typically given a Level 1 classification in the fair value hierarchy. However, one of the defining characteristics of crypto asset markets is deep fragmentation. Many crypto assets are traded on certain exchanges against other mainstream crypto assets (crypto to crypto pairs) with relatively higher transaction volume when compared to fiat currencies (crypto to fiat currency pairs). For instance, the DOGE coin, originally a light-hearted project forked from the Litecoin protocol, was traded at low volumes of several thousand USD daily. However, it became a household name following a series of tweets by Tesla CEO, Elon Musk. While the DOGE is traded against the USD with around 20 million USD daily, it is a small fraction when compared to the transaction volume of 383 million USD against Tether (USDT) and 90 million USD against Bitcoin (XBT) on other exchanges\(^{18}\). Some crypto assets are traded in certain exchanges only against certain counter crypto assets rather than fiat currencies. For example, crypto assets such as Bytecoin (BCN) and MCO (MCO) are not traded directly against the USD but are traded with XBT, Ethereum (ETH), and USDT. US-based entities holding such assets have to report these crypto asset holdings in the USD for financial reporting purposes. Thus, we need to develop a valuation methodology for those crypto-fiat pairs with minimal or no trading activity and convert them to the USD for financial reporting.

\(^{17}\) The markets for crypto assets are *pair-based* and could be crypto to crypto or crypto to fiat currency pairs.

\(^{18}\) The numbers were derived from the CoinMarketCap website.
The above examples, DOGE, BCN, and MCO, raise several questions as to how to choose the sequence of asset pairs (segments) through which we price an asset pair. In reality, there may not be any trading information specific to crypto assets to be valued. The same problem could occur with foreign exchanges (FX), where typically most sovereign currencies trade against the USD, EUR, JPY, GBP, while pairs like SEK/RUB, ZAR/SEK are not supported by the main exchanges. The exchange rate for ZAR/SEK could just as well be derived from \( \frac{\text{ZAR/USD}}{\text{SEK/USD}} \) as with \( \frac{\text{ZAR/EUR}}{\text{SEK/EUR}} \) or from \( \frac{\text{ZAR/EUR} \times \text{EUR/USD}}{\text{SEK/EUR}} \). However, in the FX market, the principal market for pairs that are traded over exchanges are the electronic broking services or Reuters exchanges, both operating from New York and are highly liquid. Any price disparities between the different paths would quickly be arbitraged by high-frequency trading firms active in these markets. Pairs that are not traded across exchanges are typically quoted by dealers or central banks based on their exchange rate versus the preferred reserve currency that is almost always one of the above.

The situation is radically different with crypto assets. In this case, most exchanges support trading crypto assets against a range of fiat currencies as well as XBT and ETH, several stable coins, and exchange tokens like Binance coin (BNB). While XBT and ETH are supported almost universally, and the choice of fiats is usually USD, EUR, or possibly some local currencies, the stable coins and token exchanges differ significantly from one exchange to the other. In some cases, the latter command a significant portion if not the lion’s share of the volume. As such, the markets are critical in the price discovery process and should not be ignored. Moreover, given the geographic and regulatory disparity between the many exchanges, price differences are not always arbitraged away, and we often see significant differences in the pricing based on the pricing path applied.
Accounting standards do not specify how assets are to be priced in these cases, but they do require the consistent use of an appropriate methodology.

Therefore, the purpose of this essay is to develop a mark-to-model methodology that allows for the valuation of thinly traded crypto asset pairs. We propose the Optimal Path Model (the OPM, hereafter) that will take advantage of observable and reliable inputs from principal markets that are active with orderly transactions. Specifically, the OPM dynamically identifies the optimal path for thinly traded crypto asset pairs from all potential paths and determines the fair value by multiplying quoted prices of segments (pairs traded in an active market or multiple active markets) in the optimal path. The fair value determination under the OPM is dynamic, obtaining fair value measures for a thinly traded crypto asset pair from the dynamically determined optimal path for the pair. Moreover, the OPM consistently aligns with a Level 2 classification in the fair value hierarchy as defined under ASC 820 and IFRS 13.

This essay is organized as follows. In Section 3.2, we provide a literature review and discuss how the current accounting guidance specifies the approaches used to identify an inactive market and how to measure fair value in such cases in Section 3.3. The OPM is developed and described in Section 3.4 and illustrated in Section 3.5 by using a simple example. Section 3.6 presents an empirical demonstration for eight thinly traded crypto assets using actual market data. Finally, the summary and conclusions are discussed in the last section of the essay.
3.2 Literature Review

Previous research has indicated that transaction volume is one element that can be used to measure an asset’s liquidity. Several authors investigated the association between liquidity (illiquidity) and stock returns (Amihud 2002; Amihud, Mendelson, and Pedersen 2005; Brennan and Subrahmanyam 1996; Pástor and Stambaugh 2003). For instance, Amihud (2002) proposed an illiquidity measure as “the average across stocks of the daily ratio of absolute stock returns to dollar volume” and found that the ex-ante, stock excess returns are positively affected by the expected market illiquidity, representing the illiquidity premium. Moreover, the effect of the market illiquidity was stronger for shares of small companies, consistent with the expectations from the theory. Pástor and Stambaugh (2003) estimated a liquidity measure in an ordinary least squares regression model in which the daily dollar transaction amount of stocks was used. The authors observed that stocks with high sensitivity to liquidity have a 7.5% higher average annual return than ones with low sensitivity.

Additional research provided both theoretical models and empirical evidence that support the conclusion that transaction volume can function as a channel to incorporate private and public market information in financial markets (e.g., Easley, O’Hara, and Srinivas 1998; Easley, Kiefer, O’Hara, and Paperman 1996) and crypto asset markets (e.g., Bianchi and Dickerson 2020; Brandvold, Molnár, Vagstad, and Valstad 2015; Makarov and Schoar 2019; Park and Chai 2020; Sockin and Xiong 2020). For instance, Easley et al. (1996) provided empirical evidence that “private information is more important for

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19 The review paper form Amihud, Mendelson, and Pedersen (2005) provided a comprehensive view between the liquidity and asset prices in the literature.
infrequently traded stocks.” Easley et al. (1998) investigated the information content of the transactions volume in options markets and found that “particular option trades being informative for the future movement of stock prices”.

Specifically for crypto asset markets, Brandvold et al. (2015) investigated the Bitcoin market on seven major exchanges from April 1, 2013, to February 25, 2014, and provided empirical evidence indicating that the price-leading exchanges had higher information share and transaction volume. Sockin and Xiong (2020) indicated that the price and transaction volume of crypto assets can be observed by participants in their trading-decision process and the transaction volume “provides a complementary source of information” when pricing crypto assets. Bianchi and Dickerson (2020) examined the information content of aggregated transaction volume and observed that the interaction term of the previous transaction volume and the lagged return has a significantly positive association with the future returns.

The extant literature provides evidence that transaction volume plays an important role in providing a signal in the price discovery process of typical financial instruments and crypto assets. This theory and empirical evidence support our use of transaction volume as a critical factor in the development of the OPM.

In the next section of the essay, we discuss how to identify thinly traded assets and differentiate these assets from assets traded in active markets.

3.3 Identification of a Thinly Traded Crypto Asset Pair

If a market for an asset is active, trades take place frequently and with a volume
level that results in reliable pricing information regularly. On the other hand, for assets with limited transaction volume or with limited activity between trades, the market might be considered thin or inactive. Professional judgment may be involved to determine if the limited transaction volume and the frequency of trades are significant enough to assume that the quoted price is no longer representative of the fair value of an asset. A fundamental issue is to ensure that a market participant would have the ability to extract relevant and faithfully represented fair value information from the market.

An orderly transaction is one in which trades are conducted in a usual and customary manner - the transaction is not forced or manipulated. Transactions between market participants that occur in a manner that is usual and customary would allow an entity to conclude that the transaction was orderly. ASC 820 and IFRS 13 indicate that the entity is not required to make an exhaustive effort to determine if the transaction is orderly; however, readily available information cannot be ignored (FASB 2011; IASB 2011).

When an entity determines that a market is not active or a transaction is not orderly, adjustments to the traded or quoted prices of an asset are needed when these prices are used as a basis for measuring the fair value of the asset. Adjustments may also be needed when using the prices of similar assets to determine fair value.

As previously discussed, some crypto assets have no direct trades against the USD (or other fiat currencies). However, entities holding such assets need fair value measures in terms of the USD (or other fiat currencies) for financial reporting purposes. Although we may need to value a crypto asset without direct trades against a fiat currency, it may exhibit relatively active trades against other mainstream crypto assets which in turn are actively traded against the USD (and other fiat currencies). In this case, we can use a mark-
to-model methodology that can determine fair value measures that are both relevant and faithfully represented by using the quoted prices in the active markets for the crypto-fiat pairs with intermediary mainstream crypto assets.

The approach suggested by the AICPA supports the above-mentioned mark-to-model methodology. Specifically, the AICPA guide to accounting for and auditing of digital assets indicates that if the transaction is orderly and for an identical instrument in an active market that is not the principal (or most advantageous) market, the transaction may require adjustments that market participants would apply to arrive at a fair value consistent with the entity’s principal (or most advantageous) market (AICPA 2020a). The entity should maximize the use of relevant observable inputs and minimize the use of unobservable inputs when measuring a fair value estimate consistent with ASC 820 and IFRS 13 (FASB 2011; IASB 2011).

The first step in developing our valuation methodology is to determine if a crypto asset pair is in fact, trading in an inactive market. The determination of whether a crypto asset pair is trading in an inactive market will be made based on a volume threshold. A volume threshold for thinly traded or illiquid assets has precedent as it is recommended by the SEC in its analysis of the national market system (NMS) for equity shares (the SEC 2018). Specifically, the SEC (2018) used the average daily share volume (ADV) as the criterion to differentiate liquid from illiquid stocks. This approach was also supported by the U.S. Department of the Treasury (the SEC 2019; the U.S. Department of the Treasury 2017). Although there is no specific accounting guidance provided to differentiate between

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20 The threshold established would be based on the evaluation of available market data with input and recommendations from a cross-section of valuation experts in industry, accounting firms, and academic researchers’ familiar with crypto assets and the supporting ecosystem.
the liquid and illiquid crypto assets, our model will employ a volume threshold as recommended by the SEC and the U.S. Department of the Treasury for equity shares.

After establishing that a crypto asset pair is thinly traded, our proposed OPM will measure the fair value for a crypto asset pair by identifying the optimal path with the highest level of observable transaction volume for the pair. Specifically, the OPM would first identify the principal markets for the thinly traded crypto asset pairs in each segment in potential path candidates by using the methodology developed by Beigman, Brennan, Hsieh, and Sannella (2021) (called the BBHS model, hereafter). The BBHS model (2021) is used to identify the principal market for each segment in each potential path to ensure that only compliant exchanges are included in the OPM. Then, the OPM would identify the path with the highest level of observable transaction volume for the crypto asset pair and determine the fair value. As noted earlier, prior literature has indicated that the transaction volume on financial markets and crypto asset exchanges is associated with the market credibility (Nasiri, Bektas, and Jafari 2018) and works as a channel to incorporate private and public market information (Bianchi and Dickerson 2020; Brandvold et al. 2015; Easley et al. 1996; Makarov and Schoar 2019; Park and Chai 2020; Sockin and Xiong 2020). In other words, the information embedded in a price with higher transaction volume for a targeted currency pair is likely to be more credible, reliable, and faithfully represented.

