

Hedging Cryptos with Bitcoin Futures

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Abstract

The introduction of derivatives on Bitcoin, in particular the launch of futures contracts on CME in December 2017 and introduction of cryptocurrency indices like the CRIX or the Bloomberg Galaxy Crypto Index enables investors to hedge risk exposures of Bitcoin by futures or contingent claims on indices. We investigate methods of finding an optimal hedge ratio h^* under different dependence structures modeled by copulae and employing different optimality definitions based on a range of risk measures. Because of volatility swings and jumps in Bitcoin prices, the traditional variance-based approach to obtain the hedge ratios is infeasible. The techniques are therefore generalised to various risk measures, such as Value-at-Risk, Expected Shortfall and more general, Spectral Risk Measures. In addition, we deploy different copulae for capturing the dependency between spot and future returns, such as the Gaussian, Student- t , NIG and Archimedean copulae. Various measures of hedge effectiveness in out-of-sample tests give insights in the practice of hedging Bitcoin. We find that across copulae and risk measures, the hedge effectiveness are very similar with the exception of the Frank copula, Expected Shortfall 99% and Value-at-Risk 99%. Our findings are based on an analysis for the time span from 29/12/2017 to 27/05/2021. The results allow

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investors to construct a stable portfolio with digital assets.

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1 Introduction

Cryptocurrencies (CCs) are a growing asset class. Many more CCs are now available on the market since the first cryptocurrency Bitcoin (BTC) surfaced (Nakamoto, 2009). In response to the rapid development of the CC market, the CME group launched a BTC future contract in Dec 2017. Trading volume in BTC futures surpassed \$2 trillion in 2020 (CryptoCompare, 2020).

In April 2021, the market value of outstanding coins had risen to 2.3t, more than 6% of the world's narrow money supply and almost 3% of the world GDP. While more and more investors (individuals and institutions) are adding CCs and their derivatives into their portfolios, we see the need to understand the downside risk and find a suitable way to hedge against extreme risks. The price of BTC even surged to USD 60,000 in April 2021. Investment into CCs therefore require proper quantification of their dynamics, but more importantly, exact understanding of their dependency with surfacing contingent claims, e.g. futures and options. This paper analyses quantitative techniques for the choice of the hedge ratio of the CC portfolios with various copulae and risk measures.

The optimal hedge ratio is the appropriate size of futures contracts which should be held such that the movements in future price cancel that of BTC. The task of determining an optimal hedge ratio is not easy. It relies on the dependence between the BTC price and future price. Copulae provide the flexibility to model multivariate random variable separately by its margins and dependence structure. The concept of copulae was originally developed (but not under this name) by Wassily Hoeffding (Hoeffding, 1940a), later popularised by the work of Abe Sklar (Sklar, 1959).


Different risk measures account for investors' risk attitude. They serve as loss functions in the searching process of optimal hedge ratio. Vast literature discussed the relationship between risk measures and investor's risk attitude, we refer readers to Artzner et al. (1999) for an axiomatic, economic reasoning approach of risk measure construction; Embrechts et al. (2002) for reasoning of using Expected Shortfall (ES) and Spectral Risk Measure (SRM) in addition to VaR; Acerbi (2002) for direct linkage between risk measures and investor's risk attitude using the concept of "risk aversion function".

Financial asset return is known to be non Gaussian (Fama, 1963). In particular, Gaussian models cannot produce so-called fat tails and asymmetry of observed probability densities, which leads to underestimate financial risks. Therefore, one cannot solely rely on 2nd order moment calculations in order to minimize downside risk. Variance as a risk measure doesn't consider the variety of investors' utility functions. However, the investors are tail-risk averse. Bollerslev et al. (2015) find that the jump tail risk is more closely associated with changes in risk-aversion. It is important to link the investor utility's functions as hedging the tail risk. Significant tail risks lead to the need to investigate even static hedges with more refined methods than minimum-variance based (Ederington and Salas, 2008).

In order to capture the risk preferences of investors, in addition to variance, we include other risk measures. We consider also Value-at-Risk (VaR), Expected Shortfall (ES), and Spectral Risk Measures (SRM). VaR is widely used by the industry and easy to understand. ES and SRM are chosen because of their coherence property, in particular, they encourage diversification. SRM is also directly related to individual's utility function. Popular examples are the exponential SRM and power SRM introduced by Dowd et al. (2008).

This paper considers hedging BTC using its future. i.e. to find an optimal hedge ratio h^* such

that the risk of a hedged portfolio $r^h = r^S - h^*r^F$ has minimal risk. Here r^S as the log return of BTC spot price, r^F the log return of BTC future. The leptokurtic properties mentioned above leads us to deploy a comprehensive way of modelling dependency namely copulae together with various risk measures as loss function to find optimal hedge ratio. We first calibrate the log returns of BTC and CME future by copulae, then find the optimal quantity of assets in the hedged portfolio according to a range of risk measures. Barbi and Romagnoli (2014) use the C-convolution operator introduced by Cherubini et al. (2011) to derive the distribution of linear combination of margins with copula as their dependence structure. We slightly amend their lemma and come up with a formula for the linear combination of random variables for our purpose.

This paper is organized as follows. Section 2 introduces the notion of optimal hedge ratio; section 3 describes the method of estimation of copulae; section 4 provides the empirical result; section 5 concludes. All calculations in this work can be reproduced. The results are reproducible with data and codes available on www.quantlet.com .

2 Optimal hedge ratio

We form a portfolio with two assets, a spot asset and a future contract, for example Bitcoin spot and CME Bitcoin future. Our objective is to minimize the risk of the exposure in the spot. To keep a simple portfolio setting, we long one unit of the spot and short h unit of the future with $h \in [0, \infty)$. Let r^S and r^F be the log returns of the spot and future price, the log return of the portfolio is

$$r^h = r^S - hr^F.$$

We call this portfolio a hedged portfolio: the price movement of spot is hedged by the price movement of future.

Risk is measured by risk measures. Assume the payoff r^h of a hedge portfolio lives in a probability space, $r^h \in L(\Omega, \mathcal{F}, \mathbb{P})$, and there is a risk measure on r^h $\rho : r^h \mapsto \mathbb{R}$. We are looking for an optimal hedge ratio (OHR) h^* which minimizes a risk measure:

$$h^* = \underset{h}{\operatorname{argmin}} \rho(r^h).$$

Most risk measures are defined as functionals of the portfolio loss distribution F_{r^h} , i.e. $\rho : F_{r^h} \mapsto \mathbb{R}$. For example, Value-at-Risk (VaR) is simply the quantile of r^h multiply with negative one $\operatorname{VaR}_{1-\alpha} = -F_{r^h}^{(-1)}(1 - \alpha) = -\inf\{x \in \mathbb{R} : 1 - \alpha \leq F_{r^h}(x)\}$, where α is a parameter chosen by investor. We need the knowledge of F_{r^h} in order to measure risk. By convolution of random variables (Härdle and Simar, 2019), $f_{r^h}(z) = \int_{-\infty}^{\infty} f_{r^S, -hr^F}(x, z - x)dx$, where $f_{r^S, -hr^F}$ is the joint pdf of r^S and $-hr^F$. Obviously the cdf of r^h and the risk measure depend on the joint distribution of r^S and $-hr^F$.

Optimising h according to $f_{r^S, -hr^F}$ is unfavorable in a sense that one needs to calibrate a new joint pdf $f_{r^S, -hr^F}$ when updating h . This is too time consuming and unnecessary. Another problem of using the joint pdf is that one lacks the flexibility to model the margins. A joint pdf completely determines the form of its marginals, for example, margins of a bivariate t -distribution are univariate t -distributions.

To overcome such a problem, we use copulae. The benefit of using copulae is two folded. First, copulae allow us to model the margins and dependence structure separately, see Sklar's Theorem.

Second, copulae are invariant under strictly monotone increasing function (Schweizer et al., 1981), see lemma below.

Theorem 1 (Hoeffding Sklar Theorem) *Let F be a joint distribution function with margins F_X, F_Y . Then, there exists a copula $C : [0, 1]^2 \mapsto [0, 1]$ such that, for all $x, y \in \mathbb{R}$*

$$F(x, y) = C\{F_X(x), F_Y(y)\}. \quad (1)$$

If the margins are continuous, then C is unique; otherwise C is unique on the range of the margins.

Conversely, if C is a copula and F_X, F_Y are univariate distribution functions, then the function F defined by (1) is a joint distribution function with margins F_X, F_Y .

Indeed, many basic results about copulae can be traced back to early works of Wassily Hoeffding (Hoeffding, 1940b, 1941). The works aimed to derive a measure of relationship of variables which is invariant under change of scale. See also Fisher and Sen (2012) for English translations of the original papers written in German. The following lemma is not hard to prove.

Lemma 1

$$C_{X,hY}\{F_X(s), F_{hY}(t)\} = C_{X,Y}\{F_X(s), F_Y(t/h)\}. \quad (2)$$

Leveraging the two features of copulae, Barbi and Romagnoli (2014) introduces the distribution of linear combination of random variables using copulae. We slightly edit the Corollary 2.1 of their work and yield the following correct expression of the distribution.

Proposition 2 *Let X and Y be two real-valued continuous random variables on a probability space $(\Omega, \mathcal{F}, \mathbf{P})$ with absolutely continuous copula $C_{X,Y}$ and marginal distribution functions F_X and F_Y . Then, the distribution function of Z is given by*

$$F_Z(z) = 1 - \int_0^1 D_1 C_{X,Y} \left[u, F_Y \left\{ \frac{F_X^{(-1)}(u) - z}{h} \right\} \right] du. \quad (3)$$

Here, $F^{(-1)}$ denotes the inverse of F , i.e., the quantile function.

