Quantitative Risk Management
Case for Week 3 (Spring)

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Let us consider the expected shortfall index of satisfaction for a very simple portfolio: \( \lambda \) shares in an asset whose value today is \( p > 0 \) and whose horizon value \( P \) is lognormal.

Let us assume that the objective measure is mark-to-market profit; therefore in the text’s notation, we have (apologies for the signs)

\[
-L = \lambda (P - p) = \lambda p \left( e^X - 1 \right)
\]

where the invariant total return is normal \( X \sim \mathcal{N}(\mu, \Sigma) \) with mean \( \mu \) and variance \( \Sigma > 0 \). The risk measure is

\[
-\varrho(L) = -r_\varrho(\lambda) = \frac{1}{1 - c} \int_0^{1-c} F_L^{-c}(q) \, dq
\]

for confidence level \( c < 1 \) in terms of the quantile function for the objective value.

1 Exact Version

In this simple situation, we can actually calculate a relatively simple expression for the value of index of satisfaction. It will be useful to compare this below with the approximate value we get from the Cornish-Fisher expansion.

We proceed to evaluate the exact version by considering the CDF of the objective.

\[
F_{-L}(z) = P\{ -L < z \}
= P\{ \lambda p \left( e^X - 1 \right) < z \}
= P\left\{ X \text{ sgn} \lambda < \log \left( 1 + \frac{z}{\lambda p} \right) \text{ sgn} \lambda \right\}
= P\left\{ \frac{X - \mu}{\sqrt{\Sigma}} \text{ sgn} \lambda < \frac{\log \left( 1 + \frac{z}{\lambda p} \right) - \mu}{\sqrt{\Sigma}} \text{ sgn} \lambda \right\}
= \Phi \left( \frac{\log \left( 1 + \frac{z}{\lambda p} \right) - \mu}{\sqrt{\Sigma} \text{ sgn} \lambda} \right)
\]

where \( \Phi(\cdot) \) is the CDF of a standard normal.
The quantile, which is the inverse of the distribution function, is therefore
\[
F_{<L}^{-1}(q) = \lambda p \left( e^{\mu + \text{sgn} \lambda \sqrt{\Sigma} \Phi^{-1}(q)} - 1 \right)
\]
So can proceed to evaluate the index of satisfaction.
\[
-r_\rho(\lambda) = \frac{1}{1 - c} \int_0^{1-c} \lambda p \left( e^{\mu + \text{sgn} \lambda \sqrt{\Sigma} \Phi^{-1}(q)} - 1 \right) dq = \lambda p \left( \int_0^{1-c} e^{\mu + \text{sgn} \lambda \sqrt{\Sigma} \Phi^{-1}(q)} dq - 1 \right) = \lambda p \left( \int_{-\infty}^{\Phi^{-1}(1-c)} e^{\mu + \text{sgn} \lambda \sqrt{\Sigma} z} \phi(z) dz - 1 \right)
\]
where the last line is achieved by the change of variable \( z = \Phi^{-1}(q) \) and \( \phi(z) = \Phi'(z) \) is the density of a standard normal.
Since
\[
e^{\mu + \text{sgn} \lambda \sqrt{\Sigma} z} \phi(z) = e^{\mu + \frac{1}{2} \Sigma} \phi \left( z - \text{sgn} \lambda \sqrt{\Sigma} \right)
\]
we have the final result,
\[
r_\rho(\lambda) = -\lambda p \left( e^{\mu + \frac{1}{2} \Sigma} \frac{1}{1 - c} \Phi \left( \Phi^{-1}(1-c) - \text{sgn} \lambda \sqrt{\Sigma} \right) - 1 \right)
\] (1)

2 Short Horizon Approximation

For short horizons, the mean and variance of the total return invariant are small. To lowest order, the exact result in (1) can be approximated by
\[
r_\rho(\lambda) \approx -\lambda p \mu + \frac{\phi \left( \Phi^{-1}(1-c) \right)}{1 - c} \lambda |p\sqrt{\Sigma} \] (2)
which is in the form \( \rho(L) = E L + k_\rho \text{std} L \) that we have seen before.
Let us spend a moment interpreting this. A long (\( \lambda > 0 \)) is less risky if the asset has a positive expected return (\( \mu > 0 \)), and a short (\( \lambda < 0 \)) is less risky if the asset has a negative expected return (\( \mu < 0 \)). In contrast, positive variance increases risk for any non-zero position.
This all seems quite reasonable for a rational risk measure.