The OPM for the Level 2 crypto asset valuations represents a market-to-model approach by adjusting “unadjusted” quoted market prices for crypto asset segments in the designated optimal path that includes trades in active markets. The development of the OPM will be discussed in the next section.
3.4 The Optimal Path Model (OPM)

The BBHS model (2021) dynamically identifies a principal market for actively traded crypto asset pairs across all available exchanges and then determines its fair value from the exchange designated as the principal market. Specifically, the BBHS model applies a ranking mechanism that considers several exchange characteristics, including oversight, the volume, and frequency of trades. To rank the credibility and quality of each exchange, a score that incorporates the key characteristics for each exchange will be assigned through the following steps (Beigman et al. 2021):

Step 1: Assign a base exchange score for each exchange for the targeted crypto asset pair based on the static exchange characteristics.

Step 2: Adjust the score by the relative monthly volume of the exchange.

Step 3: Decay the adjusted score based on the time passed since the last trade on the exchange.

Following the BBHS model, we take a similar approach to score potential paths for a thinly traded crypto asset pair by considering their static characteristics, volume, and decay. For each segment of the potential paths, representing a particular market for a pair of assets, we take the principal market designation of that market as given. For each potential path, we look separately at the set of static characteristics, volumes, and time since the last update, computing scores step by step. Finally, we take the path with the highest score as the optimal path and derive the fair value measure of the thinly crypto asset pair as the product of the exchange rates of the optimal path segments.
The mathematical specification of the model is presented in the following paragraphs.

Let $A = \{a_0, \ldots, a_k\}$ a set of assets (XBT, ETH, USDT, USDC, BAT, MCO, DOGE, CRO, etc.). We say that a market exists for the pair $(a_i, a_j)$ if the pair $a_i/a_j$ or $a_j/a_i$ is traded on at least one exchange and priced by the BBHS model, let $E$ be the set of markets that exist for asset pairs in $A$. Thus, (XBT, USDT) is an existing market as the pair is traded on multiple exchanges, while the pair (DOGE, MCO) is not an existing market. We shall call $G = (A, E)$ the asset graph. A path $\sigma_{a_0, \ldots, a_k}$ in the asset graph is a sequence $a_0, \ldots, a_k$ such that $a_i \in A$ for $0 \leq i \leq k$ and $(a_i, a_{i+1}) \in E$ for $1 \leq i \leq k - 1$.

For $a_i, a_j \in A$, let $S_{a_i,a_j}^{BES}$ be the base exchange score (BES) of the principal market for the pair $a_i/a_j$, we define the path base score (PBS) to be:

$$S_{\sigma_{a_0,\ldots,a_k}}^{PBS} = \min \{S_{a_i,a_{i+1}}^{BES} \mid 0 \leq i \leq k - 1\}. $$

In the same manner, we define the path volume to be:

$$Vol_{\sigma_{a_0,\ldots,a_k}} = \min \{Vol_{a_i,a_{i+1}} \mid 0 \leq i \leq k - 1\},$$

where $Vol_{a_i,a_j}$ is the volume on the principal market of the $a_i/a_j$ as measured in some common numerator, typically either USD or XBT, using the BBHS model. Let $\overline{Vol}$ be the overall volume passing through the graph\(^{21}\), and then we define the volume adjusted path score (VAPS) to be:

$$S_{\sigma_{a_0,\ldots,a_k}}^{VAPS} = S_{\sigma_{a_0,\ldots,a_k}}^{PBS} \times \frac{Vol_{a_0,\ldots,a_k}}{\overline{Vol}}$$

\(^{21}\) $\overline{Vol}$ is a solution to the max flow problem which can be solved efficiently (namely in polynomial time) with various algorithms. For details see Matousek and Gärtner (2007) and Papadimitriou and Steiglitz (1998).
Similarly, we define:

$$\tau_{a_0\ldots a_k} = \max \{\tau_{a_i,a_{i+1}} \mid 0 \leq i \leq k - 1\},$$

where $\tau_{a_i,a_j}$ is the time elapsed since the last trade on the determined principal market of the $a_i/a_j$. Finally, we define the decayed volume adjusted path score (DVAPS):

$$S^{DVAPS}_{a_0\ldots a_k} = e^{-\kappa \tau_{a_0\ldots a_k}} \times S^{VAPS}_{a_0\ldots a_k}$$

We then define the optimal path as the path $\sigma_{a_0\ldots a_k}^*$ such that:

$$\sigma_{a_0\ldots a_k}^* = \arg\max \left\{B_{a_0\ldots a_k} \cdot S^{DVAPS}_{a_0\ldots a_k} \mid \text{for every path } a_0, \ldots, a_k \text{ in } G\right\}^{22}$$

where $B_{a_0\ldots a_k} = \begin{cases} l_1 & k = 1 \\ l_2 & k > 1 \end{cases}$ and $l_1 > l_2$, this latter coefficient is the “level bump” reflecting a preference for direct, Level 1 valuations over indirect Level 2 valuations.

We define the fair value measure of $a_k$ to $a_0$ as:

$$a_k/a_0 = a_k^*/a_{k-1}^* \times a_{k-1}^*/a_{k-2}^* \times \cdots \times a_1^*/a_0^*.$$

The OPM model is illustrated by a simulation in the next section.

### 3.5 The OPM: An Illustration

In this section of the essay, we provide a basic example to illustrate the OPM. The illustration assumes that we would need to value MCO in terms of the USD for financial reporting purposes. However, MCO is not directly paired and traded with the USD but transacted with other crypto assets. To measure MCO at fair value for financial reporting...

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22 If there are more than two potential paths with the same highest DVAPS, then the OPM will determine the path with the least number of segments as the determined optimal path.
purposes, we will use the OPM to find the pairs of transactions with MCO that ultimately lead to the USD valuation.

In applying the OPM, the first step is to identify “segments” (crypto-crypto or crypto-fiat pairs) in all potential paths from the targeted crypto asset (MCO) to the destination fiat currency\(^{23}\) (i.e., USD, for financial reporting purposes). Figure 1 shows the complete “asset graph” for MCO-USD. As indicated in Figure 5\(^{24}\), MCO was mainly traded with other crypto assets, including XBT, ETH, and USDT, on major exchanges worldwide. Hence, three potential paths with one intermediary crypto asset would be MCO-XBT-USD, MCO-ETH-USD, and MCO-USDT-USD. In addition, some potential paths have two intermediary crypto assets, such as MCO-XBT-USDT-USD, MCO-ETH-USDT-USD, MCO-USDT-XBT-USD, and MCO-USDT-ETH-USD. It is also possible to identify potential paths with more than two intermediary crypto assets. The more crypto assets or fiat currencies that the targeted crypto asset could be traded with, the more complex the map of potential paths would become. For purposes of our illustration will employ only the potential paths with one and two intermediary crypto assets.

\(^{23}\) The destination currency is not limited to fiat currencies and can be other crypto assets based on the customized needs.

\(^{24}\) The MCO may be transacted with additional crypto assets or fiat currencies, represented by the dotted lines in Figure 5. The additional transactions may be possible in the future as MCO becomes more popular.
Figure 5: Illustration of Selected Potential Paths for MCO-USD.

Table 10 summarizes the simulated information for the illustration, including the principal market, the base exchange score, the fair value, the minute transaction volume (USD), and the time of the last trade for each segment (crypto-crypto or crypto-fiat pairs). The principal markets and base exchange scores of the segments in all potential paths are individually determined and obtained by using the BBHS model (2021). For this part of the illustration, we implemented the OPM at 16:06:00 of the day\(^{25}\). The OPM will determine the path base score (PBS), which is the minimum base exchange score among segments in each potential path, for each potential path. The result of the determination of the PBS for seven selected potential paths is presented in Panel A of Table 11.

\(^{25}\) Users can implement the OPM in any time to fit their specific purposes. We randomly selected 16:06:00 of the day because the thinly traded pairs (MCO-XBT, MCO-USDT, and MCO-ETH) had trades reported in the previous minute (from 16:05:00.000 to 16:05:59.999).
Table 10: Simulated Information for the Illustration of the Optimal Path Model (OPM).

<table>
<thead>
<tr>
<th>Segments</th>
<th>Principal Market</th>
<th>Base Exchange Score</th>
<th>Fair Value</th>
<th>Minute Transaction Volume (USD)</th>
<th>Time of the Last Trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCO-ETH</td>
<td>Exchange C</td>
<td>74.9889</td>
<td>0.0295</td>
<td>0.33</td>
<td>16:05:31.273</td>
</tr>
<tr>
<td>MCO-USDT</td>
<td>Exchange A</td>
<td>92.1846</td>
<td>4.689</td>
<td>597.17</td>
<td>16:05:52.207</td>
</tr>
<tr>
<td>MCO-XBT</td>
<td>Exchange A</td>
<td>94.9548</td>
<td>0.00054</td>
<td>606.64</td>
<td>16:05:52.143</td>
</tr>
<tr>
<td>ETH-USDT</td>
<td>Exchange A</td>
<td>96.2627</td>
<td>161</td>
<td>355,471.40</td>
<td>16:05:59.870</td>
</tr>
<tr>
<td>XBT-USDT</td>
<td>Exchange A</td>
<td>93.2820</td>
<td>8,698.97</td>
<td>7,409,847.00</td>
<td>16:05:59.988</td>
</tr>
<tr>
<td>ETH-XBT</td>
<td>Exchange A</td>
<td>96.3611</td>
<td>0.0185</td>
<td>64,553.04</td>
<td>16:05:59.620</td>
</tr>
<tr>
<td>ETH-USD</td>
<td>Exchange B</td>
<td>91.7013</td>
<td>160.7</td>
<td>79,671.79</td>
<td>16:05:57.405</td>
</tr>
<tr>
<td>USDT-USD</td>
<td>Exchange D</td>
<td>75.9979</td>
<td>0.99775</td>
<td>1,901.71</td>
<td>16:05:59.268</td>
</tr>
<tr>
<td>XBT-USD</td>
<td>Exchange B</td>
<td>86.3616</td>
<td>8,684.33</td>
<td>873,888.00</td>
<td>16:05:59.841</td>
</tr>
</tbody>
</table>

1. The illustration is supposed to implement the OPM at 16:06:00.000 of the day.
2. The principal market for each segment is determined by the BBSH model (2021).
3. The base exchange score for each segment is derived from the BBSH model (2021).
4. The fair value for each segment is derived from the BBSH model (2021) and presented on a basis of the first currency of each segment. For example, the fair value for XBT-USD is 8,684.33, meaning 8,684.33 USD / Bitcoin.
5. The minute transaction volume (USD) for each segment is the sum of transaction volume from 16:05:00.000 to 16:05:59.999 on the determined principal market.
6. The time of the last trade for each segment is derived from the determined principal market.

Panel B of Table 11 shows the determination process of the path volume, which is the minimum transaction volume among segments in each potential path. The volume adjusted path score (VAPS) will be determined after obtaining the volume weights for each path, indicated in Panel C of Table 11. Finally, the decayed volume adjusted path score (DVAPS) will be calculated after identifying the maximum time elapsed since the last trade among all segments for each potential path. The potential path with the highest DVAPS
would be designated as the *optimal path* at that moment in time. As indicated in Panel D of Table 11, the path *MCO-XBT-ETH-USD* is designated as the optimal path because it generated the highest DVAPS (45.8373) among all potential paths.

Table 11: Determination of the Path Base Score (PBS), the Path Volume, and the Volume Adjusted Path Score (VAPS) under the Optimal Path Model (OPM).