Here $D_1 C(u, v) = \frac{\partial}{\partial u} C(u, v)$ see e.g. Equation (5.15) of (McNeil et al., 2005):

$$D_1 C_{X,Y}\{F_X(x), F_Y(y)\} = \mathbf{P}(Y \leq y | X = x). \quad (4)$$

Proof. Using the identity (4) gives

$$\begin{aligned} F_Z(z) &= \mathbf{P}(X - hY \leq z) = \mathbf{E} \left\{ \mathbf{P} \left(Y \geq \frac{X - z}{h} \middle| X \right) \right\} \\ &= 1 - \mathbf{E} \left\{ \mathbf{P} \left(Y \leq \frac{X - z}{h} \middle| X \right) \right\} = 1 - \int_0^1 D_1 C_{X,Y} \left[u, F_Y \left\{ \frac{F_X^{(-1)}(u) - z}{h} \right\} \right] du. \end{aligned}$$

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Corollary 1 *Given the formulation of the above portfolio, the pdf of Z can be written as*

$$f_Z(z) = \left| \frac{1}{h} \right| \int_0^1 c_{X,Y} \left[F_Y \left\{ \frac{F_X^{(-1)}(u) - z}{h} \right\}, u \right] \cdot f_Y \left\{ \frac{F_X^{(-1)}(u) - z}{h} \right\} du \quad (5)$$

, or

$$f_Z(z) = \int_0^1 c_{X,Y} \left[F_X \left\{ z + hF_Y^{(-1)}(u) \right\}, u \right] \cdot f_X \left\{ z + hF_Y^{(-1)}(u) \right\} du. \quad (6)$$

The two expressions are equivalent. Notice that the pdf of Z in the above proposition is readily accessible as long as we have the copula density and the marginal densities. The proof and a generic expression can be found in the appendix.

3 Empirical Procedure

We discuss the empirical procedure to obtain the OHR.

First, we split the time series of spots and future into sets of training and testing data. The training data is the first 300 observations and its corresponding testing data is the consecutive 5 observations. We roll 5 observations forward to obtain the next training and test data and repeat this until the end of the time series. Notice that the testing data are non-overlapping.

Next, we obtain the OHR as follows:

1. **Construct Univariate Kernel Density Function (KDE).** With the training data, we obtain the spot and future's univariate kernel density function using the Gaussian kernel with bandwidth determined by the refined plug-in method (Härdle et al., 2004, section 3.3.3).
2. **Calibrate Copulae.** We then calibrate copulae outlined in 3.1 via the method of moments described in 3.3.1.
3. **Select Copula.** We compute the Akaike Information Criterion. The copula with the lowest AIC is used for the next step. Discussion of this step is in 3.5.
4. **Search for OHR.** We search OHRs using different risk measures as loss function numerically by drawing samples from the selected copula and KDEs. Risk measures used as risk reduction objectives are outlined in 3.6
5. **Obtain testing log-return of hedged portfolio.** We apply the OHRs to the testing data $r_h = r_s - h^* r_f$.

3.1 Copulae

As we saw from the last section, risk measures we considered are all functionals of the joint distribution of r^S and r^F . We test different copulae: Gaussian-, t -, Frank-, Gumbel-, Clayton-, Plackett-, mixture, and factor copula. This hedging exercise concerns only portfolios with two assets, we only present the bivariate version of copulae and some important features of a copula, they include Kendall's τ , Spearman's ρ , upper tail dependence $\lambda_U \stackrel{\text{def}}{=} \lim_{q \rightarrow 1^-} \mathbf{P}\{X > F_X^{(-1)}(q) | Y > F_Y^{(-1)}(q)\}$ and lower tail dependence $\lambda_L \stackrel{\text{def}}{=} \lim_{q \rightarrow 0^+} \mathbf{P}\{X \leq F_X^{(-1)}(q) | Y \leq F_Y^{(-1)}(q)\}$. Furthermore, we denote the Fréchet-Hoeffding lower bound as \mathbf{W} , product copula as $\mathbf{\Pi}$, and the Fréchet-Hoeffding upper

bound as \mathbf{M} , they represent cases of perfect negative dependence, independence, and perfect positive dependence respectively. For further detail, we refer readers to Joe (1997) and Nelsen (1999). See also Härdle and Okhrin (2010).

3.1.1 Elliptical Copulae

Elliptical copulae define dependence structures associated with elliptical distributions. The bivariate Gaussian copula is:

$$\begin{aligned} C(u, v) &= \Phi_{2,\rho}\{\Phi^{-1}(u), \Phi^{-1}(v)\} \\ &= \int_{-\infty}^{\Phi^{-1}(u)} \int_{-\infty}^{\Phi^{-1}(v)} \frac{1}{2\pi\sqrt{1-\rho^2}} \exp\left\{\frac{s^2 - 2\rho st + t^2}{2(1-\rho^2)}\right\} ds dt \end{aligned} \quad (7)$$

where $\Phi_{2,\rho}$ is the cdf of bivariate Normal distribution with zero mean, unit variance, and correlation ρ , and Φ^{-1} is quantile function univariate standard normal distribution. Please note that we use ρ here to represent the correlation parameter in a Gaussian copula only for traditional purposes. In other sections, $\rho(\cdot)$ is a risk measure. The Gaussian copula density is

$$\begin{aligned} c_\rho(u, v) &= \frac{\varphi_{2,\rho}\{\Phi^{-1}(u), \Phi^{-1}(v)\}}{\varphi\{\Phi^{-1}(u)\} \cdot \varphi\{\Phi^{-1}(v)\}} \\ &= \frac{1}{2\pi\sqrt{1-\rho^2}} \exp\left\{-\frac{u^2 - 2\rho uv + v^2}{2(1-\rho^2)}\right\}, \end{aligned} \quad (8)$$

where $\varphi_{2,\rho}(\cdot)$ is the pdf of $\Phi_{2,\rho}$, and $\varphi(\cdot)$ the standard normal distribution pdf.

The Kendall's τ_K and Spearman's ρ_S of a bivariate Gaussian Copula are

$$\tau_K(\rho) = \frac{2}{\pi} \arcsin \rho \quad (9)$$

$$\rho_S(\rho) = \frac{6}{\pi} \arcsin \frac{\rho}{2} \quad (10)$$

The t -Copula has a form

$$\begin{aligned} C(u, v) &= \mathbf{T}_{2,\rho,\nu}\{T_\nu^{-1}(u), T_\nu^{-1}(v)\} \\ &= \int_{-\infty}^{T_\nu^{-1}(u)} \int_{-\infty}^{T_\nu^{-1}(v)} \frac{\Gamma\left(\frac{\nu+2}{2}\right)}{\Gamma\left(\frac{\nu}{2}\right) \pi \nu \sqrt{1-\rho^2}} \end{aligned} \quad (11)$$

$$\left(1 + \frac{s^2 - 2st\rho + t^2}{\nu}\right)^{-\frac{\nu+2}{2}} ds dt, \quad (12)$$

where $\mathbf{T}_{2,\rho,\nu}(\cdot, \cdot)$ denotes the cdf of bivariate t distribution with scale parameter ρ and degree of freedom ν , $T_\nu^{-1}(\cdot)$ is the quantile function of a standard t distribution with degree of freedom ρ .

The copula density is

$$c(u, v) = \frac{\mathbf{t}_{2,\rho,\nu}\{T_\nu^{-1}(u), T_\nu^{-1}(v)\}}{t_\nu\{T_\nu^{-1}(u)\} \cdot t_\nu\{T_\nu^{-1}(v)\}}, \quad (13)$$

where $\mathbf{t}_{2,\rho,\nu}$ is the pdf of $\mathbf{T}_{2,\rho,\nu}(\cdot, \cdot)$, and t_ν the density of standard t distribution.

Like all the other elliptical copulae, t copula's Kendall's τ is identical to that of Gaussian copula (see Demarta and McNeil, 2005, and references therein).

3.1.2 Archimedean Copulae

The family of Archimedean copulae forms a large class of copulae with many convenient features. In general, they take a form

$$\mathbf{C}(u, v) = \psi^{-1}\{\psi(u), \psi(v)\}, \quad (14)$$

where $\psi : [0, 1] \rightarrow [0, \infty)$ is a continuous, strictly decreasing and convex function such that $\psi(1) = 0$ for any permissible dependence parameter θ . ψ is also called generator. ψ^{-1} is the inverse of the generator.

The Frank copula (B3 in Joe (1997)) is a radial symmetric copula and cannot produce any tail dependence. It takes the form

$$\mathbf{C}_\theta(u, v) = \frac{1}{\theta} \log \left\{ 1 + \frac{(e^{-\theta u} - 1)(e^{-\theta v} - 1)}{e^{-\theta} - 1} \right\} \quad (15)$$

where $\theta \in [0, \infty]$ is the dependency parameter. $\mathbf{C}_{-\infty} = \mathbf{M}$, $\mathbf{C}_1 = \mathbf{\Pi}$, and $\mathbf{C}_\infty = \mathbf{W}$.

The Copula density is

$$\mathbf{c}_\theta(u, v) = \frac{\theta e^{\theta(u+v)(e^\theta - 1)}}{\{e^\theta - e^{\theta u} - e^{\theta v} + e^{\theta(u+v)}\}^2} \quad (16)$$

Frank copula has Kendall's τ and Spearman's ρ as follow:

$$\tau_K(\theta) = 1 - 4 \frac{D_1\{-\log(\theta)\}}{\log(\theta)}, \quad (17)$$

and

$$\rho_S(\theta) = 1 - 12 \frac{D_2\{-\log(\theta)\} - D_1\{\log(\theta)\}}{\log(\theta)}, \quad (18)$$

where D_1 and D_2 are the Debye function of order 1 and 2. Debye function is $D_n = \frac{n}{x^n} \int_0^x \frac{t^n}{e^t - 1} dt$.

Gumbel copula (B6 in Joe (1997)) has upper tail dependence with the dependence parameter $\lambda^U = 2 - 2^{\frac{1}{\theta}}$ and displays no lower tail dependence.

$$\mathbf{C}_\theta(u, v) = \exp - \{(-\log(u))^\theta + (-\log(v))^\theta\}^{\frac{1}{\theta}}, \quad (19)$$

where $\theta \in [1, \infty)$ is the dependence parameter. While Gumbel copula cannot model perfect counter dependence (Nelsen, 2002), $\mathbf{C}_1 = \mathbf{\Pi}$ models the independence, and $\lim_{\theta \rightarrow \infty} \mathbf{C}_\theta = \mathbf{W}$ models the perfect dependence.

$$\tau_K(\theta) = \frac{\theta - 1}{\theta} \quad (20)$$

The Clayton copula, by contrast to Gumbel copula, generates lower tail dependence in a form $\lambda^L = 2^{-\frac{1}{\theta}}$, but cannot generate upper tail dependence.

