

# Modeling Risk Preferences Using Taylor Series Expansions of Utility Functions

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January 8, 2020

## 1 Mean-Variance and Expected Utility Models

The logical connection which exists between the mean-variance and expected utility models is made apparent by considering a second-order Taylor series of an arbitrary risk averse utility function  $U(W)$  in which  $U(W)$  is approximated for values of  $W$  which deviate from  $E(W)$ :<sup>1</sup>

$$U(W) \cong U(E(W)) + U'(W - E(W)) + (1/2)U''(W - E(W))^2. \quad (1)$$

Next, we find expected utility by calculating the expected value of equation (1):

$$\begin{aligned} E(U(W)) &\cong U(E(W)) + U'E(W - E(W)) + (1/2)U''E(W - E(W))^2 \\ &\cong U(E(W)) + (1/2)U''E(W - E(W))^2 \\ &\cong U(E(W)) + (1/2)U''\sigma_W^2. \end{aligned} \quad (2)$$

Since risk aversion implies that marginal utility is positive ( $U' > 0$ ) and diminishing in wealth ( $U'' < 0$ ), it follows from equation (2) that  $E(U(W))$  is positively related to  $E(W)$  and negatively related to  $\sigma_W^2$ . In other words, the mean-variance model obtains as a special case of the expected utility model.

## 2 Mean-Variance-Skewness-Kurtosis & Expected Utility Models

Aspects of risk beyond variance such as skewness and kurtosis are accommodated by considering higher order approximations of expected utility. For example, consider a fourth-order Taylor

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<sup>1</sup>Risk averse utility functions feature positive marginal utility which is diminishing in wealth. There are many such functions which have these properties; e.g., logarithmic (where  $U(W) = \ln W$ ) and power utilities (where  $U(W) = W^n$  and  $0 < n < 1$ ), to name a few.

series approximation of  $U(W)$  for values of  $W$  which deviate from  $E(W)$ :

$$U(W) \cong U(E(W)) + U'(W - E(W)) + (1/2)U''(W - E(W))^2 + (1/6)U'''(W - E(W))^3 + (1/24)U''''(W - E(W))^4. \quad (3)$$

Next, we find expected utility by calculating the expected value of equation (3):

$$\begin{aligned} E(U(W)) &\cong U(E(W)) + U'E(W - E(W)) + (1/2)U''E(W - E(W))^2 + \\ &\quad (1/6)U'''E(W - E(W))^3 + (1/24)U''''E(W - E(W))^4 \\ &\cong U(E(W)) + (1/2)U''\sigma_W^2 + (1/6)U'''Sk_W + (1/24)U''''K_W, \end{aligned} \quad (4)$$

where  $Sk_W$  corresponds to skewness and  $K_W$  corresponds to kurtosis. Since  $U' > 0, U'' < 0, U''' > 0$ , and  $U'''' < 0$  for risk averse utility functions, it follows that expected utility is positively related to  $E(W)$  and  $Sk_W$ , and negatively related to  $\sigma_W^2$  and  $K_W$ .

### 3 Numerical Example

Next, consider the following numerical example. Suppose initial wealth  $W_0 = \$0, U(W) = \sqrt{W}$ , and state-contingent wealth for two mutually exclusive risks is as follows:

$$W_1 = \begin{cases} 3.5858 & \text{with probability } .45 \\ 6.1571 & \text{with probability } .55 \end{cases} \quad \text{and } W_2 = \begin{cases} 0 & \text{with probability } .03 \\ 5 & \text{with probability } .94 \\ 10 & \text{with probability } .03 \end{cases}$$

Which risk should one take – risk 1 or risk 2? Since  $E(U(W_1)) = .45(\sqrt{3.5858}) + .55(\sqrt{6.1571}) = 2.2169$  and  $E(U(W_2)) = .03(\sqrt{0}) + .94(\sqrt{5}) + .03(\sqrt{10}) = 2.1968$ , the expected utility model indicates that risk 1 is preferred to risk 2.