**Panel A: The Determination of the *Path Base Score (PBS)* under the Optimal Path Model (OPM).**

<table>
<thead>
<tr>
<th>Potential Paths</th>
<th>Base Exchange Score from the BBHS model (2021)</th>
<th>Path Base Score (PBS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCO-XBT-USD</td>
<td>74.9889</td>
<td>86.3616</td>
</tr>
<tr>
<td>MCO-ETH-USD</td>
<td>94.9548</td>
<td>86.3616</td>
</tr>
<tr>
<td>MCO-USDT-USD</td>
<td>91.7013</td>
<td>74.9889</td>
</tr>
<tr>
<td>MCO-XBT-ETH-USD</td>
<td>94.9548</td>
<td>75.9979</td>
</tr>
<tr>
<td>MCO-XBT-USDT-USD</td>
<td>93.2820</td>
<td>75.9979</td>
</tr>
<tr>
<td>MCO-ETH-XBT-USD</td>
<td>74.9889</td>
<td>75.9979</td>
</tr>
<tr>
<td>MCO-ETH-USDT-USD</td>
<td>96.3611</td>
<td>75.9979</td>
</tr>
<tr>
<td>MCO-USDT-ETH-USD</td>
<td>91.7013</td>
<td>74.9889</td>
</tr>
<tr>
<td>MCO-USDT-XBT-USD</td>
<td>91.7013</td>
<td>74.9889</td>
</tr>
</tbody>
</table>

* The *path base score (PBS)* under the OPM is the *minimum* of base exchange scores of segments in each potential path, indicated with the **bold** numbers.

**Panel B: Determination of the *Path Volume* under the Optimal Path Model (OPM).**

<table>
<thead>
<tr>
<th>Potential Paths</th>
<th>Minute Transaction Volume (USD) on the Principal Market Determined by the BBHS model (2021)</th>
<th>Path Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCO-XBT-USD</td>
<td>606.64</td>
<td>873,883</td>
</tr>
<tr>
<td>MCO-ETH-USD</td>
<td>0.33</td>
<td>606.64</td>
</tr>
<tr>
<td>MCO-USDT-USD</td>
<td>0.33</td>
<td>606.64</td>
</tr>
<tr>
<td>MCO-XBT-ETH-USD</td>
<td>606.64</td>
<td>0.33</td>
</tr>
<tr>
<td>MCO-XBT-USDT-USD</td>
<td>79,671.76</td>
<td>0.33</td>
</tr>
<tr>
<td>MCO-ETH-XBT-USD</td>
<td>1,901.71</td>
<td>0.33</td>
</tr>
<tr>
<td>MCO-ETH-USDT-USD</td>
<td>64,553.04</td>
<td>0.33</td>
</tr>
<tr>
<td>MCO-USDT-ETH-USD</td>
<td>355,471.4</td>
<td>0.33</td>
</tr>
<tr>
<td>MCO-USDT-XBT-USD</td>
<td>7,409,847</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* The *path volume* under the OPM is the *minimum* of transaction volume (USD) on the determined principal market of segments in each potential path, indicated with the **bold** numbers.
Panel C: Determination of the *Volume Adjusted Path Score (VAPS)* under the Optimal Path Model (OPM).

<table>
<thead>
<tr>
<th>Potential Paths</th>
<th>Path Base Score (PBS)</th>
<th>Volume Weights</th>
<th>Volume Adjusted Path Score (VAPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCO-XBT-USD</td>
<td>86.3616</td>
<td>606.64 / 1,204.14*</td>
<td>43.5087</td>
</tr>
<tr>
<td>MCO-ETH-USD</td>
<td>74.9889</td>
<td>0.33 / 1,204.14</td>
<td>0.0202518</td>
</tr>
<tr>
<td>MCO-USDT-USD</td>
<td>75.9979</td>
<td>597.17 / 1,204.14</td>
<td>37.6899</td>
</tr>
<tr>
<td>MCO-XBT-ETH-USD</td>
<td>91.7013</td>
<td>606.64 / 1,204.14</td>
<td>46.1989</td>
</tr>
<tr>
<td>MCO-XBT-USDT-USD</td>
<td>75.9979</td>
<td>606.64 / 1,204.14</td>
<td>38.2875</td>
</tr>
<tr>
<td>MCO-ETH-XBT-USD</td>
<td>74.9889</td>
<td>0.33 / 1,204.14</td>
<td>0.0202518</td>
</tr>
<tr>
<td>MCO-ETH-USDT-USD</td>
<td>74.9889</td>
<td>0.33 / 1,204.14</td>
<td>0.0202518</td>
</tr>
<tr>
<td>MCO-USDT-ETH-USD</td>
<td>91.7013</td>
<td>597.17 / 1,204.14</td>
<td>45.4777</td>
</tr>
<tr>
<td>MCO-USDT-XBT-USD</td>
<td>86.3616</td>
<td>597.17 / 1,204.14</td>
<td>42.8296</td>
</tr>
</tbody>
</table>

*1,204.14 (= 606.64 + 597.17 + 0.33) is “the overall volume passing through the graph”.

Panel D: Determination of the *Decayed Volume Adjusted Path Score (DVAPS)* under the Optimal Path Model (OPM).

<table>
<thead>
<tr>
<th>Potential Paths</th>
<th>Volume Adjusted Path Score (VAPS)</th>
<th>Time of the Last Trade</th>
<th>Decayed Volume Adjusted Path Score (DVAPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCO-XBT-USD</td>
<td>43.5087</td>
<td>16:05:52.143</td>
<td>43.1682</td>
</tr>
<tr>
<td>MCO-ETH-USD</td>
<td>0.0202518</td>
<td>16:05:52.207</td>
<td>0.0196783</td>
</tr>
<tr>
<td>MCO-USDT-USD</td>
<td>37.6899</td>
<td>16:05:52.207</td>
<td>37.3973</td>
</tr>
<tr>
<td><strong>MCO-XBT-ETH-USD</strong></td>
<td>46.1989</td>
<td>16:05:52.143</td>
<td><strong>45.8373</strong></td>
</tr>
<tr>
<td>MCO-XBT-USDT-USD</td>
<td>38.2875</td>
<td>16:05:52.143</td>
<td>37.9878</td>
</tr>
<tr>
<td>MCO-ETH-XBT-USD</td>
<td>0.0202518</td>
<td>16:05:52.207</td>
<td>0.0196783</td>
</tr>
<tr>
<td>MCO-ETH-USDT-USD</td>
<td>0.0202518</td>
<td>16:05:52.207</td>
<td>0.0196783</td>
</tr>
<tr>
<td>MCO-USDT-ETH-USD</td>
<td>45.4777</td>
<td>16:05:52.207</td>
<td>45.1247</td>
</tr>
<tr>
<td>MCO-USDT-XBT-USD</td>
<td>42.8296</td>
<td>16:05:52.207</td>
<td>42.4971</td>
</tr>
</tbody>
</table>

* The time of the last trade for each potential path is derived from the trade with longest time lag among all segments of each potential path.
After determining the optimal path, the fair value measure for MCO-USD would be the product of exchange rates (ERs) of segments in the optimal path. Therefore, as the designated optimal path is MCO-XBT-ETH-USD, the fair value measure for MCO-USD would be

\[ FV_{MCO-USD} = ER_{MCO-XBT} \times ER_{XBT-ETH} \times ER_{ETH-USD} = 0.00054 \times \left( \frac{1}{0.0185} \right) \times 160.7 = 4.6907. \]

### 3.6 The OPM: An Empirical Demonstration

In this section, we demonstrate the proposed OPM, determining the optimal path and the fair value measures for pairs of thinly traded cryptocurrencies to the USD. The empirical demonstration uses actual market data. In addition, we will compare the fair value measures generated by the model with the actual prices of trades of the pairs, if they are available.

Specifically, we test eight different thinly traded cryptocurrencies, including Basic Attention Token (BAT), Dogecoin (DOGE), STASIS EURO (EURS), Ankr (ANKR), Bytecoin (BCN), Crypto.com Coin (CRO), MCO (MCO), and NEM (XEM). The first three cryptocurrencies had direct trades to the USD available on at least one exchange, while the remaining five cryptocurrencies did not have any direct USD trades during the test period covering January 1, 2019, to June 30, 2020 (totaling 787,680 minutes).

Figure 6 shows the minute transaction volume from thinly traded cryptocurrencies to other mainstream cryptocurrencies and the USD (if available) during

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26 The names of exchanges used in the empirical demonstration section were anonymized as Exchange A to D.
the test period. Volumes from BAT, DOGE, EURS, ANKR, BCN, CRO, MCO, and XEM to other cryptocurrencies and the USD (if available) are displayed in Panel A, B, C, D, E, F, G, and H, respectively. For BAT (Panel A) and DOGE (Panel B), the transaction volume to the USD is much lower compared to the volume for XBT, ETH, USDT, or USDC. Interestingly, the transaction volume for the USD is the same level as the volume for USDT for EURS (Panel C). Although the remaining cryptocurrencies (Panel D-H) had no direct trades against the USD, they had frequent trades and sufficient transaction volume with XBT, ETH, USDT, USDC, or BNB.
Figure 6 Minute Transaction Volume from Thinly Traded Cryptocurrencies to Other Mainstream Cryptocurrencies and the USD (if available).

This figure presents the minute transaction volume from thinly traded cryptocurrencies to other mainstream cryptocurrencies and the USD (if available) from January 1, 2019, to June 30, 2020. Volumes from Basic Attention Token (BAT), Dogecoin (DOGE), STASIS EURO (EURS), Ankr (ANKR), Bytecoin (BCN), Crypto.com Coin (CRO), MCO (MCO), and NEM (XEM) to other cryptocurrencies and the USD (if available) are displayed in Panel A, B, C, D, E, F, G, and H, respectively.

Panel A Basic Attention Token (BAT), with available trades for BAT-USD
Panel B Dogecoin (DOGE), with available trades for DOGE-USD

Panel C STASIS EURO (EURS), with available trades for EURS-USD
Panel D Ankr (ANKR), without available trades for ANKR-USD

Panel E Bytecoin (BCN), without available trades for BCN-USD
Panel F Crypto.com Coin (CRO), without available trades for CRO-USD

Panel G MCO (MCO), without available trades for MCO-USD
Panel H NEM (XEM), without available trades for XEM-USD

In the empirical demonstration, the OPM is tested at the end of each minute for the period from January 1, 2019, to June 30, 2020 (totaling 787,680 minutes). Table 12 presents the number (percentage) of minutes available for the fair value measures from the OPM and the prices of direct trades to the USD for the eight selected thinly traded cryptocurrencies. For instance, the BAT-USD trades were accessible on four exchanges; however, they are infrequently traded. Specifically, only 28,079 (3.56%), 19,219 (2.44%), 25,117 (3.19%), and 5,698 (0.72%) minutes had trades on the four exchanges for BAT-USD during the test period, while the OPM could generate fair value measures for BAT-USD in 757,923 (96.22%) minutes. Furthermore, DOGE-USD could only be transacted on Exchange A in 6,735 (0.86%) minutes, but there were 783,579 (99.48%) minutes having fair value measures from the OPM during the test period. For ANKR, BCN, CRO, MCO,
and XEM those cryptocurrencies with no direct trades against the USD, the OPM could still determine fair value measures in terms of USD in 339,567 (43.11%), 254,746 (32.34%), 623,970 (79.22%), 667,862 (84.79%), and 777,042 (98.65%), respectively. The OPM can provide timely, reliable, and frequent fair value measures for those thinly traded cryptocurrencies with few or even no direct trades against the USD.

Table 12 The Number of Minutes with Available Fair Value Measure by the Optimal Path Model (OPM) and with Available Prices of Trades to the USD from January 1, 2019, to June 30, 2020.