The Clayton copula takes the form

$$C_\theta(u, v) = \left\{ \max(u^{-\theta} + v^{-\theta} - 1, 0) \right\}^{-\frac{1}{\theta}}, \quad (21)$$

where $\theta \in (-\infty, \infty)$ is the dependency parameter. $\lim_{\theta \rightarrow -\infty} C_\theta = \mathbf{M}$, $C_0 = \mathbf{\Pi}$, and $\lim_{\theta \rightarrow \infty} C_\theta = \mathbf{W}$.

Kendall's τ to this copula dependency is

$$\tau_K(\theta) = \frac{\theta}{\theta + 2}. \quad (22)$$

3.1.3 Mixture Copula

Mixture copula is a linear combination of copulae. For a 2-dimensional random variable $\mathbf{X} = (X_1, X_2)^\top$, its distribution can be written as linear combination K copulae

$$\mathbf{P}(X_1 \leq x_1, X_2 \leq x_2) = \sum_{k=1}^K p^{(k)} \cdot C^{(k)}\{F_{X_1}^{(k)}(x_1; \gamma_1^{(k)}), F_{X_2}^{(k)}(x_2; \gamma_2^{(k)}); \boldsymbol{\theta}^{(k)}\} \quad (23)$$

where $p^{(k)} \in [0, 1]$ is the weight of each component, $\gamma^{(k)}$ is the parameter of the marginal distribution in the k^{th} component, and $\boldsymbol{\theta}^{(k)}$ is the dependence parameter with the copula of the k^{th} component. The weights add up to one $\sum_{k=1}^K p^{(k)} = 1$.

We deploy a simplified version of the above representation by assuming the margins of \mathbf{X} are not mixture. By Sklar's theorem one may write

$$C(u, v) = \sum_{k=1}^K p^{(k)} \cdot C^{(k)}\{F_{X_1}^{-1}(u), F_{X_2}^{-1}(v); \boldsymbol{\theta}^{(k)}\}. \quad (24)$$

The copula density is again a linear combination of copula density

$$c(u, v) = \sum_{k=1}^K p^{(k)} \cdot c^{(k)}\{F_{X_1}^{-1}(u), F_{X_2}^{-1}(v); \boldsymbol{\theta}^{(k)}\}. \quad (25)$$

While Kendall's τ of mixture copula is not known in close form, the Spearman's ρ is

Proposition 3 *Let $\rho_S^{(k)}$ be the Spearman's ρ of the k^{th} component and $\sum_{k=1}^K p^{(k)} = 1$ holds, the Spearman's ρ of a mixture copula is*

$$\rho_S = \sum_{k=1}^K p^{(k)} \cdot \rho_S^{(k)} \quad (26)$$

Proof. Spearman's ρ is defined as (Nelsen, 1999)

$$\rho_S = 12 \int_{\mathbb{I}^2} \mathbf{C}(s, t) ds dt - 3. \quad (27)$$

Rewrite the mixture copula into summation of components

$$\rho_S = 12 \int_{\mathbb{I}^2} \sum_{k=1}^K p^{(k)} \cdot \mathbf{C}^{(k)}(s, t) ds dt - 3. \quad (28)$$

■

Example 4 The Fréchet class can be seen as an example of mixture copula. It is a convex combinations of \mathbf{W} , $\mathbf{\Pi}$, and \mathbf{M} (Nelsen, 1999)

$$\mathbf{C}_{\alpha, \beta}(u, v) = \alpha \mathbf{M}(u, v) + (1 - \alpha - \beta) \mathbf{\Pi}(u, v) + \beta \mathbf{W}(u, v), \quad (29)$$

where α and β are the dependence parameters, with $\alpha, \beta \geq 0$ and $\alpha + \beta \leq 1$. Its Kendall's τ and Spearman's ρ are

$$\tau_K(\alpha, \beta) = \frac{(\alpha - \beta)(\alpha + \beta + 2)}{3} \quad (30)$$

, and

$$\rho_S(\alpha, \beta) = \alpha - \beta \quad (31)$$

We use a mixture of Gaussian and independent copula in our analysis. We write the copula

$$\mathbf{C}(u, v) = p \cdot \mathbf{C}^{\text{Gaussian}}(u, v) + (1 - p)(uv). \quad (32)$$

The corresponding copula density is

$$\mathbf{c}(u, v) = p \cdot \mathbf{c}^{\text{Gaussian}}(u, v) + (1 - p). \quad (33)$$

This mixture allows us to model how much "random noise" appear in the dependency structure. In this hedging exercise, the structure of the "random noise" is not of our concern nor we can hedge the noise by a two-asset portfolio. However, the proportion of the "random noise" does affect the distribution of r^h , so as the optimal hedging ratio h^* . One can consider the mixture copula as a handful tool for stress testing. Similar to this Gaussian mix Independent copula, t copula is also a two parameter copula allow us to model the noise, but its interpretation of parameters is not as intuitive as that of a mixture. The mixing variable p is the proportion of a manageable (hedgable) Gaussian copula, while the remaining proportion $1 - p$ cannot be managed.

3.2 Other Copula

The Plackett copula has an expression

$$\mathbf{C}_\theta(u, v) = \frac{1 + (\theta - 1)(u + v)}{2(\theta - 1)} - \frac{\sqrt{\{1 + (\theta - 1)(u + v)\}^2 - 4uv\theta(\theta - 1)}}{2(\theta - 1)} \quad (34)$$

$$\rho_S(\theta) = \frac{\theta + 1}{\theta - 1} - \frac{2\theta \log \theta}{(\theta - 1)^2} \quad (35)$$

We include Plackett copula in our analysis as it possesses a special property, the cross-product ratio is equal to the dependence parameter

$$\begin{aligned} & \frac{\mathbf{P}(U \leq u, V \leq v) \cdot \mathbf{P}(U > u, V > v)}{\mathbf{P}(U \leq u, V > v) \cdot \mathbf{P}(U > u, V \leq v)} \\ &= \frac{\mathbf{C}_\theta(u, v) \{1 - u - v + \mathbf{C}_\theta(u, v)\}}{\{u - \mathbf{C}_\theta(u, v)\} \{v - \mathbf{C}_\theta(u, v)\}} \\ &= \theta. \end{aligned} \quad (36)$$

That is, the dependence parameter is equal to the ratio between number of concordance pairs and number of discordance pairs of a bivariate random variable.

3.3 Estimation

3.3.1 Simulated Method of Moments

This method is suggested by (Oh and Patton, 2013). In our setting, rank correlation e.g. Spearman's ρ or Kendall's τ , and quantile dependence measures at different levels λ_q are calibrated against their empirical counterparts.

Spearman's rho, Kendall's tau, and quantile dependence of a pair (X, Y) with copula C are defined as

$$\rho_S = 12 \int \int_{I^2} C_\theta(u, v) \, du \, dv - 3 \quad (37)$$

$$\tau_K = 4 \mathbf{E}[C_\theta\{F_X(x), F_Y(y)\}] - 1, \quad (38)$$

$$\lambda_q = \begin{cases} \mathbf{P}(F_X(X) \leq q | F_Y(Y) \leq q) = \frac{C_\theta(q, q)}{q}, & \text{if } q \in (0, 0.5], \\ \mathbf{P}(F_X(X) > q | F_Y(Y) > q) = \frac{1 - 2q + C_\theta(q, q)}{1 - q}, & \text{if } q \in (0.5, 1). \end{cases} \quad (39)$$

The empirical counterparts are

$$\begin{aligned} \hat{\rho}_S &= \frac{12}{n} \sum_{k=1}^n \hat{F}_X(x_k) \hat{F}_Y(y_k) - 3, \\ \hat{\tau}_K &= \frac{4}{n} \sum_{k=1}^n \hat{C}\{\hat{F}_X(x_k), \hat{F}_X(y_k)\} - 1, \\ \hat{\lambda}_q &= \begin{cases} \frac{1}{n} \sum_{k=1}^n \frac{\mathbf{1}_{\{\hat{F}_X(x_k) \leq q, \hat{F}_Y(y_k) \leq q\}}}{q}, & \text{if } q \in (0, 0.5], \\ \frac{1}{n} \sum_{k=1}^n \frac{\mathbf{1}_{\{\hat{F}_X(x_k) > q, \hat{F}_Y(y_k) > q\}}}{1 - q}, & \text{if } q \in (0.5, 1). \end{cases} \end{aligned}$$

where $\hat{F}(x) \stackrel{\text{def}}{=} \frac{1}{n} \sum_{k=1}^n \mathbf{1}_{\{x_i \leq x\}}$ and $\hat{C}(u, v) \stackrel{\text{def}}{=} \frac{1}{n} \sum_{k=1}^n \mathbf{1}_{\{u_i \leq u, v_i \leq v\}}$.

We denote by $\tilde{\mathbf{m}}(\boldsymbol{\theta})$ the m -dimensional vector of dependence measures according to the dependence parameters $\boldsymbol{\theta}$, and $\hat{\mathbf{m}}$ be the corresponding empirical counterpart. The difference between dependence measures and their counterpart is denoted by

$$\mathbf{g}(\boldsymbol{\theta}) = \hat{\mathbf{m}} - \tilde{\mathbf{m}}(\boldsymbol{\theta}).$$

The SMM estimator is

$$\hat{\boldsymbol{\theta}} = \underset{\boldsymbol{\theta} \in \Theta}{\operatorname{argmin}} \mathbf{g}(\boldsymbol{\theta})^\top \hat{\mathbf{W}} \mathbf{g}(\boldsymbol{\theta}),$$

where $\hat{\mathbf{W}}$ is some positive definite weight matrix.

In this work, we use $\tilde{\mathbf{m}}(\boldsymbol{\theta}) = (\rho_S, \lambda_{0.05}, \lambda_{0.1}, \lambda_{0.9}, \lambda_{0.95})^\top$ for calibration of Bitcoin price and CME Bitcoin future.