Next, we decompose expected utility into its component parts. We begin by calculating means ( $E(W_1)$  and  $E(W_2)$ ), variances ( $\sigma_{W_1}^2$  and  $\sigma_{W_2}^2$ ), skewness ( $Sk_{W_1}$  and  $Sk_{W_2}$ ), and kurtosis ( $K_{W_1}$  and  $K_{W_2}$ ) for risks 1 and 2:

$W_{1s}$	$p_{1s}$	$E(W_1)$ calculation	$\sigma_{W_1}^2$ calculation	$Sk_{W_1}$ calculation	$K_{W_1}$ calculation
3.5858	45%	1.61	0.900	-1.273	1.800
6.1571	55%	3.39	0.736	0.852	0.986
		<b>5.00</b>	<b>1.636</b>	<b>-0.421</b>	<b>2.786</b>
$W_{2s}$	$p_{2s}$	$E(W_2)$ calculation	$\sigma_{W_2}^2$ calculation	$Sk_{W_2}$ calculation	$K_{W_2}$ calculation
0	3%	0.00	0.750	-3.750	18.750
5	94%	4.70	0.000	0.000	0.000
10	3%	0.30	0.750	3.750	18.750
		<b>5.00</b>	<b>1.500</b>	<b>0.000</b>	<b>37.500</b>

A quick review of this table indicates that 1) risks 1 and 2 share the same mean (5), 2) risk 1's variance is greater than risk 2's variance (1.636 compared with 1.5), 3) risk 1 is negatively skewed ( $Sk_{W_1} = -.421$ ) whereas risk 2 is symmetric ( $Sk_{W_2} = 0$ ), and 4) risk 1 has "thin" tails ( $K_{W_1} = 2.786$ ) whereas risk 2 has "fat" tails ( $K_{W_2} = 37.5$ ).

This numerical example illustrates an important shortcoming of the so-called mean-variance model. Under the mean-variance model, risk is defined as variance and other risk attributes such as skewness and kurtosis are not considered. On the basis of mean and variance only, risk 2 appears to be the better choice. However, there are important differences in skewness and kurtosis between the two risks. Since expected utility is positively related to skewness, risk 1's negative skewness also (in addition to its higher variance) represents an unfavorable attribute. However, risk 1's "thin" tails represent a particularly favorable attribute which outweighs the unfavorable effects of its higher variance and negative skewness. When all four statistical attributes (expected value, variance, skewness, and kurtosis) are taken into consideration, risk 1 is preferred to risk 2.

The following table calculates the determinants of expected utility (where  $U(W) = \sqrt{W}$ ) for risks 1 and 2 based upon the approximation for expected utility given by equation (4); i.e.,  $E(U(W)) \cong U(E(W)) + (1/2)U''\sigma_W^2 + (1/6)U'''Sk_W + (1/24)U''''K_W$ :<sup>2</sup>

<sup>2</sup>A spreadsheet of this table is available at [http://fn4335.garven.com/spring2023/riskpref\\_taylorseries.xls](http://fn4335.garven.com/spring2023/riskpref_taylorseries.xls).

$E(U(W_1))$	$U(E(W_1))$	$(1/2)(-.25E(W_1)^{-1.5})\sigma_{w_1}^2$	$(1/6)(.375E(W_1)^{-2.5})Sk_{W_1}$	$(1/24)(-.9375E(W_1)^{-3.5})K_{W_1}$	Sum of Columns 2-5
2.2169	2.2361	-0.0183	-0.0005	-0.0004	2.2169
$E(U(W_2))$	$U(E(W_2))$	$(1/2)(-.25E(W_2)^{-1.5})\sigma_{w_2}^2$	$(1/6)(.375E(W_2)^{-2.5})Sk_{W_2}$	$(1/24)(-.9375E(W_2)^{-3.5})K_{W_2}$	
2.1968	2.2361	-0.0168	0.0000	-0.0052	2.2141