<table>
<thead>
<tr>
<th>Crypto Assets</th>
<th>Optimal Path Model</th>
<th>Direct Trade to USD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exchange A</td>
<td>Exchange B</td>
</tr>
<tr>
<td>Basic Attention Token (BAT)</td>
<td>757,923 (96.22%)</td>
<td>28,079 (3.56%)</td>
</tr>
<tr>
<td>Dogecoin (DOGE)</td>
<td>783,579 (99.48%)</td>
<td>6,735 (0.86%)</td>
</tr>
<tr>
<td>STASIS EURO (EURS)</td>
<td>16,373 (2.08%)</td>
<td>N/A</td>
</tr>
<tr>
<td>Ankr (ANKR)</td>
<td>339,567 (43.11%)</td>
<td>N/A</td>
</tr>
<tr>
<td>Bytecoin (BCN)</td>
<td>254,746 (32.34%)</td>
<td>N/A</td>
</tr>
<tr>
<td>Crypto.com Coin (CRO)</td>
<td>623,970 (79.22%)</td>
<td>N/A</td>
</tr>
<tr>
<td>MCO (MCO)</td>
<td>667,862 (84.79%)</td>
<td>N/A</td>
</tr>
<tr>
<td>NEM (XEM)</td>
<td>777,042 (98.65%)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- We perform the methodology in each minute from January 1, 2019, to June 30, 2020, totaling 787,680 minutes.
Figure 7 shows the minute fair value measures from the OPM for thinly traded cryptocurrencies and prices of trades from thinly traded cryptocurrencies to the USD (if available) during the test period. The fair value measures and prices (if available) from BAT, DOGE, EURS, ANKR, BCN, CRO, MCO, and XEM to other cryptocurrencies and the USD (if available) are displayed in Panel A, B, C, D, E, F, G, and H, respectively.

**Figure 7 Minute Fair Value Measures from the Optimal Path Model (OPM) for Thinly Traded Cryptocurrencies and Prices from Thinly Traded Cryptocurrencies-USD Trades (if available).**

This figure presents the minute fair value measures from the Optimal Path Model (OPM) for thinly traded cryptocurrencies and prices of trades from thinly traded cryptocurrencies to the USD (if available) from January 1, 2019, to June 30, 2020. The fair value measures and prices (if available) from Basic Attention Token (BAT), Dogecoin (DOGE), STASIS EURO (EURS), Ankr (ANKR), Bytecoin (BCN), Crypto.com Coin (CRO), MCO (MCO), and NEM (XEM) are displayed in Panel A, B, C, D, E, F, G, and H, respectively.
Panel A Basic Attention Token (BAT), with available trades for BAT-USD

Panel B Dogecoin (DOGE), with available trades for DOGE-USD
Panel C STASIS EURO (EURS), with available trades for EURS-USD

Panel D Ankr (ANKR), without available trades for ANKR-USD
Panel E Bytecoin (BCN), without available trades for BCN-USD

Panel F Crypto.com Coin (CRO), without available trades for CRO-USD
Panel G MCO (MCO), without available trades for MCO-USD

Panel H NEM (XEM), without available trades for XEM-USD
The fair value measures and the actual prices for BAT-USD were well matched with each other for most minutes. However, the OPM had one fair value outlier at 7:35 AM on January 15, 2020. This outlier might result from the real-time, atypical transaction behavior in the determined optimal path or a possible data integrity issue on exchanges. Moreover, there were some price outliers (large abnormal price jumps comparing the adjacent minutes) of real trades for BAT-USD at 8:10 AM on April 8, 2020, and from 5:00 to 6:00 PM on May 5, 2020. As presented in Figure 8, the real trades of BAT-USD experienced abnormal price jumps during the one hour; however, the OPM constantly generated relatively stable fair value measures in those 60 minutes.
Figure 8 Minute Fair Value Measures from the Optimal Path Model and Prices from Real Trades for BAT-USD from 17:00 to 18:00 on May 5, 2020.

This figure presents the minute fair value measures from the Optimal Path Model (OPM) and prices from real trades for BAT-USD from 17:00 to 18:00 on May 5, 2020. The real trades of BAT-USD experienced abnormal price jumps during the one hour. However, the OPM constantly generated stable fair value measures during the period.

Some thinly traded cryptocurrencies, such as DOGE and EURS, would be initially traded with other mainstream cryptocurrencies rather than fiat currencies. As displayed in Panel B and C of Figure 7, the OPM could identify the optimal path and determine the fair values for DOGE-USD and EURS-USD even if there were no direct trades from DOGE and EURS against the USD at the beginning of the test period. Furthermore, Panel C of Figure 7 revealed that the real trades of EURS-USD experienced many significant
abnormal price jumps, but the fair value measures from the OPM were relatively stable and, therefore, more reliable.

Panel D to H of Figure 7 shows the fair value measures from ANKR\textsuperscript{27}, BCN, CRO\textsuperscript{28}, MCO, and XEM to the USD, respectively. Still, the OPM enabled the fair value (in terms of the USD) generation for those thinly traded cryptocurrencies without feasible direct trades to the USD, although there was a clear fair value outlier for the ANKR case.

### 3.7 Summary and Conclusions

Standards-aligned valuation methodologies for crypto assets are a critical component of the ongoing acceptance and adoption of these emerging economic phenomena built on blockchain technology. Commercial mark-to-market methodologies for actively traded crypto assets in orderly markets exist and are offered in commercially available software products, but dynamic standards-aligned valuation models for thinly traded (or Level 2 assets under ASC 820) crypto assets are needed to provide more comprehensive pricing and asset valuation. This essay addresses this need by proposing the OPM to determine fair value for thinly traded crypto asset pairs. The standards-aligned OPM enables the dynamic identification of the optimal path for the pairs by scoring the static characteristics, transaction volume, and the time elapsed from the last trade for all potential paths. The fair value measures are derived by multiplying the exchange rates of segments in the determined optimal path. Empirical evidence is also provided, supporting the assertion that the OPM can derive more timely and reliable fair value measures from a

\textsuperscript{27} The ANKR trade data was not available until March 5, 2019.

\textsuperscript{28} The CRO trade data was not available until March 7, 2019.
crypto asset to a fiat currency with few or even no direct trades on exchanges for financial reporting purposes. While thinly traded crypto asset represents a small part of the total trading volume, they account for a significant part of the total crypto transaction activity and many crypto assets may move between valuation levels as they emerge and mature. Our standards-aligned model will ensure broader valuation coverage in the rapidly expanding crypto asset space and may be applied to a wide variety of crypto asset types and pairs. Future research is needed to explore the development of models for valuing assets or asset pairs where there are no observable transactions resulting in a “Level 3” classification in the ASC 820 fair value hierarchy.
CHAPTER 4 A FRAMEWORK FOR AUDITING CRYPTO ASSET ECOSYSTEM

4.1 Introduction

Crypto assets are gradually being adapted into real business activities. As more and more entities are progressively involved in trading, investing\(^{29}\), and accepting\(^{30}\) crypto assets, it becomes more important for external auditors to provide reasonable assurance on financial statements which encompass material crypto asset activities. However, the completely different nature of the crypto asset ecosystem generates new risks and issues, making auditors more difficult to obtain reasonable and sufficient audit evidence for financial statement audits. Auditors need a clear framework and guidance on the audits involving the crypto asset ecosystem.

On the one hand, auditing standard setters and professional organizations, such as the Public Company Accounting Oversight Board (PCAOB), American Institute of Certified Public Accountants (AICPA), Chartered Professional Accountants Canada (CPA Canada), and Canadian Public Accountability Board (CPAB), have provided non-authoritative auditing guidelines for auditors. These guidelines focus on a very limited part of the whole audit process needed to address audits of crypto assets. On the other hand, auditing frameworks and approaches associated with blockchains and smart contracts have been discussed and proposed in prior literature (Appelbaum and Nehmer 2020; Dai and Vasarhelyi 2017; Rozario and Thomas 2019; Vincent and Wilkins 2019). Building on top of the guidance and literature, this research focuses on discussing emerging and unique

\(^{29}\) The Tesla, Inc. disclosed that they made a $1.5 billion bitcoin investment in January 2021 in its latest 10-K filing. The Investor Relation section of Tesla website. Available at: https://ir.tesla.com/sec-filings

risks and challenges in auditing crypto asset transactions and building a comprehensive framework providing specific guidance for auditors by emphasizing the complex relationship between the client and the crypto asset ecosystem.

The entity may trade (buy or sell) crypto assets from centralized exchanges or over-the-counter (OTC) markets for investing purposes, use custodial services from custodians, accept crypto assets in the sales of goods or services on permissioned or permissionless blockchains, or participate in various activities in the decentralized finance (DeFi) environment. All of these actions lead to the entity’s direct and/or indirect (by custodial service providers) holding of crypto assets. Auditors should address different risks, issues, and challenges from various crypto asset activities.

This essay has the following contributions. First of all, we propose a comprehensive framework for auditing the crypto asset ecosystem. This framework would be beneficial for different stakeholders, including general companies, crypto asset funds, participants in the crypto asset ecosystem, various service providers, accounting firms, and standard setters. Second, we identify various participants in the crypto asset ecosystem and illustrate their relationship with the audited entity. This illustration is critical to identify specific risks and issues between the entity and each participant that auditors should pay attention to and address. Lastly, this research, to the best of our knowledge, is the first academic one in the accounting domain discussing the auditing for entities involving in Decentralized Finance (DeFi) activities, a highly developing and evolving area in recent years. The discussion provides more insights into the practice.

This essay is organized as follows. We begin with the introduction of the crypto asset ecosystem and depict the interaction between the entity and the ecosystem in Section
4.2. Current non-authoritative guidance in auditing crypto asset transactions from standard setters and professional organizations is reviewed in Section 4.3. The framework to audit crypto asset transactions is presented, and unique risks and issues related to crypto assets audits are identified and discussed in Section 4.4. Finally, the essay is concluded in Section 4.5.

4.2 The Interaction between the Entity and the Crypto Asset Ecosystem

Crypto assets\(^{31}\) could be generally classified into two groups: *coins*\(^{32}\) “which operate on their own independent network” and *tokens*\(^{33}\) “which operate on top of a coin network as a platform” (Wu, Wheatley, and Sornette 2018). The popular *coins*\(^{34}\), for example, include Bitcoin, Ethereum, Litecoin, etc. *Tokens*, on the other hand, could be further categorized based on their functionality and characteristics into (1) asset-backed tokens\(^{35}\), (2) utility tokens\(^{36}\), and (3) security tokens\(^{37}\) (PwC 2019). The underlying asset(s) of *asset-backed tokens* could be the single or the mixture of fiat currencies, commodities,

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\(^{31}\) We would consistently use the term “crypto assets” in this paper. Some other papers or publications may use other terms, such as cryptocurrencies and digital assets.

\(^{32}\) “The term ‘coin’ generally refers to a cryptographic asset that has the express purpose of acting solely as a medium of exchange (PwC 2019).”

\(^{33}\) “The term ‘token’ refers to an asset that gives the holder additional functionality or utility (PwC 2019).”

\(^{34}\) The CoinMarketCap website also classifies cryptocurrencies into coins (https://coinmarketcap.com/coins/) and tokens (https://coinmarketcap.com/tokens/) and displays their price information separately.

\(^{35}\) “An asset-backed token is a digital token based on blockchain technology that signifies and derives its value from something that does not exist on the blockchain but instead is a representation of ownership of a physical asset (for example, natural resources such as gold or oil) (PwC 2019).”

\(^{36}\) “Utility tokens are digital tokens based on blockchain technology that provide users with access to a product or service, and they derive their value from that right. Utility tokens give holders no ownership in a company’s platform or assets and, although they might be traded between holders, they are not primarily used as a medium of exchange (PwC 2019).”

\(^{37}\) “Security tokens are digital tokens based on blockchain technology that are similar in nature to traditional securities. They can provide an economic stake in a legal entity: sometimes a right to receive cash or another financial asset, which might be discretionary or mandatory; sometimes the ability to vote in company decisions and/or a residual interest in the entity (PwC 2019).”
natural resources, real estate, collectibles, etc. *Stablecoins*, one kind of asset-backed tokens, is designed to keep the price stability of tokens to address the price volatility issue (Dwyer 2015; Estrada 2017) of coins and offers programmability to integrate with smart contracts (Deloitte 2020), the foundation of the Decentralized Finance (DeFi) ecosystem.