3.4 Maximum Likelihood Estimation

By the Hoeffding-Sklar theorem, the joint density of a d -dimensional random variable \mathbf{X} with sample size n can be written as

$$\mathbf{f}_{\mathbf{X}}(x_1, \dots, x_d) = \mathbf{c}\{F_{X_1}(x_1), \dots, F_{X_d}(x_d)\} \prod_{j=1}^d f_{X_j}(x_j). \quad (40)$$

We follow the treatment of MLE documented in section 10.1 of Joe (1997), namely the inference functions for margins or IFM method. The log-likelihood $\sum_{i=1}^n \mathbf{f}_{\mathbf{X}}(X_{i,1}, \dots, X_{i,d})$ can be decomposed into a dependence part and a marginal part,

$$L(\boldsymbol{\theta}) = \sum_{i=1}^n \mathbf{c}\{F_{X_1}(x_{i,1}; \boldsymbol{\delta}_1), \dots, F_{X_d}(x_{i,d}; \boldsymbol{\delta}_d); \boldsymbol{\gamma}\} + \sum_{i=1}^n \sum_{j=1}^d f_{X_j}(x_{i,j}; \boldsymbol{\delta}_j) \quad (41)$$

$$= L_C(\boldsymbol{\delta}_1, \dots, \boldsymbol{\delta}_d, \boldsymbol{\gamma}) + \sum_{j=1}^d L_j(\boldsymbol{\delta}_j) \quad (42)$$

where $\boldsymbol{\delta}_j$ is the parameter of the j -th margin, $\boldsymbol{\gamma}$ is the parameter of the parametric copula, and $\boldsymbol{\theta} = (\boldsymbol{\delta}_1, \dots, \boldsymbol{\delta}_d, \boldsymbol{\gamma})$.

Instead of searching the $\boldsymbol{\theta}$ is a high dimensional space, Joe (1997) suggests to search for $\hat{\boldsymbol{\delta}}_1, \dots, \hat{\boldsymbol{\delta}}_d$ that maximize $L_1(\boldsymbol{\delta}_1), \dots, L_d(\boldsymbol{\delta}_d)$, then search for $\hat{\boldsymbol{\gamma}}$ that maximize $L_C(\hat{\boldsymbol{\delta}}_1, \dots, \hat{\boldsymbol{\delta}}_d, \boldsymbol{\gamma})$.

That is, under regularity conditions, $(\hat{\boldsymbol{\delta}}_1, \dots, \hat{\boldsymbol{\delta}}_d, \hat{\boldsymbol{\gamma}})$ is the solution of

$$\left(\frac{\partial L_1}{\partial \boldsymbol{\delta}_1}, \dots, \frac{\partial L_d}{\partial \boldsymbol{\delta}_d}, \frac{\partial L_C}{\partial \boldsymbol{\gamma}} \right) = \mathbf{0}. \quad (43)$$

However, the IFM requires making assumption on the distribution of the margins. Genest et al. (1995) suggests to replace the estimation of marginals parameters estimation by non-parametric estimation. Given non-parametric estimator \hat{F}_i of the margins F_i , the estimator of the dependence

parameters γ is

$$\hat{\gamma} = \underset{\gamma}{\operatorname{argmax}} \sum_{i=1}^n c\{\hat{F}_{X_1}(x_{i,1}), \dots, \hat{F}_{X_d}(x_{i,d}); \gamma\}. \quad (44)$$

3.4.1 Comparison

Both the simulated method of moments and the maximum likelihood estimation are unbiased. The question though which procedure is more suitable for hedging.

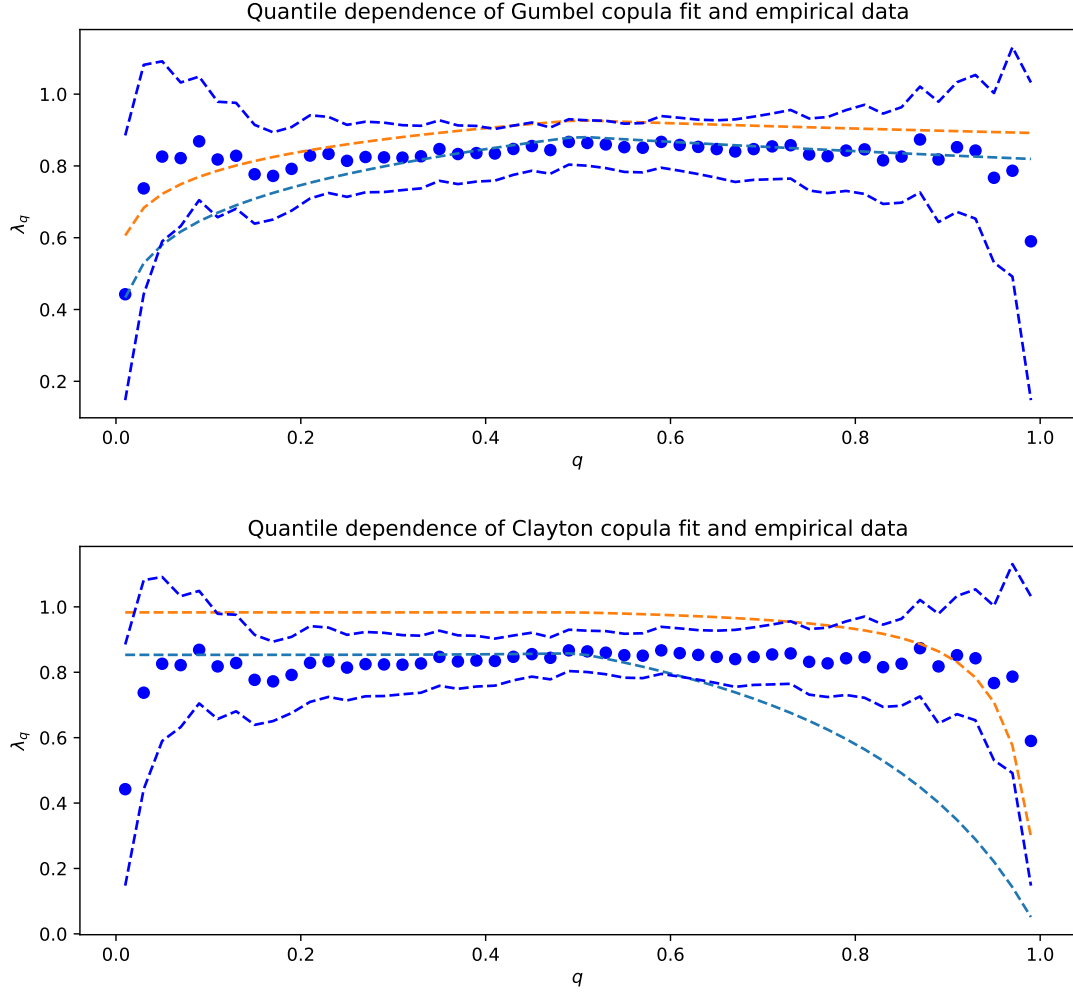



Figure 1: Quantile dependences of Gumbel, and Clayton Copula. The blue circle dots are the quantile dependence estimates of Bitcoin and CME future, blue dotted lines are the estimates' 90% confidence interval. Orange dotted line is the copula implied quantile dependence by MM estimation. Light blue dotted line is the copula implied quantile dependence by MLE estimation. 

Figure 1 shows the empirical quantile dependence of Bitcoin and CME future and the copula implied quantile dependence from MLE and MM calibration procedures. Although the MLE is a better fit to a range of quantile dependence in the middle, it fails to address the situation in the tails. Our data empirically has weaker quantile dependence in the ends, and those points generate PnL to the hedged portfolio. MM is preferred visually as it produces a better fit to the dependence structure in the two extremes. Therefore, we deploy the method of moments throughout the analysis. We choose the 5th-, 10th-, 90th-, 95th-quantile, and Spearman's ρ as the moments.

3.5 Copula Selection

The dependency structure of price data changes across time, in which both the dependency parameters and the type of dependency, dependencies between cryptos and the BTCF are no exception. In this hedging exercise, we find a best fitting copula to model the dependency for every set of training data. We select the best fitting copula that provides the lowest Akaike Information Criterion (AIC)

$$\text{AIC} = 2k - 2\log(L)$$

, where k is the number of estimated parameters and L is the likelihood.

Notice that there are other model selection procedures and criteria, e.g. TIC, likelihood ratio test. For a survey of model selection and inference, see Anderson et al. (1998). Among various copula selection procedures, AIC is a popular choice for its applicability, for example Breymann et al. (2003) use the AIC to select best fitting copulae. In our case, the AICs are calculated only with dependency likelihood since the marginals are modelled in kernel density. The selected copula will then be used to search for OHR.

3.6 Risk Measures

We consider a variety of risk measures: variance, Value-at-Risk (VaR), Expected Shortfall (ES), and Exponential Risk Measure (ERM). A summary of risk measures being used in portfolio selection problem can be found in Härdle et al. (2008).

Let Z be a random variable of distribution F_Z .

1. Variance is $\text{Var}(F_Z)$
2. VaR of a given confidence level α is $\text{VaR}(F_Z) = -F_Z^{(-1)}(1 - \alpha)$
3. ES with parameter α is $\text{ES}(F_Z) = -\frac{1}{1-\alpha} \int_0^{1-\alpha} F_Z^{(-1)}(p) dp$
4. ERM with Arrow-Pratt coefficient of absolute risk aversion k is $\text{ERM}_k(F_Z) = \int_0^{1-\alpha} \phi(p) F_Z^{(-1)}(p) dp$ where ϕ is a weight function described in (46) below.

VaR, ES, and ERM fall into the class of Spectral Risk Measure (SRM). SRM has the form (Acerbi, 2002)

$$\rho_\phi(r^h) = - \int_0^1 \phi(p) F_Z^{(-1)}(p) dp, \quad (45)$$

where p is the loss quantile and $\phi(p)$ is a user-defined weighting function defined over $[0, 1]$. We consider only admissible risk spectra $\phi(p)$

- i ϕ is positive
- ii ϕ is decreasing
- iii integrates to one.

The VaR's $\phi(p)$ gives all its weight on the $1 - \alpha$ quantile of Z and zero elsewhere, i.e. the weighting function is a Dirac delta function, hence violates the ii property of admissible risk spectra. The ES' $\phi(p)$ gives all tail quantiles the same weight of $\frac{1}{1-\alpha}$ and non-tail quantiles zero weight. ERM assumes investor's risk preference is in a form of exponential utility function $U(x) = 1 - e^{-kx}$, its corresponding risk spectrum is defined as

$$\phi(p) = \frac{ke^{-k(1-p)}}{1 - e^{-k}}, \quad (46)$$

where k is the Arrow-Pratt coefficient of absolute risk aversion.

The parameter k has an economic interpretation of being the ratio between the second derivative and first derivative of investor's utility function on a risky asset

$$k = -\frac{U''(x)}{U'(x)}, \quad (47)$$

for x in all possible outcomes. In case of the exponential utility, k is the constant absolute risk aversion (CARA).