3 Cornish-Fisher Approximation

It is unusual to have a simple analytic expression for the expected shortfall such as (1). This is why the Cornish-Fisher expansion can be useful in practice. In order to use this, we need several low central moments for the loss. In a Delta-Gamma setting, we can replace the objective by the quadratic
\[
-L = \lambda p \left( e^X - 1 \right) \approx \lambda p \left( X + \frac{1}{2} X^2 \right)
\]
hence $\Theta_\lambda = 0$, $\Delta_\lambda = \lambda p$, and $\Gamma_\lambda = \lambda p$. Let us define a new objective\(^1\) to represent this approximation.

$$\Xi_\lambda = \lambda p \left( X + \frac{1}{2} X^2 \right)$$

It is straightforward (but tedious) to work out that the first several central moments of this are

$$E(\Xi_\lambda) = \lambda p \left( \mu + \frac{1}{2} \mu^2 + \frac{1}{2} \Sigma \right)$$

$$Sd(\Xi_\lambda) = |\lambda| p \nu \sqrt{\Sigma} \sqrt{(1 + \mu)^2 + \frac{1}{2} \Sigma}$$

$$Sk(\Xi_\lambda) = 3 \sgn \lambda \sqrt{\Sigma} \frac{(1 + \mu)^2 + \frac{1}{2} \Sigma}{(1 + \mu)^2 + \frac{1}{2} \Sigma}^{3/2}$$

The third-order Cornish-Fisher expansion for expected shortfall in general is

$$-r_\varphi(\lambda) \approx E(\Xi_\lambda) + Sd(\Xi_\lambda) \left( z_1 + \frac{z_2 - 1}{6} Sk(\Xi_\lambda) \right)$$

with coefficients

$$z_1 = \frac{1}{1 - c} \int_{0}^{1-c} \Phi^{-1}(q) dq = - \frac{\phi \left( \Phi^{-1}(1-c) \right)}{1-c}$$

$$z_2 = \frac{1}{1 - c} \int_{0}^{1-c} \Phi^{-1}(q)^2 dq = 1 - \frac{\phi \left( \Phi^{-1}(1-c) \right)}{1-c} \Phi^{-1}(1-c)$$

depending on the confidence level $c < 1^2$.

Putting this together, we get a third expression for the index of satisfaction.

$$r_\varphi(\lambda) \approx -\lambda p \left( \mu + \frac{1}{2} \mu^2 + \frac{1}{2} \Sigma \right) + \frac{\phi \left( \Phi^{-1}(1-c) \right)}{1-c} |\lambda| p \nu \sqrt{\Sigma}$$

$$\cdot \left( \sqrt{(1 + \mu)^2 + \frac{1}{2} \Sigma} + \frac{1}{2} \sgn \lambda \left( 1 + \mu \right) + \frac{1}{2} \nu \sqrt{\Sigma} \frac{1}{(1 + \mu)^2 + \frac{1}{2} \Sigma} \Phi^{-1}(1-c) \sqrt{\Sigma} \right)$$

This result agrees with (2) to lowest order in $\mu$ and $\sqrt{\Sigma}$.

\(^1\)The objective random variable is the profit, which is the negative of the loss.

\(^2\)The trick to these integrals is to realize that $\phi'(z) = -z \phi(z)$. 

3
4 Modeling Default

Our horizon asset value $P$ is bounded below by zero in this set-up. But if this is a model for a financial asset, we probably need to consider how the possibility of default would change the value of the expected shortfall. An amendment to the market model to consider is

$$-L' = \lambda p (Ye^X - 1)$$

where $X \sim \mathcal{N}(\mu, \Sigma)$ as before, but now we add an independent default indicator $Y \sim \text{Bern}(1 - h)$ for default probability $h$.

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3Since we cannot observe default events in the historical record for the total return, there is no reason to alter the objective model for the invariant.