The crypto asset ecosystem where the entity participates may be described with the following seven major components: (1) permissioned blockchains, (2) permissionless blockchains, (3) decentralized finance (DeFi), (4) oracles, (5) centralized exchanges, (6) custodians, and (7) over-the-counter (OTC) markets. Figure 9 illustrates the complex relationships among components embedded in the entity’s side and the crypto asset ecosystem. Different components have their unique audit risks and issues that should be considered.

The entity may buy or sell crypto assets from centralized exchanges or OTC markets depending on its trading behavior and intention. For example, OTC markets provide market participants (usually institutional investors and high-volume traders) with advantages such as more personalized services, better transaction prices, higher trading limits, and faster trading times (Nezamaikin and Zbirovskaya 2019). On the other hand, the entity would have access to more kinds of crypto assets that can be traded and custodian services from centralized exchanges. Entities would select different platforms depending on their trading purposes.
Figure 9 The Relationships between the Entity and the Crypto Asset Ecosystem

This figure shows the relationship between the entity and the crypto asset ecosystem. There are seven major categories of players in the crypto asset ecosystem, including (1) permissioned blockchains, (2) permissionless blockchains, (3) decentralized finance (DeFi), (4) oracles, (5) centralized exchanges, (6) custodians, and (7) over-the-counter (OTC) market. On the entity side, its bank account would connect to centralized exchanges and OTC markets to trade crypto assets. Crypto assets in its (cold or hot) wallets would be directly transferred with permissioned and permissionless blockchains, DeFi applications, custodians, centralized exchanges, and OTC markets. In terms of accounting records, it is necessary to reconcile transaction information on those players in the ecosystem with the accounting information stored in the ERP system.

The entity may accept crypto assets in the sales of goods or services, recognizing revenue on its accounting records, and transfer crypto assets on permissioned or permissionless blockchains directly from the transaction counterparty. Moreover, some entities may exchange tokens or even choose to be “miners” to earn rewards on blockchains in exchange for helping secure the network. All these activities are permanently and immutably recorded on blockchains and serve as audit trails of the entities' activities.
Decentralized finance (DeFi), “open financial infrastructures built upon public smart contract platforms such as the Ethereum blockchain (Schär 2020),” attracts more and more attention in recent years by providing participants with more “decentralized, innovative, interoperable, borderless, and transparent” services (Chen and Bellavitis 2020). Specific services and products in the DeFi environment include decentralized exchanges, stablecoins, money market (borrowing and lending), swap, insurance, derivatives, and many other applications. Oracles\(^\text{38}\), connecting the physical world with the virtual DeFi environment by providing key external information such as exchange rates, play an important role in smoothly executing smart contracts on DeFi applications. The entity may be involved in one or many activities in the DeFi world.

Traditionally, fiat currency flows within the entity or between entities are transferred and settled by *centralized* financial institutes such as banks. The accounting information and other relevant documents are embedded and stored in the entity’s enterprise resource planning (ERP) system. However, when the entity engages in the crypto asset ecosystem, the situation gets much more complicated. The entity’s fiat currency flow is linked with the crypto assets by connecting bank accounts to centralized exchanges or OTC markets to trade crypto assets. Then, the entity may decide to hold crypto assets in its wallets within the centralized exchanges or store them with custodian service providers. Afterward, the entity can transfer the crypto assets to wallets that can store crypto assets and directly connect to other centralized exchanges, blockchain platforms, or decentralized applications (DApps), holding and transferring crypto assets on its own behalf. The wallets

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\(^{38}\) “An agent that finds and verifies information, bringing the real world and the blockchain by providing data to smart contracts for execution of said contracts under specified conditions (Crypto Glossary from CoinMarketCap).” Available at: [https://coinmarketcap.com/alexandria/glossary](https://coinmarketcap.com/alexandria/glossary)
may be generally categorized into two classes, “hot” and “cold” wallets, according to their Internet connection timing. A hot wallet is always online, connected to the Internet, and is ready to trade its crypto assets balances with other wallets, while a cold wallet stays offline until the entity (the holder of the wallet) would like to send (receive) crypto assets to (from) other wallets. Hot wallets generally have a shorter transaction processing time, suitable for entities with higher transaction volume, but are at higher risk of being hacked or attacked compared to cold wallets. Entities may deploy the optimal wallet usage after considering the nature and risk of different wallets and the volume of their crypto asset transactions.

The typical methodology for the preparation of financial statements is relatively straightforward; all relevant accounting records and supportive documents are stored and available in the ERP system. However, when dealing with the crypto asset ecosystem, how to reconcile the complete transaction records and related information between the ERP system and centralized components (exchanges and OTC markets) and decentralized components (permissioned blockchains, permissionless blockchains, oracles, and DeFi applications) would become a new and challenging task for auditors.

4.3 Current Guidance in Auditing Crypto Assets from Standard Setters and Professional Organizations

There are no specific authoritative auditing standards specifying the audit issues when the audited entity is materially involved in crypto asset transactions. Nevertheless, many standard setters and audit profession organizations, such as the Public Company Accounting Oversight Board (PCAOB), the American Institute of Certified Public
Accountants (AICPA), Chartered Professional Accountants Canada (CPA Canada), and Canadian Public Accountability Board (CPAB), have issued publications to deliver some guidance in auditing an entity with crypto asset transactions. In this section, we briefly review and summarize the main points from publications issued by those organizations.

4.3.1 The Public Company Accounting Oversight Board (PCAOB) (2020)

The PCAOB (2020) issued a publication, established rules to provide guidance for auditors when their clients are materially involved in crypto asset transactions or hold a material amount of crypto assets. This publication also provides audit committees with questions that they can ask their external auditors to evaluate their prior experience and competency in auditing crypto assets. Specifically, the PCAOB (2020) listed responsibilities under the existing standards that auditors should comply with, including (1) quality control system at the firm level, (2) planning, and (3) risk assessment at the audit engagement level. About quality control, for instance, “a firm should establish policies and procedures for deciding whether to accept or continue a client relationship and whether to perform a specific engagement for that client (PCAOB 2020).” The accounting firm needs to consider new risks related to crypto asset transactions and reasonably ensure that auditors in the audit engagement team have sufficient professional competency in terms of specialized knowledge and experience about crypto assets before it decides to continue or accept the audit engagement. In the planning phase, the auditor needs to leverage the level of specialized knowledge needed, such as, but not limited to, the underlying blockchain technology, cryptography, the evolving business models and transactions in the crypto asset ecosystem, and legal and accounting regulations on crypto assets.
The auditor is required to identify and assess risks of material misstatement of the financial statements and then design and implement appropriate audit procedures to collect sufficient audit evidence supporting the audit opinion formation. Hence, in the *risk assessment* phase, the PCAOB (2020) listed some essential factors that auditors may pay attention to, including:

- Where did the client store its crypto assets, in its own wallet or by a third party?
- For the current physical year, how many kinds of crypto assets are traded and holding? How much did all crypto asset transactions occur? What’s the number of customers and suppliers of the client accepting and trading crypto assets?
- What are the client’s primary business models and strategies related to crypto assets?
- How does the client recognize the identity of customers and suppliers consistently complying with the know-your-customer (KYC) and anti-money-laundering (AML) policies and identifying related parties?

In terms of the internal control over financial reporting (ICFR), PCAOB (2020) indicated that auditors might need to understand the entity’s control activities on (1) the generation and management of private keys, (2) the reliability of information derived from blockchains, (3) the reconciliation of transaction records between the client’s accounting system and on blockchains, and (4) transactions recorded outside of the blockchain, or “off-chain,” such as centralized crypto assets exchanges. On the other hand, the entity may ask
its auditors about their experience and level of domain knowledge, the firm’s specialized audit tools for crypto asset transactions, and the judgment of independence (PCAOB 2020).

4.3.2 The American Institute of Certified Public Accountants (AICPA)

The AICPA issued a practice aid, *Accounting for and Auditing of Digital Assets*, and intended to provide auditors with nonauthoritative guidance in accounting treatments and auditing of crypto asset transactions. About auditing contents of the publication, it concentrates on discussing relevant elements to be considered by auditors when they determine the entity *acceptance and continuance*, including (1) necessary skill sets and competencies of auditors, (2) necessary skill sets and competencies of the management of the entity, (3) The integrity of the management and the business strategy of the entity, and (4) processes and controls on information technology (IT) of the entity (AICPA 2020a). In each section, it indicated all relevant paragraphs in auditing standards, raised specific challenges for crypto assets audits, and listed possible procedures to deal with the challenges.

Accounting firms may encounter challenges in maintaining and updating the skill sets and competencies of the engagement team (partner, staff personnel, internal and external specialists, etc.) for the audit in crypto assets. Those challenges may include: (1) how to get updated in technological, regulatory, legal, financial, industry, and accounting and auditing changes, (2) how to recruit new personnel equipping with blockchain and crypto assets domain knowledge, (3) how to monitor and supervise the audit work, and (4) how to train the incumbent and future auditors for the team and within the firm (AICPA 2020a). In terms of skill sets and competencies of the entity, on the other hand, the risks
may originate from: (1) how the entity designs and implements internal controls to deal with the unique risks in the crypto asset ecosystem, (2) how the entity maintains the completeness and accuracy of the accounting records and books and reconciles the information between the entity and the third-party service providers, (3) whether the staff preparing financial reporting has sufficient knowledge in blockchains and crypto assets, and (4) whether the entity has the access and uses the services from external specialists (AICPA 2020a).

Auditors are also required to understand the overall operation and business strategy and the integrity of the entity before accepting the client. In the crypto assets audit setting, the related risks may come from (1) the entity’s compliance with related laws and regulations such as KYC and AML policies, (2) how to match identities of the related party of the entity on blockchains to understand whether the entity might involve in illegal or fraudulent transactions, (3) the materiality level of the entity’s crypto asset transaction volume (the number of crypto asset transactions and the balances of crypto assets, etc.) (AICPA 2020a).

Auditors must understand the design and evaluate the effectiveness of the entity’s internal controls over financial reporting (ICFR). This publication emphasized the ICFR from the perspective of crypto assets. For instance, auditors may need to consider how the entity (1) authorize and track crypto asset transactions, (2) hold and secure crypto assets on its own behalf or by a third-party custodian, and (3) identify, authorize, approve, and record transactions with related parties on blockchains (AICPA 2020a).

4.3.3 Chartered Professional Accountants Canada (CPA Canada)

CPA Canada issued a publication, Audit Considerations Related to Crypto Assets
and Transactions, concentrating on discussing (1) client acceptance and continuance, (2) the entity’s IT system for crypto asset transactions, and (3) matters when identifying and assessing risks of material misstatement in crypto asset transactions and balances (CPA Canada 2018). When it comes to client acceptance and continuance, auditors should consider (1) the integrity of the entity, (2) the purpose of the entity to involve in crypto asset transactions, (3) the entity’s understanding of risks of crypto assets, (4) the internal controls of the entity on crypto asset transactions, and (5) the experience and competency of the engagement team to perform the audit (CPA Canada 2018). Further, the most important part of the publication is that nine “what could go wrong” conditions are exemplified. Moreover, possibly misstated assertions (Accuracy, valuation and allocation, Completeness, Existence, Cut-off, Occurrence, and Rights (Ownership)) were also identified and illustrated for each example. Those explanations provide auditors with useful guidance when they perform the audit on crypto asset transactions.