4 Data

In the empirical analysis, we consider the risk reduction capability of the BTC-future (BTCF) on five cryptos, BTC, ETH, ADA, LTC, and XRP, and five crypto indexes, BITX, BITW100, CRIX, BITW20, and BITW70. For each of the 10 hedging portfolios, a crypto or index is considered as the spot and held in a unit size long position, and the BTCF is held in short position of OHR unit in order to reduce the risk of the spot. All the hedging portfolios are cross asset hedging except the BTCF portfolio. ETH, ADA, LTC, and XRP are popular cryptos tradable in various exchanges and have large market capitalization. BITX, BITW100, and CRIX are market-cap weighted crypto indexes with BTC as constituent. BITX and BITW100 tracks the total return of the 10 and 100 cryptos with largest market-cap respectively. CRIX decides the number of constituents by AIC and track that number of cryptos with largest market-cap. In our case, the number of constituents in CRIX is 5. BITW20 is also a market-cap weighted crypto index but with 20 largest market-cap cryptos outside the constituents of BITX. BITW70 has the same construction as BITW20 but with 70 largest market-cap cryptos outside BITX and BITW20. Therefore, BTC is excluded as constituent in BITW20 and BITW70.

We collect the spots' and BTCF's daily price at 15:00 US Central Time (CT). The reason of choosing this particular time is that the CME group determines the daily settlements for BTCFs based on the trading activities on CME Globex between 14:59 and 15:00 CT. 15:00 CT is also the reporting time of the daily closing price by the Bloomberg Terminal (BBT). Cryptos data are collected from a data provider called Tiingo. Tiingo aggregates crypto OHLC (open, high, low, and close) prices fed by APIs from various exchanges. Tiingo covers major exchanges, e.g. Binance, Gemini, Poloniex etc., so Tiingo's aggregated OHLC price is a good representation a market tradable price. For each crypto, we match the opening price at 15:00 CT from Tiingo with the daily closing price of BTCF from BBT. Since CRIX is not available at 15:00 CT, we recalculate a hourly CRIX using the monthly constituents weights and the hourly OHLC price data collected from Tiingo. BITX, BITW20,

BITW70, and BITW100 are collected from the official website of their publisher Bitwise.com. The daily reporting time of the Bitwise indexes is 15:00 CT.

At the time of writing, the CRIX' is undergoing the listing process on the S&P Dow Jones Indices, the official CRIX data will then be calculated with Lukka Prime Data and available to public via S&P.

5 Results

5.1 Copula Selection Results

The copula selection result provides insight that help us understand the crypto market better, so we illustrate the copula selection result in this section. Decisions of the AIC procedure are summarised in table 1.

Overall, t -copula, rotated Gumbel (rotGumbel), and the NIG factor copula are the most frequently chosen copulae by the AIC procedure.

The t -copula is frequently chosen by AIC to model the dependency between the BTC and BTC involved indices, CRIX, BITX, BITW100, and the BTC future. BTC and BTC involved indices exhibit strong tail dependence (both upper and lower tail) with BTCF. We could interpret tail dependence much more of a tendency for one asset to be extreme when another is extreme and vice versa (McNeil et al., 2015). In fact, the t copula has been suggested in various empirical studies to model financial data, such as Zeevi and Mashal (2002) and Breymann et al. (2003). Those studies suggest t -copula is a better model over the Gaussian copula which financial data often seem to exhibit tail dependence.

On the other hand, the radially symmetric feature makes the t -copula not a good choice to model the other hedging pairs. Demarta and McNeil (2005) describe the symmetry feature "strong", because if (U_1, \dots, U_d) is a vector distributed in t -copula, then $(U_1, \dots, U_d) \stackrel{\mathcal{L}}{=} (1 - U_1, \dots, 1 - U_d)$. This symmetry can be justified in the dependence structure between a future and its underlying by the theory of future pricing, which suggests the price of a future is a function of the underlying price (Hull, 2003). However, there is no such relationship between a future and an asset which is not the underlying, and so the radial symmetry becomes a drawback to model other hedging pairs e.g. ETH and BITX70. Another drawback of the t -copula is the lack of flexibility to model off-diagonal region since Rho and nu jointly control the density of the off-diagonal region. This is why sometimes the Gaussian Mix Independence (GMI) better model the dependence.

Among the three popular copulae, rotGumbel copula shows its ability to model the dependency between ETH and BTCF, 94 out of 112 training sets are best fitted with the rotated Gumbel. rotGumbel also performs well when modelling dependency between XRP, BITW20, BITW70, and the BTCF. In particular, the whole time series of the two indices, BITW20 and BITW70, are best fitted solely with the rotated Gumbel copula. The frequently chosen rotated Gumbel indicates the styled fact of financial data: prices tends to drop together.

In fact, Clayton's AIC in many of the training sets is the second lowest, just higher than that of rotated Gumbel. This is because the Clayton copula has the same ability to model the lower quantile dependence. However, Clayton's radial like feature does not match the behaviour of the financial data.

It is worth to mention that although the NIG factor copula is penalised heavily due to its three parameters setup, it is frequently chosen to be the best copula to model the dependency between

Copula/Asset	t	Plackett	GMI	rotGumbel	NIG
Individual Cryptos					
BTC	73	4	2	1	31
ETH	3	6	8	94	1
ADA	0	0	0	0	112
LTC	13	0	3	32	64
XRP	0	31	3	78	0
Crypto Indices with BTC Constituent					
BITX	39	0	14	16	12
CRIX	47	0	11	3	27
BITW100	42	0	8	29	2
Crypto Indices without BTC Constituent					
BITW20	0	0	0	78	3
BITW70	0	0	0	80	1

Table 1: Copula Selection Results.

individual cryptos and the BTC future. An extreme case would be ADA, only NIG factor is chosen in our dataset. Another dependency structure being best described by the NIG factor copula is the pair of LTC-BTC future. 64 out of 112 training sets are best fitted by the NIG factor copula. Indices like BITX and CRIX are sometimes best fitted with the NIG factor copula as well, accounting for modelling 12 and 27 training sets respectively. The popularity of the NIG factor reflects the ability of the copula to model very complex dependency structure. NIG factor copula is able to model the tail, radial asymmetry, and off diagonal behaviour.

Frank copula is generally not a good choice to model financial data just like what Barbi and Romagnoli (2014) has reported. Plackett is known for its dependence parameter can be written as the cross-product ratio (Joe, 1997). However, this feature does not bring the Plackett Copula advantage over other copulae to model the dependence structure between cryptos and BTCF.

5.2 OHRs and Returns of Hedged Portfolios

We present an overview of the OHR and hedged portfolios log returns results in this section. Overall, the performance of the hedge largely depend on the spot assets, while the choice of risk minimisation objective does not affect much of the log return of hedge ratio. We present the summary statistics of the hedged portfolios returns in table 2 that aimed at minimising ERM $k = 10$.

We can see from table 2 that the summary statistics of hedged portfolio returns differ. As expected, the BTC-involved portfolios, i.e. portfolios with BTC, CRIX, BITX, and BITW100 as spot, have a relatively small standard deviations (std) and maximum drawdowns (MD). However, the kurtosis (kurt) of the portfolio returns are higher than the other portfolios except XRP. This result suggests that the variance of the BTC-involved spots are well hedged but not the jump risk (extreme events). In fact, extreme events are hard to model and predict, even the BTC-BTCF portfolio cannot escape from this. Nonetheless, the skewness (skew) are close to zero.

Portfolios with spot of crypto indices that are not BTC-involved, i.e. BITW20 and BITW70, have relatively lower std and MD than portfolio with individual cryptos as spot. This indicates the overall

	Mean (10^{-3})	Std (10^{-3})	Skew	Kurt	LQ (10^{-3})	MD (10^{-3})
BTC	0.1948	3.9138	-0.8949	11.867	-1.2785	31.8969
CRIX	0.8048	8.8261	0.0677	14.939	-3.6619	70.5299
BITX	0.5896	10.0776	-0.4427	13.084	-3.5729	78.5815
BITW100	0.8526	12.0317	-1.6522	20.556	-4.2111	111.8459
BITW20	2.5642	36.0091	-0.3446	4.215	-13.5096	215.9201
BITW70	2.8181	39.0745	-0.6952	4.874	-16.0984	245.2498
ADA	1.3983	54.0242	1.0344	4.201	-26.5629	194.0610
ETH	1.0541	37.9113	0.8743	6.759	-17.0680	188.7288
LTC	-2.0647	42.7759	-0.0729	5.628	-22.2628	280.8793
XRP	-1.7083	64.9295	1.1923	21.932	-22.8506	525.6895

Table 2: Log returns statistics of hedged portfolios aimed at minimizing ERM $k = 10$.

market is indeed follow the BTC or the BTCF’s development, but individual cryptos can have their own price movement just as discuss in the last section.

Next, we illustrate the OHR time series of the BTC-BTCF and other hedge portfolios in figure 2 and 4 respectively. The two most fluctuating OHR time series are generated by minimising ES 99% and VaR 99%. ES 99% and VaR 99% are calculated based on a small fraction of data from the left tail of portfolio return, so the resulting OHR time series are relatively sensitive to extremes in the training data. The other OHR time series do not deviate from each other a lot.

In figure 4, we can observe a large range of OHR in other hedge portfolios. For BTC-involved indices, the OHRs are ranging from 0.75 to 1.05, slightly wider than range of BTC-BTCF’s OHR.

Again, we present the OHR time series generated by minimising ES 99% and VaR 99% are more fluctuating in different hedge portfolios. Furthermore, we can see more clearly in figure 4 that OHR minimising ES 99% are more extreme.

5.3 Hedging Effectiveness Results

In this section, we analyse the out-of-sample hedging effectiveness (HE) of BTCF as hedging. HE is defined as

$$HE = 1 - \frac{\rho_h}{\rho_s},$$

a measure of the percentage reduction of portfolio risk attribute, in our case the spot ρ_s , to hedged portfolio risk attribute ρ_h . A higher HE indicates a higher hedging effectiveness and larger risk reduction.

The HE above is a generalisation of Ederington measure of hedging performance, where we, in addition to variance, include other risk measures: Expected Shortfall 5% and 1% (ES5 and ES1), Value-at-Risk 5% and 1% (VaR5 and VaR1), and ERM. In particular, ES5 is recommended by the Basel Committee on Banking Supervision (BCBS) to replace VaR as a quantitative risk metrics system. The proposed reform aimed at enhancing the risk metric system’s ability to capture tail risk. We obtain a time series of out-of-sample r^h of each hedging pair and each risk reduction objective by concatenating the out-of-sample results. Then, we apply stationary block bootstrapping (SB) to the

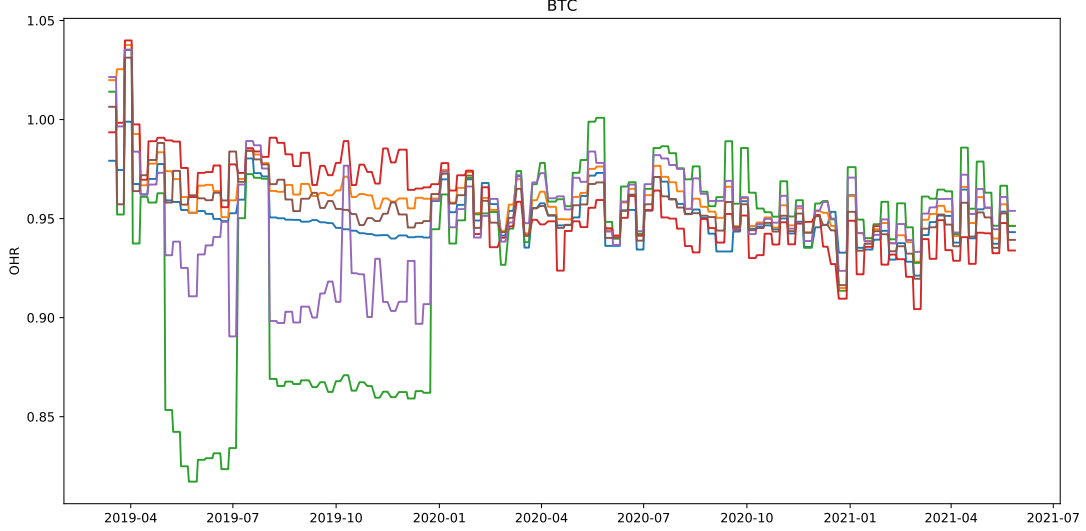



Figure 2: OHR of BTC-BTCF portfolio with different risk minimizing objectives. The blue line is OHR minimizing variance, orange line is that of ES 95%, green line is that of ES 99%, red line is that of VaR 95%, purple line is that of VaR 99%, and brown line is that of ERM $k = 10$. 

time series introduced by Politis and Romano (1994) in our analysis in order to preserve the temporal structure of the data while sampling. The SB procedure is as follow. Assume a time series with N observations $\{X_t\}_{t \in [1, N]}$ is a strong stationary, weakly dependence time series of interest, we form blocks of samples $B = \{X_i, \dots, X_{i+j-1}\}$. Index i is a random variable uniformly distributed over $[1, 2, \dots, N]$ and j is geometric distributed random variable with parameter p . The block index i and block length j are independent. For any index k which is greater than N , the sample X_k is defined to be $X_{k \pmod N}$. For each block, we calculate the hedging effectiveness with different risk measures mentioned above. We choose $p = 0.005$, implying the expected block length is 200. 100 blocks are drawn for each risk minimising objective and spot.

From figure 3, we report, as expected, the BTC involving spots, the BTC, CRIX, BITX and BITW100, are well hedged by the BTCF. Surprisingly, the performances are consistent across different risk reduction objectives and different HE evaluation. The median HE to BTC generated by various risk reduction objectives is ranging from 89.45% to 99.31%, median HE to CRIX is ranging from 81.13% to 95.22%, median HE to BITX is ranging from 79.06% to 94.84%, median HE to BITW100 is ranging from 71.07% to 92.98%.

The HE of BTCF to other cryptos and indices are substantially lower than to the BTC involving spots, but the consistency the performances across different risk reduction objectives and HE evaluation remains. The median HE to BITW20 generated by various risk reduction objectives is ranging from 24.67% to 47.02%, median HE to BITW70 is ranging from 23.61% to 49.30%, median HE to ADA is ranging from 9.01% to 29.30%, median HE to ETH is ranging from 30.07% to 36.18%, median HE to LTC is ranging from 37.74% to 51.30%, median HE to XRP is ranging from 0.46% to 30.89%.

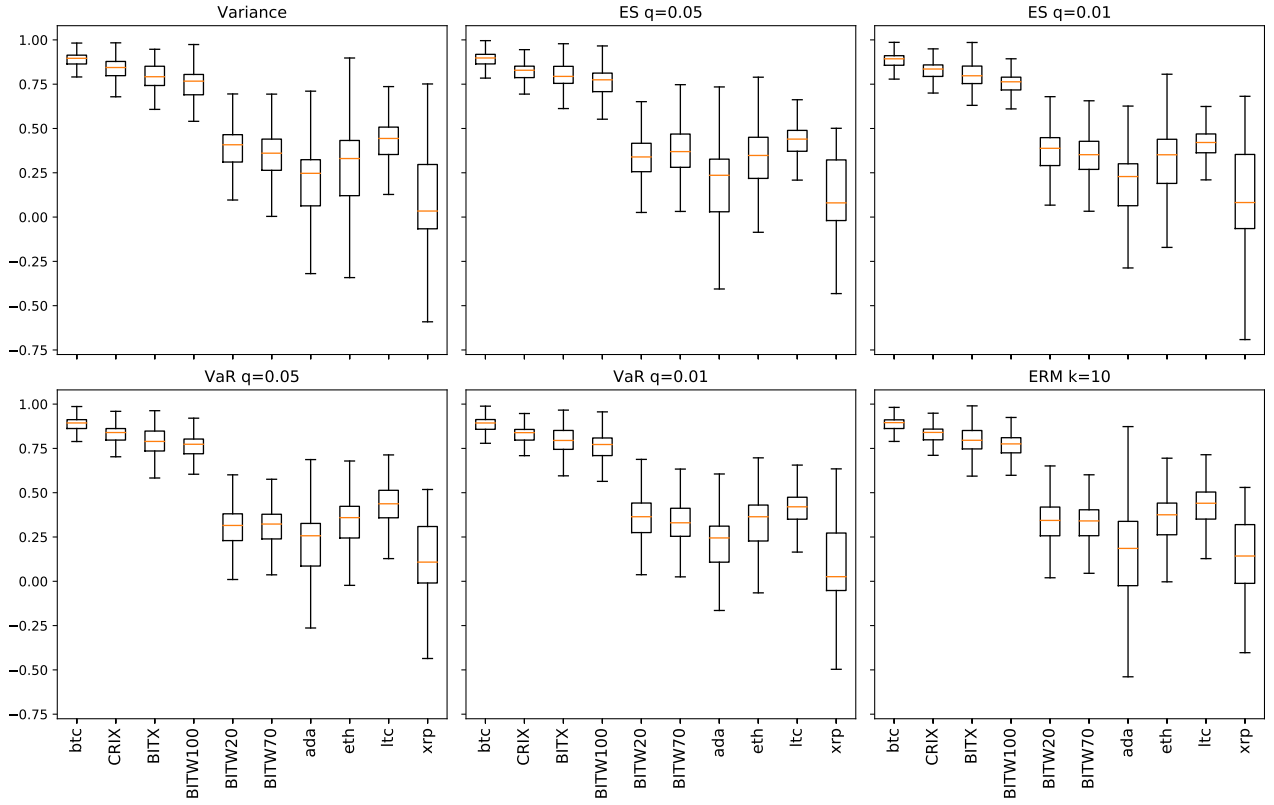



Figure 3: HE evaluated in different risk measures to various assets generated by minimizing ES5. The boxplots indicate the the median, upper quartile, lower quartile, minimum and maximum of the bootstrapped HE. 

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6 Appendix

6.1 Density of linear combination of random variables

Proposition 5 *Let $\mathbf{X} = (X_1, \dots, X_d)^\top$ be real-valued random variables with corresponding copula density $\mathbf{c}_{X_1, \dots, X_d}$, and continuous marginals F_{X_1}, \dots, F_{X_d} . Then, pdf of the linear combination of marginals $Z = n_1 \cdot X_1 + \dots + n_d \cdot X_d$ is*

$$f_Z(z) = |n_1^{-1}| \int_{[0,1]^{d-1}} \mathbf{c}_{X_1, \dots, X_d} \{F_{X_1} \circ S(z), u_2, \dots, u_d\} \cdot f_{X_1} \circ S(z) du_2 \dots du_d \quad (48)$$

$$S(z) = \frac{1}{n_1} \cdot z - \frac{n_2}{n_1} \cdot F_{X_2}^{(-1)}(u_2) - \dots - \frac{n_d}{n_1} \cdot F_{X_d}^{(-1)}(u_d) \quad (49)$$

Proof. Rewrite $Z = n_1 \cdot X_1 + \dots + n_d \cdot X_d$ in matrix form

$$\begin{bmatrix} Z \\ X_2 \\ \vdots \\ X_d \end{bmatrix} = \begin{bmatrix} n_1 & n_2 & \cdots & n_d \\ 0 & 1 & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_d \end{bmatrix} = \mathbf{A} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_d \end{bmatrix}. \quad (50)$$

By transformation variables

$$\mathbf{f}_{Z, X_2, \dots, X_d}(z, x_2, \dots, x_d) = \mathbf{f}_{X_1, \dots, X_d} \left(\mathbf{A}^{-1} \begin{bmatrix} z \\ x_2 \\ \vdots \\ x_d \end{bmatrix} \right) \cdot |\det \mathbf{A}^{-1}| \quad (51)$$

$$= |n_1^{-1}| \mathbf{f}_{X_1, \dots, X_d} \{S(z), x_2, \dots, x_d\} \quad (52)$$

Let $u_i = F_{X_i}(x_i)$ and use the relationship

$$\mathbf{c}_{X_1, \dots, X_d}(u_1, \dots, u_d) = \frac{\mathbf{f}_{X_1, \dots, X_d}(x_1, \dots, x_d)}{\prod_{i=1}^d f_{X_i}(x_i)}, \quad (53)$$

we have

$$\mathbf{f}_{Z, X_2, \dots, X_d}(z, x_2, \dots, x_d) = \quad (54)$$

$$|n_1^{-1}| \cdot \mathbf{c}_{X_1, \dots, X_d} \{F_{X_1} \circ S(z), u_2, \dots, u_d\} \cdot f_{X_1} \{S(z)\} \cdot \prod_{i=2}^d f_{X_i}(x_i) \quad (55)$$