4.3.4 Canadian Public Accountability Board (CPAB)

The CPAB regularly published inspection insights reports (CPAB 2018, 2019) and shared its findings, perspectives, and expectations on the audit related to crypto asset transactions. Specifically, in the 2018 report, client acceptance, existence and ownership rights on crypto assets, revenue recognition for “miners,” impairment and valuation for crypto assets, and related party transactions are discussed (CPAB 2018). It is noteworthy that the publication indicated that auditors should identify and document the related risks of the existence and ownership rights assertions on crypto assets, including “(i) invalid transactions are recorded on the blockchain, (ii) validated transactions are not recorded
on the blockchain, and (iii) validated transactions are subsequently modified (CPAB 2018).” Auditors may use the “blockchain explorer” to review the transaction history on blockchains (Kuzuno and Karam 2017; CPAB 2018) and examine the entity’s controls on its private key management to care for the existence and ownership rights assertions (CPAB 2018).

On the other hand, five common deficiencies in the practice related to crypto asset audits were identified in the 2019 report, including (1) inadequate understanding of audit risks, (2) without further reliability evaluation on the information obtained from other third parties (such as centralized exchanges and custodians), (3) without evaluating the information reliability obtained from blockchains, (4) not collecting sufficient audit evidence on the entity’s ownership of crypto assets, and (5) not collecting sufficient audit evidence on mining activities of the entity (CPAB 2019).

From the review of these non-authoritative auditing guidances, it could be observed that some publication focused on one specific area or phase in the audit, for instance, the client acceptance and continuance, the communication with the audit committee, and the events or assertions that might be affected by crypto asset transactions. This separation lacks an integrated view of the audit when an entity engages in crypto asset activities. This research intends to provide a comprehensive map for auditors when auditing an entity dealing with crypto asset transactions.

4.4 The Framework of Auditing Crypto Asset Transactions

The essence of the research is that we propose a framework for auditing crypto
assets in Table 13. Given the unique characteristics and risks of the crypto asset ecosystem, we further list comprehensive but not exhaustive issues in auditing crypto asset transactions and discuss what factors should be considered and how to address those factors.
Table 13 The Framework for Auditing Crypto Asset Ecosystem

<table>
<thead>
<tr>
<th>Audit Stage</th>
<th>Audit Tasks</th>
<th>Unique Risks and Issues in the Crypto Asset Ecosystem</th>
</tr>
</thead>
</table>
| Client Acceptance and Continuance | | ● Evaluate the independence level of the engagement team.  
● Evaluate the competencies and knowledge in blockchains and crypto assets of auditors in the engagement team (AICPA 2020a; CPA Canada 2018).  
● Evaluate the competencies and knowledge in blockchains and crypto assets of the entity (AICPA 2020a; CPA Canada 2018).  
● Evaluate whether there is a need to use the work from specialists to perform the audit.  
● Evaluate the integrity of the entity (CPA Canada 2018).  
● Follow the relevant ethical requirements (CPA Canada 2018).  
● Understand the purpose and operation strategy of the entity involving in crypto asset transactions (AICPA 2020a).  
● Understand the entity’s ITGC (AICPA 2020a; CPA Canada 2018) and system controls on crypto asset activities (CPA Canada 2018). |
| Audit Planning | | ● Understand the materiality level of crypto asset transactions and the significant behavior change in crypto asset transactions (CPA Canada 2018).  
● Evaluate the competencies and knowledge in blockchains and crypto assets of the entity (AICPA 2020a; CPA Canada 2018).  
● Understand the purpose and operation strategy of the entity involving in crypto asset transactions (AICPA 2020a).  
● Understand the entity’s ITGC (AICPA 2020a; CPA Canada 2018) and system controls on crypto asset activities (CPA Canada 2018). |
<table>
<thead>
<tr>
<th>Risk Assessment</th>
<th>• Understand the accounting policies related to crypto assets, such as fair value measurement and revenue recognition.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Establish the materiality level for the financial statements and for accounts and disclosures, especially for those related to crypto asset transactions.</td>
</tr>
<tr>
<td></td>
<td>• Identify related risks of blockchains and crypto assets on the entity’s financial reporting, such as information security risk and private key management risks.</td>
</tr>
<tr>
<td></td>
<td>• Examine and understand the scope of the SOC 1 and SOC 2 reports from centralized stakeholders in the crypto asset ecosystem and audit reports for smart contracts, oracles, stablecoin reserve accounts, and blockchain protocols.</td>
</tr>
<tr>
<td></td>
<td>• Evaluate the ability of to implement on-chain and off-chain reconciliation with the accounting records stored in the ERP system of the entity.</td>
</tr>
<tr>
<td>Assess the Internal Control over Financial Reporting (ICFR)</td>
<td>• Evaluate the entity’s controls over significant crypto asset transactions, related party transactions, and significant management estimates.</td>
</tr>
<tr>
<td></td>
<td>• Identifying significant accounts and disclosures related to crypto asset transactions and their relevant assertions (existence or occurrence, completeness, valuation or allocation, rights and obligations, and presentation and disclosure).</td>
</tr>
<tr>
<td></td>
<td>• Examine and understand the scope of the SOC 1 and SOC 2 reports from centralized stakeholders in the crypto asset ecosystem.</td>
</tr>
<tr>
<td>Test of Controls</td>
<td>• Test design and operating effectiveness of controls over private keys (the generation, usage, authorization, storage, etc.).</td>
</tr>
<tr>
<td></td>
<td>• Test design and operating effectiveness of controls over the crypto asset transactions with centralized service providers (exchanges, custodians, etc.)</td>
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<tr>
<td>Completi on</td>
<td>Substantive Procedures</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td>• Use analytical procedures as substantive tests (for example, for entities performing mining activities).</td>
</tr>
<tr>
<td></td>
<td>• Send confirmations to the centralized service providers (such as exchanges and custodians) in the crypto asset ecosystem.</td>
</tr>
<tr>
<td></td>
<td>• Consider the probability of illegal crypto-asset activities of the entity.</td>
</tr>
<tr>
<td></td>
<td>• Understand the relationship between the entity and the related parties and evaluate the relationship is appropriately identified in blockchain environments.</td>
</tr>
<tr>
<td></td>
<td>• Understand the entity’s valuation approaches for the fair value measurement of crypto assets and evaluate the compliance of the fair value measurement.</td>
</tr>
<tr>
<td></td>
<td>• Engage with specialists for the above issues, if it is necessary.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Completi on</th>
<th>Overall Review of Financial Report</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Estimate the impact of subsequent events related to crypto assets and perform appropriate audit procedures, if it is necessary.</td>
</tr>
<tr>
<td></td>
<td>• Perform analytical procedures.</td>
</tr>
<tr>
<td></td>
<td>• Accumulate and evaluate identified misstatements during the audit related to crypto asset transactions.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Completi on</th>
<th>Audit Report</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Disclose any engagements with other specialists for the essential services.</td>
</tr>
<tr>
<td></td>
<td>• Determine crypto assets-related issues as a Critical Audit Matter (CAM) in the auditor’s report, if it has a significant impact on the audit of the financial statements.</td>
</tr>
</tbody>
</table>

4.4.1 SOC 1 and SOC 2 Reports

Service Organization Controls (SOC) reports are “internal control reports on the services provided by a service organization providing valuable information that users need
to assess and address the risks associated with an outsourced service.\textsuperscript{39} The relevant principles and specific criteria to be considered for SOC reports are developed by the AICPA. SOC 1 reports provide users of the services and auditors of the users with the information about controls at the service organization relevant to users’ internal control over financial reporting (ICFR), enabling the auditors to evaluate the impact of the controls on users’ financial reporting. There are two types of SOC 1 reports: Type 1 (SOC 1 Type 1) report shows the fairness of the system and the suitability of the related controls, while Type 2 (SOC 1 Type 2) report, based on Type 1, adds the evaluation of the operating effectiveness of the controls in a specific time period\textsuperscript{40}. On the other hand, SOC 2 reports provide users of the services and auditors of the users with information about controls at the service organization relevant to security, availability, processing integrity, confidentiality, or privacy. Similar to SOC 1, there are also two types of SOC 2 reports: Type 1 (SOC 2 Type 1) report shows the fairness of the system and the suitability of the relevant controls, while Type 2 (SOC 2 Type 2) report adds the evaluation of the operating effectiveness of the controls\textsuperscript{41}.

For all those independent service providers in the crypto asset ecosystem, such as centralized exchanges, custodians, oracles, and the blockchains and DeFi networks all need a way to provide users of the services and auditors of users with a confidence level that the services provided and subsequent controls are appropriately designed and operating effectively to ensure the integrity of the service provided. In 2018, CPAB (2018) indicated

\textsuperscript{39} SOC for Service Organizations. AICPA website. Available at: https://www.aicpa.org/interestareas/frc/assuranceadvisoryservices/socforserviceorganizations.html.

\textsuperscript{40} More information about SOC 1 reports is available at: https://www.aicpa.org/interestareas/frc/assuranceadvisoryservices/aicpasoc1report.html.

\textsuperscript{41} More information about SOC 2 reports is available at: https://www.aicpa.org/interestareas/frc/assuranceadvisoryservices/aicpasoc2report.html.
that “no service auditors’ reports are available that attest to the effectiveness of internal controls in place at crypto-exchanges and custodians (CPAB 2018).” However, with the rapid development of the crypto asset ecosystem, more and more service providers have SOC 1 and/or SOC 2 reports available to the service users and auditors of the users. For instance, Coinbase Custody was the first custodial service provider that completed the SOC 1 Type 2 and SOC 2 Type 2 examinations conducted by Grant Thornton in 201942, and Gemini was the first provider which passed the examinations for both custody and exchange services conducted by Deloitte and Touche in 202143. The SOC 1 and SOC 2 examinations and reports would help the crypto asset ecosystem continue to flourish with the trust of service users in the centralized service providers. The use and requirement of SOC-type third-party assurance are critical to the ongoing adoption and growth of the crypto asset ecosystem.

The adoption of the SOC (SOC 1 or SOC 2) examination as a type of system audit (information technology general controls, ITGC) accreditation for centralized database-oriented entities (such as exchanges and custodians) in the crypto asset ecosystem is appropriate. However, the SOC examination does not apply to blockchains and DeFi applications because of their decentralized nature. The assurance on blockchains and DeFi applications require completely different evaluation criteria comparing to the SOC examination and will be discussed in later sections “Smart Contract Code Assurance” and “Audit for Blockchain Protocols.”

4.4.2 Smart Contract Code Assurance

Smart contracts, the underlying foundation of many blockchains and the DeFi environments, need to be independently examined and evaluated whether they are written in the way they intended to be. The physical transaction rules, processes, and criteria are translated into virtual codes in smart contracts by humans, and this translation might create potential and undiscovered risks to be attacked and hacked (ISACA 2020). Most all of the hacks within the blockchain ecosystem to date have revolved around unforeseen errors or manipulation of smart contracts on blockchains and now on emerging DeFi platforms. For example, LendF.me (the lending function) on dForce (the DeFi platform) was attacked in April 2020, and the reason was thought to be “dForce supposedly copying Compound Finances v1 contracts which did not safeguard from the specific attack.” Therefore, it is noteworthy for auditors whether the smart contracts of the DeFi applications where the entity participates are independently verified and assured. Many specialized firms are providing assurance services auditing smart contract code security. For instance, OpenZeppelin\(^\text{45}\) provided security audits for smart contract protocols of some popular DeFi platforms, such as Compound\(^\text{46}\) and Brave\(^\text{47}\), and the audit reports are publicly available. With the assurance on those smart contract protocols where the entity performs its blockchain or DeFi activities, the auditor could understand, identify, and further control audit risks of the audit related to the DeFi environment by using the report from external specialists. It is important to remember that no smart contract code is completely fault-

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\(^{44}\) “DeFi Hacks & Historical Cryptocurrency Exploits.” 2020. Available at: https://defirate.com/hacks/.

\(^{45}\) OpenZeppelin website. https://openzeppelin.com/

\(^{46}\) Compound audit report by OpenZeppelin. April 2019. Available at: https://blog.openzeppelin.com/compound-audit/.

\(^{47}\) Basic Attention Token (BAT) audit report by OpenZeppelin. May 2017. Available at: https://blog.openzeppelin.com/basic-attention-token-bat-audit/.
tolerant regardless of the rigor of pre-installation review. As we see with phone “Apps” developed by smart software engineers which even after exhaustive reviews they find code bugs almost every month for many successful “Apps.”

4.4.3 Audit of Oracles

The authenticity of off-chain data, such as exchange rates of crypto assets, provided by oracles, is critical for the implementation of smart contracts in the DeFi environment (ISACA 2020). However, oracles do not always provide accurate numbers to smart contracts. For instance, Liu and Szalachowski (2020) investigated and reported the price deviations of ETH-USD between the active oracles (MakerDAO, Compound, and Synthetix) and the claimed price sources, respectively. These price deviations would heavily impact the accuracy of smart contract execution, eroding people’s trust in the DeFi environment. Hence, audits of oracles are necessary to ensure the authenticity and accuracy of off-chain numbers offered by these oracles. For example, Compound’s Open Oracle System48, one of the major oracles, was audited by OpenZeppelin, and one high severe issue that “inconsistencies in stored data may lead to incorrect median price” was identified and explained. These audits may help oracles fix those identified issues, improving the quality of data injected into the DeFi environment. Moreover, the involvement of assured centralized data providers in oracles may also help enhance the data quality. For instance, Kraken announced49 that it would provide its minute spot

48 Compound’s Open Oracle System audit report by OpenZeppelin. February 2020. Available at: https://blog.openzeppelin.com/compound-open-oracle-audit/
exchange rates (the Kraken Oracle Rates) to a node on Chainlink, another leading oracle in the DeFi world.

4.4.4 Audit for Blockchain Protocols

The reliability of blockchain protocols was identified as a challenge to verify the existence of crypto assets (Pimentel, Boulianne, Eskandari, and Clark 2020). As the underlying technology of the crypto asset ecosystem, the blockchain protocols should be independently assured first to further assure the assertions for crypto assets that run on those blockchain protocols. Although the Bitcoin and Ethereum blockchains, two dominant blockchain environments, have never been hacked until now (ISACA 2020), it is not guaranteed it will not happen. Furthermore, there are more emerging blockchain protocols, permissioned or permissionless, that are running, and the assurance on them should be provided to ensure their security.

Auditors cannot simply rely on the records on blockchains until the security of blockchain protocols is reasonably verified and assured. Blockchain protocols should be independently audited to assure the integrity and authenticity of transactions and record on blockchains. Many factors of blockchains, such as the consensus mechanism, the cryptography, and the size of the users (nodes), would affect the reliability of blockchain protocols (ISACA 2020; Pimentel et al. 2020). For instance, the risk of the 51% attack issue should be evaluated after understanding the blockchain consensus mechanism (Proof-of-
Work (PoW)\textsuperscript{50}, Proof-of-Stake (PoS)\textsuperscript{51}, etc.) and the size of the community. The subsequent hack or breach events on blockchains should also be alerted (Castonguay and Smith 2020).

4.4.5 Audit for Reserve Accounts of Stablecoins

Stablecoins “include mechanisms designed to minimize price volatility by linking their values (for example, a ‘peg’) to the value of a more traditional asset, such as a fiat currency or a commodity (AICPA 2020a)” and are regarded as the driver of the DeFi growth. Therefore, validating whether the reserve account of the pegged asset(s) maintains a sufficient balance as the outstanding stablecoin builds the confidence in the stablecoin. Tether (USDT), with the highest outstanding circulation among all stablecoins, was criticized that it could not be audited while others could. This inauditability might be a reason alleviating the public’s trust in USDT, driving its total supply down to around 80\%\textsuperscript{52}.

On the other hand, Circle, the institute issued USD Coin (USDC), regularly performed the US Dollars reserve audits by the independent accounting firm Grant Thornton\textsuperscript{53}. The latest audit report on the “reserve account“ indicated that all the USDC tokens outstanding (3,002,021,340 USDC) are fully backed by the US Dollars in its custody account ($3,004,921,958) at 11:59 PM (PT) on November 30, 2020\textsuperscript{54}. Moreover,

\textsuperscript{50} Proof-of-Work (PoW) is “a blockchain consensus mechanism involving solving of computationally intensive puzzles to validate transactions and create new blocks. (Crypto Glossary from CoinMarketCap).” Available at: https://coinmarketcap.com/alexandria/glossary.
\textsuperscript{51} Proof-of-Stake (PoS) is “a blockchain consensus mechanism involving choosing the creator of the next block via various combinations of random selection and wealth or age of staked coins or tokens. (Crypto Glossary from CoinMarketCap).” Available at: https://coinmarketcap.com/alexandria/glossary.
\textsuperscript{52} “Tether’s Stablecoin Dominance Drops Below 80% as Audit Controversy Lingers On.” September 27, 2020. Available at: https://news.bitcoin.com/tethers-stablecoin-dominance-drops-below-80-as-audit-controversy-lingers-on-on/.
\textsuperscript{53} The regular “reserve account” audit reports, starting from October 2018, are available at the Circle’s website, https://www.centre.io/usdc-transparency.
\textsuperscript{54} Independent Accountant’s Report from Grant Thornton. Available at:
Paxos, the issuer of Binance USD (BUSD), also provided monthly attestation reports from another accounting firm Withum\textsuperscript{55}. The latest audit report on “reserve account“ indicated that all the BUSD tokens outstanding (984,118,176.56 BUSD) are exactly backed by the US Dollars in the accounts held by Paxos at U.S. depository institutions ($984,118,176.56) at 5:00 PM (ET) on December 31, 2020\textsuperscript{56}.

4.4.6 Understand the Purpose of the Entity to Involve in Crypto Asset Transactions

Understanding the purpose of the entity to involve in the crypto asset ecosystem is an important step for auditors to evaluate the audit risks of the entity. Whether it is the regular transaction nature with its suppliers and/or customers, speculative short-term or long-term investment, or strategic purchase tokens to participate in some innovative projects would heavily impact the plan and execution of the audit. The nature of the crypto asset ecosystem, such as the amount, the platform (centralized or decentralized), and the number of transaction counterparties in the crypto asset ecosystem, also needs to be considered. This issue is especially critical for the client initially involve in crypto asset transactions or significantly change its transaction behavior for the audit period.

Furthermore, auditors would also need to examine the exchange rate risk management strategy on crypto assets. For instance, understanding the portfolio of crypto assets and the hedging activities for crypto assets (e.g., purchase derivatives) would be

\textsuperscript{55} The regular “reserve account“ audit reports, starting from September 2019, are available at the Paxos’s website, \url{https://www.paxos.com/attestations/}.

necessary to be performed for auditors.

4.4.7 “Off-chain” and “On-chain” Transactions Reconciliation

Cangemi and Brennan (2019) indicated that “blockchain networks often have incomplete or a limited amount of data needed to perform an audit of a complete process of end-to-end transactions.” Auditors must consider how to reconcile “on-chain (off-chain)” transactions between the entity’s accounting modules in the Enterprise Resource Planning (ERP) systems and blockchains and wallets (centralized exchanges and OTC markets) to ensure all relevant assertions. This reconciliation would help auditors assess the completeness, existence, and occurrence assertions. To accomplish this goal, accounting firms may seek external professional service providers or develop in-house tools. For example, PwC’s proprietary tool, Halo, assists auditors in providing assurance services to entities engaging crypto asset transactions and claims the tool could independently verify the ownership of crypto assets and that the entity’s private keys will not be shared with PwC and other organizations\(^\text{57}\). EY’s Blockchain Analyzer “is designed to facilitate and support Audit teams in the reconciliation of data between the client’s books and records and the public ledger\(^\text{58}\).” The tool development may require accounting firms to hire specialists with crypto assets and blockchain domain knowledge (Vincent and Wilkins 2020) and invest more capital and time.

“The vast majority of economic transactions with crypto assets today are not


Centralized exchanges tend to commingle intra-exchange transactions (Pimentel et al. 2020) and only post the “net” amount records on blockchains. In other words, the transaction detail of each entity would never be recorded on blockchains. Those “off-chain” transactions could only be extracted from internal databases of centralized exchanges. If an auditor is examining crypto asset transactions for an entity and only extracts transactional data from blockchains where the crypto assets that the entity transacted reside, they will fail to secure a complete transaction data set to audit. Auditors need to identify the whole map of centralized exchanges, custodians, and OTC markets where the entity traded its crypto assets to completely examine all transactions.

4.4.8 Valuation (Fair Value Measurement)

Because of the extremely high price volatility, how to accurately and objectively measure the fair value of crypto assets becomes an important issue to address. The trading nature of crypto assets that the blockchains and exchanges are operated 24/7 and worldwide is different from other typical financial instruments, which have a clear-cut “closing” trading timing, making the valuation for crypto assets more difficult. Under the existing accounting classification for crypto assets, indefinite-lived intangibles for most entities (AICPA 2020a)\(^{59}\), the accurate fair value measurement would help auditors examine the valuation assertion for crypto assets. Specifically, for instance, to understand whether the performed impairment test and the recognized amount of the impairment loss are

\(^{59}\) Crypto assets (cryptocurrencies) would be classified as “inventories” if the entity “holds cryptocurrencies for sale in the ordinary course of business (PwC 2019).”
reasonable, auditors may use the valuation service from the engagement team or external specialists to support their audit opinion. Beigman, Brennan, Hsieh, and Sannella (2021) proposed a methodology for the fair value measurement of actively traded cryptocurrencies. The methodology could dynamically identify the principal market for the specific crypto-crypto or crypto-fiat currency pair and determine the fair value for the pair at any designated time interval, consistently complying with the accounting guidance about fair value measurement under ASC 820 and IFRS 13.

4.4.9 Private Key Management and General Information Technology Control

To audit crypto asset transactions, private key management (the generation, usage, authorization, storage, etc.) and ITGC of the entity are necessary for auditors to understand, evaluate, and examine (CPA Canada 2020). The ownership of private keys is directly linked with the ownership of related crypto assets, supporting the relevant assertions such as existence and rights and obligations (AICPA 2020a; CPAB 2018; CPA Canada 2018; Vincent and Wilkins 2020). However, auditors need to be careful about the difference between the ownership of crypto assets on the balance sheet date and the audit procedure execution date (Pimentel et al. 2020).

For the entity with a highly automated IT environment, auditors “may conclude that substantive procedures alone cannot provide sufficient appropriate audit evidence at the assertion level (CPA Canada 2020)” and need to rely on the design and the implementing effectiveness of ITGC related to crypto assets.
4.4.10 Identification of Related Parties

Auditors are required “to obtain sufficient appropriate audit evidence to determine whether related parties and relationships and transactions with related parties have been properly identified, accounted for, and disclosed in the financial statements (PCAOB 2014).” The pseudonymous nature of blockchains and the often complete anonymity of Defi platforms make the auditors’ task much more difficult to link and identify the relationship between the virtual addresses and the physical identity of the transaction counterparties, increasing the risk of the failure to identify and disclose related party transactions. Auditors need to identify the complete list of possible related parties, especially those that have crypto asset transactions with the entity, link the addresses with the related parties, and extract the history of all the transaction records between the entity and related parties. Blockchain Explorer services or other proprietary tools of accounting firms may help to address this issue to identify related parties of the entity on blockchains and examine those transactions.