The claim (48) is obtained by integrating out x_2, \dots, x_d by substituting $dx_i = \frac{1}{f_{X_i}(x_i)} du_i$. ■

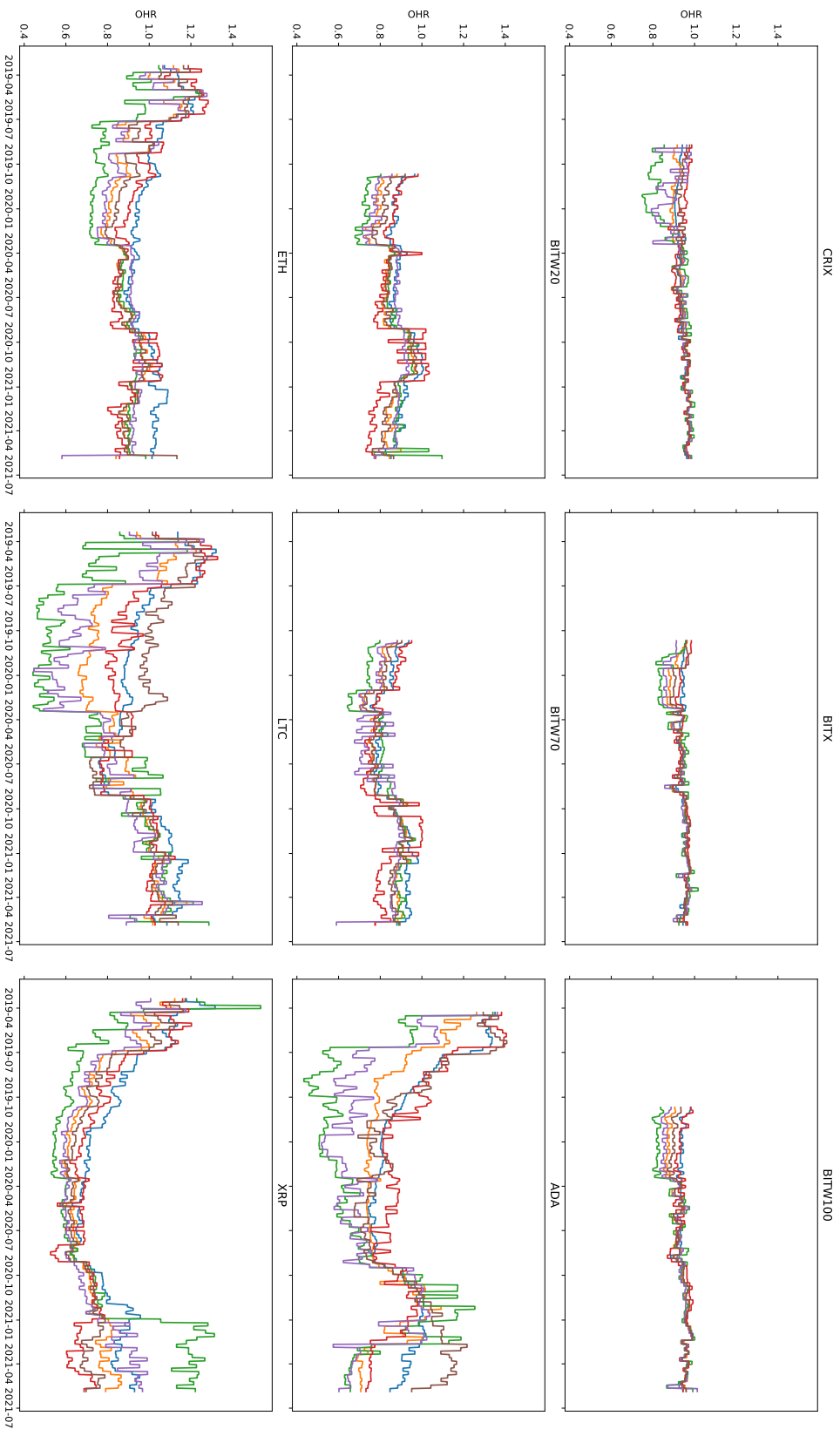


Figure 4: OHR time series. The blue line is OHR minimizing variance, orange line is that of ES 95%, green line is that of ES 99%, red line is that of VaR 95%, purple line is that of VaR 99%, and brown line is that of ERM $k = 10$. 

	Var	ES5	ES1	VaR5	VaR1	ERM
BTC	99.31 (98.40, 99.86)	99.25 (98.34, 99.82)	99.27 (98.12, 99.86)	99.25 (98.46, 99.78)	99.28 (98.28, 99.86)	99.30 (98.23, 99.86)
CRIX	95.02 (85.98, 98.52)	95.04 (87.00, 98.86)	95.22 (83.30, 97.91)	95.04 (86.04, 98.67)	95.07 (85.40, 98.62)	95.01 (84.14, 98.70)
BITX	94.84 (84.37, 98.28)	94.70 (73.72, 98.14)	94.67 (82.33, 97.78)	94.77 (83.14, 97.77)	94.77 (77.69, 97.98)	94.80 (78.11, 98.48)
BITW100	92.07 (73.32, 98.54)	92.60 (73.45, 97.38)	92.93 (77.25, 97.29)	92.61 (69.38, 97.66)	92.98 (76.04, 97.52)	92.98 (76.85, 97.33)
BITW20	43.55 (-30.18, 79.60)	45.23 (-68.19, 82.07)	44.97 (-85.52, 83.94)	44.96 (-31.97, 73.62)	45.23 (-48.61, 80.95)	45.03 (-8.90, 77.35)
BITW70	56.04 (0.15, 88.03)	50.02 (24.05, 85.20)	50.62 (15.39, 79.82)	51.53 (26.59, 82.52)	55.96 (0.33, 87.92)	51.08 (15.67, 85.45)
ADA	25.68 (-28.78, 77.79)	24.84 (-16.57, 66.57)	23.64 (-29.80, 69.98)	31.36 (-7.76, 66.96)	29.82 (-9.47, 63.61)	29.52 (-20.61, 73.02)
ETH	52.37 (-3.42, 77.97)	50.11 (-33.27, 79.83)	52.18 (-31.37, 76.85)	51.37 (-20.98, 79.51)	51.96 (-10.88, 77.82)	52.01 (-22.41, 77.25)
LTC	63.44 (13.20, 79.49)	63.98 (24.15, 78.81)	62.60 (-4.69, 82.24)	62.66 (17.31, 80.70)	61.91 (20.63, 77.07)	61.56 (10.01, 77.70)
XRP	8.74 (-96.85, 64.17)	9.77 (-59.11, 58.79)	7.93 (-138.77, 67.92)	13.31 (-32.20, 65.09)	15.75 (-60.90, 62.55)	17.47 (-37.66, 66.10)

Table 3: BTCF's Hedging Effectiveness to various assets generated by variance as risk reduction objectives.

	Var	ES5	ES1	VaR5	VaR1	ERM
BTC	89.53 (76.12, 96.61)	89.61 (74.80, 96.50)	90.06 (72.73, 96.08)	89.28 (72.48, 97.00)	89.56 (76.06, 97.11)	89.70 (76.21, 96.82)
CRIX	82.86 (17.60, 94.06)	83.88 (28.77, 96.97)	82.61 (17.49, 93.35)	83.00 (17.42, 94.86)	83.88 (17.68, 98.17)	83.87 (17.64, 96.71)
BITX	79.13 (14.24, 94.51)	79.43 (12.27, 95.93)	79.06 (7.56, 95.92)	80.48 (15.20, 97.22)	79.66 (17.52, 95.62)	79.09 (14.24, 94.82)
BITW100	76.72 (-16.03, 96.39)	76.93 (-13.96, 97.50)	77.19 (5.03, 95.69)	77.01 (-14.42, 97.38)	76.98 (-12.81, 97.04)	78.02 (43.40, 97.40)
BITW20	33.23 (-38.83, 118.59)	33.88 (-33.00, 92.83)	35.32 (-34.89, 130.64)	31.88 (-20.74, 104.16)	33.11 (-35.13, 86.43)	39.18 (0.14, 83.71)
BITW70	38.80 (-66.27, 99.80)	34.20 (-32.09, 90.66)	34.52 (-36.15, 91.29)	32.31 (-25.36, 83.22)	33.95 (-25.07, 91.86)	34.20 (-32.02, 88.59)
ADA	24.94 (-63.48, 60.88)	24.39 (-55.58, 52.86)	22.17 (-69.28, 59.55)	25.83 (-69.95, 54.54)	24.59 (-74.04, 68.74)	18.41 (-124.65, 75.89)
ETH	35.67 (-81.90, 74.46)	36.95 (-122.44, 69.69)	36.61 (-40.06, 70.90)	37.17 (-104.62, 73.28)	36.44 (-161.21, 71.94)	37.07 (-135.54, 72.57)
LTC	45.22 (-33.52, 68.60)	44.53 (-15.71, 65.71)	41.72 (-41.54, 64.15)	43.75 (-17.77, 64.35)	45.08 (-35.28, 67.23)	43.84 (-22.45, 63.83)
XRP	11.98 (-46.99, 48.36)	5.62 (-61.93, 46.20)	30.89 (-41.34, 54.99)	13.41 (-34.40, 47.49)	17.99 (-49.67, 47.69)	16.35 (-40.29, 46.29)

Table 4: BTCF's Hedging Effectiveness to various assets generated by ES5 as risk reduction objectives.