4.4.11 Revenue Recognition

Revenue recognition is an important issue for entities performing crypto assets “mining”\(^60\)” or “staking”\(^61\)” activities whose revenues are material to their operating

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\(^60\) Mining is “a process where blocks are added to a blockchain, verifying transactions. It is also the process through which new bitcoin or some altcoins are created (Crypto Glossary from CoinMarketCap).” Available at: [https://coinmarketcap.com/alexandria/glossary](https://coinmarketcap.com/alexandria/glossary).

\(^61\) Staking is the “participation in a proof-of-stake (PoS) system to put your tokens in to serve as a validator to the blockchain and receive rewards (Crypto Glossary from CoinMarketCap).” Available at: [https://coinmarketcap.com/alexandria/glossary](https://coinmarketcap.com/alexandria/glossary).
performance (CPAB 2018). Airdrops⁶² also invoke this revenue recognition issue. The timing, the exchange rate, and the amount of mining/staking rewards to recognize as revenues on their accounting books need to be accurately controlled and recorded. The auditor should understand the relevant accounting processes and treatments of the entity about its revenue recognition for crypto asset transactions and ensure those processes and treatments are consistently implemented.

The above issues on revenue recognitions are also essential to apply for DeFi activities, such as lending and borrowing of crypto assets. For example, what methodology (or exchange rate) is used to translate crypto assets into functional currencies and when to recognize related interest expense or income are topics that auditors should care about.

4.4.12 Subsequent Events

It could be disclosed as a subsequent event when the entity decides to participate in the crypto asset environment during the audit report date and the end of the fiscal year significantly. For example, Tesla, Inc., a calendar-year company issuing its 10-K filing on February 8, 2021⁶³, disclosed its $1.5 billion of bitcoin investment in January 2021 as a subsequent event - the purpose, the initial recognition, and the subsequent accounting policy of the bitcoin investment were explained.

Given the high price volatility of crypto assets, it might be possible that the price of crypto assets in which an entity is holding a material amount on the balance sheet date

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⁶² Airdrop is “a marketing campaign that distributes a specific cryptocurrency or token to an audience (Crypto Glossary from CoinMarketCap).” Available at: https://coinmarketcap.com/alexandria/glossary.

⁶³ The Investor Relation section of Tesla website. Available at: https://ir.tesla.com/sec-filings
is significantly (upward or downward) changed during the subsequent period\textsuperscript{64}. If that’s the case, the management and the auditor may consider disclosing the information about the price change in the financial statements to keep them from being misleading (PCAOB 2017). For instance, in the 10-Q filing of the Grayscale Bitcoin Trust for the quarter ended on September 30, 2020, the fair value of one bitcoin used in the preparation of financial statements was determined as $10,708.57. The Grayscale Bitcoin Trust, however, disclosed one subsequent event that “as of the close of business on November 2, 2020, the fair value of Bitcoin determined in accordance with the Trust’s accounting policy was $13,676.00 per Bitcoin.\textsuperscript{65}” Furthermore, if the centralized exchanges, custodians, blockchains, or DeFi applications, for example, that the entity frequently traded on were hacked, the hacks and their impacts might need to be disclosed in the financial statements to inform their users.

4.4.13 Independence

“Independence of mind is the state of mind that permits a member to perform an attest service without being affected by influences that compromise professional judgment, thereby allowing an individual to act with integrity and exercise objectivity and professional skepticism (AICPA 2020b).” Under the crypto asset ecosystem setting, for instance, it needs to be considered whether the independence level is affected if one entity

\textsuperscript{64} The price of a Dogecoin (DOGE), whose market capitalization ranked as #13 on Jan. 31, 2021, was $0.004836 at 11:44:03 PM on Dec. 31, 2020. However, it dramatically increased to $0.070872 per Dogecoin at 11:44:03 PM on Jan. 28, 2021, a 1,466\% price jump. This significant price change might be treated as a subsequent event and disclosed in the financial statement of the entity, if the entity’s Dogecoin holding amount is material. Relevant price information was derived from the CoinMarketCap website, available at: https://coinmarketcap.com/currencies/dogecoin/.

\textsuperscript{65} The 10-Q filing of the Grayscale Bitcoin Trust for the quarter ended on September 30, 2020 is available at: https://sec.report/Document/0001564590-20-051953/#NOTES_TO_UNAUDITED_FINANCIAL_STATEMENTS.
is audited by an accounting firm that also issued SOC reports for an exchange where the entity traded crypto assets, or which also audited smart contracts which the entity involved DeFi activities. Moreover, it could become an independence threat when the auditor obtains the entity’s private key(s) to perform relevant existence or control tests (ABC 2019; Vincent and Wilkins 2020).

4.4.14 Critical Audit Matters

Auditors may determine to disclose a critical audit matter (CAM)\(^66\) item in the independent auditor’s report when the entity significantly participates in the crypto asset ecosystem or holds material balances of crypto assets. For example, in the 10-K filing of Grayscale Bitcoin Trust for the fiscal year ended on December 31, 2019, the auditor disclosed one CAM item as “Investments in Bitcoin.” Many external factors about crypto assets that we discussed increase the risks out of the entity’s controls. The CAM disclosure mentioned that, for example, “the currently unregulated and immature nature of the Bitcoin market including clearing, settlement, custody and trading mechanisms, the dependency on information technology to sustain Bitcoin continuity, as well as valuation and volume volatility all subject Bitcoin to unique risks of theft, loss, or other misappropriation as well as valuation uncertainty.”\(^67\) We expect that more auditors would identify crypto asset-related issues as CAMs in auditor’s reports after more and more entities are gradually

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\(^66\) “A critical audit matter is any matter arising from the audit of the financial statements that was communicated or required to be communicated to the audit committee and that: (1) relates to accounts or disclosures that are material to the financial statements and (2) involved especially challenging, subjective, or complex auditor judgment (PCAOB 2017).”

stepping in the crypto asset ecosystem.

4.4.15 The Regulation Ambiguity in Nomenclature, Auditing, and Accounting

There is a lack of authoritative regulatory guidance for accounting treatments and auditing standards for blockchains and crypto asset transactions. It is the “wild west” out there with individuals or entities with material positions in new and existing crypto assets just trying to figure out on their own how to best report these within existing accounting standards. Furthermore, data stored on the blockchain ecosystem often lack conformity and established standards such that the nomenclature may vary from blockchain to blockchain, from exchange to exchange. The review and normalization of data within the blockchain ecosystem would be a critical part of a meaningful audit.

4.4.16 The Data Storage Limitation on Blockchains

Generally speaking, crypto asset blockchains, as most blockchains, have a very limited amount of transactional information on the chain due to distribution issues. “Blockchains by design carry a limited amount of information in the database in order to ensure privacy (Cangemi and Brennan 2019).” The ledger cannot be allowed to expand so much that it can no longer be efficiently distributed to miners or stakers in a timely and efficient manner – known as blockchain “bloat.” For instance, the anecdotal news⁶⁸ indicated that the size of the whole Bitcoin blockchain dramatically increased from 60 MB

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in January 2011 to 320 GB in January 2021 because blockchains keep all history of transaction records without any deletions. Auditors should take this increase of Bitcoin blockchain and other developing blockchains into consideration in terms of the design and execution of audits.

### 4.4.17 The Realization of Continuous Auditing

The characteristics (decentralization, immutability, and completeness) of on-chain records enable continuous auditing and monitoring to be realized (Dai and Vasarhelyi 2017; Liu, Wu, and Xu 2019). The realization would progress the audit from the traditional sample-based toward to the full population-based, increasing the strength of the audit evidence and the efficiency and effectiveness of audits.

### 4.5 Conclusions

Even as the crypto asset ecosystem continues to grow and evolve, the authoritative auditing standards are still on their way. This essay reviews the recent non-authoritative guidance from professional organizations on crypto assets-related audits, proposes a framework of auditing in the crypto asset ecosystem, and discusses unique risks, issues, and challenges for auditing crypto assets. This research provides researchers, standard setters, practitioners, and auditors with a comprehensive view of auditing the crypto asset ecosystem.

This essay contributes to the literature in the following perspectives. First of all, we propose a comprehensive framework for auditing the crypto asset ecosystem. This
framework would be beneficial for different stakeholders, including general companies, crypto asset funds, service providers in the crypto asset ecosystem, standard setters, and accounting firms. Second, we depict the whole crypto asset ecosystem by identifying different groups of players in the ecosystem and illustrating their relationship with the entity. The whole picture of the ecosystem would assist auditors with identifying and addressing specific issues and risks during the audit involving crypto asset transactions.

Finally, this research is the first academic one in the accounting domain discussing the auditing for entities involving in DeFi activities, providing more insights into the practice.

Accounting education should be innovated. The specialized knowledge in blockchains and crypto assets of the audit engagement team and the entity are heavily emphasized in those professional guidances (AICPA 2020a; CPA Canada 2018; PCAOB 2020). Therefore, accounting education needs to teach not only general accounting and auditing standards but also auditing advanced technologies, such as blockchains and crypto assets. Students’ knowledge of advanced technologies will become their competitive advantage as accounting professionals in the next generation.

The development of blockchains and crypto assets not only brings new challenges and risks but also provides brand-new assurance opportunities to the accounting and auditing practice (Bennett, Charbonneau, Leopold, Mezon, Paradine, Seilipoti, and Villmann 2020; Calderón and Stratopoulos 2020; Dai and Vasarhelyi 2017). This essay identifies some of the assurance possibilities (SOC 1 and 2 examinations, smart contract code assurance, audits for oracles and blockchain protocols, and continuous auditing) that auditors can pursue after addressing relevant conceptual and technical issues. These possibilities would significantly change the landscape of the crypto asset ecosystem audit
in the future.
CHAPTER 5 CONCLUSION AND FUTURE RESEARCH

This dissertation contributes to the accounting literature and the practice by proposing two fair value measurement methodologies for actively and thinly traded cryptocurrencies to provide reliable and faithfully representative cryptocurrency fair value for financial reporting purposes. The first methodology enables users to dynamically identify the principal market of the targeted actively traded cryptocurrency and determine the fair value in any designated time intervals. The second methodology provides fair value measures for thinly traded cryptocurrencies that have few or even no available actual trades between the cryptocurrencies and the USD (the reporting currency for the financial reporting). The optimal path, created by pairs with much higher transaction volume with other mainstream intermediary cryptocurrencies, is identified for the thinly traded cryptocurrency to generate reliable fair value measures under the second methodology.

The accounting standards about the fair value measurement under ASC 820 and IFRS 13 are consistently followed by both methodologies for cryptocurrencies. Both methodologies, executed automatically, offer more reliable and faithfully representative fair value measures to users to prepare their financial reporting and will be beneficial to general companies, qualified investment companies, hedge funds, and accounting firms.

This dissertation also contributes to the auditing literature by proposing a framework for auditing the crypto asset ecosystem. Moreover, the relationship between various participants in the crypto asset ecosystem and the audited entity is also identified, which is helpful to discover specific risks and challenges that auditors should address. The third essay, to my best knowledge, is the first academic research in the accounting domain discussing the auditing for entities involving in DeFi activities, a highly developing and
evolving field. This framework would be beneficial for different stakeholders, including general companies, crypto asset funds, participants in the crypto asset ecosystem, various service providers, accounting firms, and standard setters.

The distinct and unprecedented characteristics of cryptocurrencies are worthy of exploring and investigating. For instance, the microstructure, the price discovery, and the order book flows of fragmented cryptocurrency markets would be the subsequent research topics. Furthermore, the accounting and auditing of central bank digital currency (CBDC), sharing some characteristics with cryptocurrencies, is also a suitable research topic and will contribute to the literature and the practice.
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