	Var	ES5	ES1	VaR5	VaR1	ERM
BTC	89.94 (76.14, 96.99)	89.61 (74.30, 96.59)	89.58 (71.78, 99.56)	89.45 (76.45, 97.28)	89.83 (77.43, 98.84)	89.78 (76.21, 96.71)
CRIX	82.70 (17.60, 96.30)	83.10 (17.69, 95.87)	82.73 (21.62, 95.68)	82.74 (23.50, 96.23)	83.20 (29.14, 98.17)	82.80 (17.58, 94.74)
BITX	77.26 (14.24, 94.73)	79.28 (11.28, 90.62)	77.32 (10.61, 95.92)	79.71 (15.20, 96.31)	78.57 (13.22, 95.62)	79.56 (14.24, 94.82)
BITW100	71.07 (-16.03, 97.98)	76.96 (-13.94, 97.50)	76.39 (39.65, 97.29)	71.47 (-14.42, 96.01)	77.04 (14.04, 92.76)	77.19 (-12.34, 90.08)
BITW20	46.51 (-35.56, 84.36)	46.72 (-33.00, 85.76)	44.38 (-36.06, 67.05)	46.80 (-30.65, 85.43)	46.29 (-35.13, 97.78)	46.27 (-32.72, 85.46)
BITW70	47.67 (-44.48, 66.74)	48.33 (-59.82, 91.50)	48.13 (-34.30, 90.15)	49.14 (-24.67, 86.79)	48.41 (-33.48, 90.91)	48.54 (-40.69, 88.54)
ADA	25.14 (-82.96, 65.94)	26.53 (-55.55, 66.27)	22.99 (-58.72, 62.64)	30.69 (-54.03, 64.28)	27.45 (-46.38, 65.49)	24.54 (-73.52, 70.12)
ETH	35.66 (-145.05, 72.13)	34.90 (-83.94, 74.05)	32.80 (-216.93, 74.31)	32.74 (-231.17, 81.89)	32.87 (-181.97, 85.99)	34.97 (-82.21, 73.95)
LTC	48.47 (-49.11, 69.38)	49.95 (-41.86, 69.00)	41.75 (-26.36, 64.15)	44.87 (-19.21, 71.32)	40.38 (-14.88, 64.78)	49.69 (-43.62, 68.71)
XRP	14.30 (-46.99, 52.33)	6.10 (-43.18, 52.87)	2.12 (-69.14, 57.56)	6.52 (-36.40, 58.62)	12.73 (-49.67, 54.07)	6.47 (-40.29, 51.13)

Table 5: BTCF's Hedging Effectiveness to various assets generated by ES1 as risk reduction objectives.

	Var	ES5	ES1	VaR5	VaR1	ERM
BTC	90.63 (76.14, 96.92)	91.57 (45.43, 111.65)	91.06 (62.57, 97.14)	90.68 (52.72, 97.39)	90.63 (65.56, 96.69)	90.55 (76.21, 96.71)
CRIX	82.78 (17.60, 96.00)	82.55 (17.69, 96.97)	85.89 (52.08, 102.36)	83.29 (29.72, 96.23)	82.82 (17.68, 98.17)	83.31 (17.64, 96.67)
BITX	80.41 (14.24, 94.70)	80.81 (12.27, 104.27)	80.69 (10.61, 95.92)	81.01 (15.20, 95.03)	80.25 (13.22, 96.63)	80.04 (14.24, 96.77)
BITW100	76.16 (-14.51, 96.35)	76.68 (-10.30, 96.61)	76.64 (-18.22, 97.29)	76.84 (-9.40, 97.38)	72.57 (-9.40, 89.55)	76.60 (9.63, 97.40)
BITW20	24.88 (-35.56, 91.15)	21.26 (-23.85, 67.95)	27.00 (-34.82, 126.95)	15.64 (-30.65, 65.43)	25.19 (-35.13, 96.54)	37.49 (-22.68, 188.71)
BITW70	30.53 (-66.27, 95.86)	28.34 (-57.01, 90.99)	34.13 (-59.52, 96.17)	26.96 (-24.58, 86.54)	34.18 (-88.64, 91.86)	30.25 (-40.69, 93.81)
ADA	16.41 (-60.63, 60.88)	13.95 (-92.23, 50.45)	11.89 (-44.49, 69.90)	17.49 (-59.28, 53.04)	13.66 (-67.42, 60.57)	9.01 (-124.17, 75.89)
ETH	33.22 (-166.80, 89.87)	35.08 (-137.57, 67.37)	36.79 (-134.39, 67.48)	34.63 (-175.16, 66.12)	32.80 (-153.11, 74.71)	36.43 (-157.40, 73.95)
LTC	36.69 (-116.22, 69.38)	38.08 (-93.67, 67.07)	36.29 (-17.99, 64.15)	39.03 (-45.19, 67.24)	36.61 (-26.42, 62.75)	36.57 (-80.88, 67.98)
XRP	17.39 (-46.99, 52.33)	4.74 (-65.41, 47.14)	-0.53 (-96.19, 53.67)	17.92 (-36.40, 49.22)	11.22 (-49.67, 47.69)	12.53 (-40.29, 47.48)

Table 6: BTCF's Hedging Effectiveness to various assets generated by VaR5 as risk reduction objectives.

	Var	ES5	ES1	VaR5	VaR1	ERM
BTC	89.30 (76.14, 96.92)	89.61 (76.08, 96.50)	89.28 (54.74, 96.14)	88.56 (75.18, 97.28)	89.66 (65.14, 95.95)	89.24 (76.18, 96.63)
CRIX	82.64 (17.60, 94.90)	83.23 (17.69, 92.93)	81.51 (55.37, 97.24)	83.72 (17.48, 95.33)	82.04 (55.38, 98.89)	84.03 (17.64, 93.19)
BITX	83.12 (14.24, 95.92)	75.57 (12.27, 95.93)	77.05 (7.56, 95.92)	83.41 (15.20, 95.03)	83.53 (13.22, 95.62)	83.50 (14.24, 94.82)
BITW100	80.49 (9.70, 96.35)	79.95 (9.65, 96.58)	80.13 (9.56, 95.69)	79.69 (9.70, 97.38)	79.89 (-13.27, 95.39)	71.62 (-12.38, 97.40)
BITW20	46.51 (-38.57, 105.55)	46.64 (-33.00, 85.58)	47.02 (-34.82, 70.43)	41.90 (-28.32, 83.81)	46.29 (-35.13, 116.79)	46.51 (-33.36, 105.31)
BITW70	47.67 (-39.94, 95.86)	48.33 (-41.90, 95.89)	47.47 (-39.17, 90.15)	49.30 (-47.76, 83.22)	48.41 (-34.83, 90.91)	48.54 (-32.02, 88.54)
ADA	28.73 (-65.49, 65.94)	26.53 (-55.55, 65.28)	25.33 (-63.85, 62.64)	29.30 (-59.64, 66.70)	27.08 (-46.38, 65.49)	23.35 (-247.26, 73.50)
ETH	36.18 (-145.05, 74.46)	35.80 (-46.16, 65.88)	35.78 (-54.71, 73.77)	35.72 (-48.49, 69.51)	35.84 (-129.48, 68.84)	35.81 (-41.44, 69.66)
LTC	51.30 (-30.65, 72.54)	44.00 (-14.68, 66.23)	42.63 (-17.28, 64.15)	50.48 (-45.25, 71.32)	41.09 (-31.94, 64.78)	45.53 (-22.45, 67.81)
XRP	0.46 (-71.76, 52.33)	16.52 (-42.32, 48.10)	1.38 (-101.75, 60.92)	17.89 (-36.40, 49.22)	12.73 (-49.67, 47.69)	0.92 (-58.73, 42.71)

Table 7: BTCF's Hedging Effectiveness to various assets generated by VaR1 as risk reduction objectives.

	Var	ES5	ES1	VaR5	VaR1	ERM
BTC	90.28 (79.82, 97.26)	90.41 (76.94, 97.38)	89.67 (76.12, 97.22)	90.53 (63.24, 114.09)	89.95 (79.04, 98.47)	90.26 (77.22, 98.50)
CRIX	81.50 (19.30, 94.66)	82.91 (43.11, 134.78)	81.13 (16.91, 95.80)	81.96 (20.19, 97.03)	81.21 (3.99, 95.20)	81.24 (-2.93, 94.49)
BITX	78.66 (-2.26, 97.78)	78.51 (-27.79, 98.56)	78.62 (14.26, 98.19)	78.64 (25.67, 98.39)	77.79 (0.40, 94.60)	78.48 (-14.88, 99.22)
BITW100	74.92 (8.39, 99.58)	75.03 (-14.42, 121.87)	74.63 (1.02, 99.56)	75.30 (-4.40, 182.78)	76.59 (41.45, 102.33)	75.15 (-51.91, 200.59)
BITW20	31.64 (-95.35, 184.48)	24.67 (-141.82, 143.05)	25.39 (-70.91, 184.16)	25.26 (-65.94, 155.68)	32.51 (-72.34, 234.25)	29.67 (-53.73, 276.22)
BITW70	32.08 (-49.39, 105.27)	32.26 (-49.92, 100.01)	32.06 (-49.60, 95.18)	31.02 (-45.35, 93.56)	35.14 (-51.07, 98.41)	23.61 (-45.55, 76.13)
ADA	19.05 (-86.73, 61.01)	18.87 (-81.69, 58.02)	13.74 (-99.05, 62.93)	25.15 (-35.70, 56.39)	16.77 (-65.85, 50.37)	9.65 (-167.12, 76.43)
ETH	32.52 (-75.20, 76.01)	30.07 (-148.09, 82.48)	33.92 (-135.34, 71.72)	32.91 (-72.39, 70.54)	34.45 (-44.38, 79.13)	33.06 (-35.75, 70.72)
LTC	37.74 (-110.35, 67.48)	39.20 (-42.31, 62.83)	37.84 (-82.02, 59.01)	39.29 (-65.25, 66.67)	38.65 (-56.82, 58.00)	38.78 (-47.67, 69.88)
XRP	17.52 (-71.75, 49.17)	14.45 (-44.28, 47.18)	9.37 (-92.85, 49.13)	11.08 (-59.84, 46.08)	14.45 (-67.71, 46.28)	14.26 (-45.40, 45.12)

Table 8: BTCF's Hedging Effectiveness to various assets generated by ERM as risk reduction objectives.

	Mean	Std	Skew	Kurt	LQ	MD
Variance	-1.9087	65.2591	1.1831	21.605	-23.5520	-525.2360
ES 95%	-1.6368	64.6722	1.2248	22.287	-22.8830	-525.6981
ES 99%	-1.5243	65.1684	1.2394	22.097	-23.2401	-525.6996
VaR 95%	-1.7582	65.2438	1.1665	21.493	-23.4130	-525.6673
VaR 95%	-1.4074	64.6029	1.2587	22.457	-23.1024	-525.7274
ERM	-1.7083	64.9295	1.1923	21.932	-22.8506	-525.6895

Table 9: Log returns statistics of BTC-BTCF hedged portfolios under different risk minimisation objectives.