Risk and uncertainty

Lecture note ECN 275/ENC 375:
Natural resource and environmental economics

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1. Introduction

Choice under uncertainty and how to choose among risky project alternatives is one of the most rapidly growing fields in economics. This lecture note gives a small insight into this vast area. I believe that the informational issues are among the most interesting aspects in risk theory. To provide a better foundation for the informational issues, I also present other important aspects of the risk and uncertainty literature.

It is worth noting that the perspectives on risk and uncertainty vary among the various branches of economics. A common – but wrongful – claim is that neoclassical (main stream) economics does embody risk and uncertainty. The opposite is true. It is within the neoclassical economic paradigm that these issues have been dealt with in the most fruitful and operational way, for instance through the introduction of subjective probabilities. Still, you should be aware of the position held by the Austrian school of economic thought:

> *A world in which there is autonomous and creative decision making is one in which the future is not merely unknown, but unknowable. There is nothing in the present state of the world that enables us to predict the future states because the latter is underdetermined by the former. (This of course, does not preclude the analyst from, ex post, making the once future intelligible on the basis of what happened in the past.). Subjectivism and action under uncertainty are thus inseparable ideas.* (O'Driscoll and Rizzo, 1985:2).

The position held by the Austrians is not that different from that held of decision scientists or main stream economists: Good decision analysis does not guarantee that the best choices are made, but increases the likelihood of these choices being made.[1] The pivotal issue is information − or the lack of it. In this connection good decision tools are also characterized by the way they present information to the decision maker.

The rest of this note is structured as follows. The next section deals with the demarcation of incomplete knowledge, uncertainty, and risk. Section three discusses risk preferences, while section four adresses risk and welfare. Section five looks more closely at ways of presenting risky decisions with focus on decision trees. In section six I discuss the impacts of irreversibility on valuation. The final section provides some extensions for welfare and sustainability.

2. Incomplete knowledge, uncertainty and risk

Lack of complete knowledge is essential to environmental issues and sustainability. Discussions surrounding climate change is one example of this with questions like what are the impacts on the climate from climate gas emissions, what are the net emissions, etc. I will not go into detail on this, but just briefly address the meaning of the terms and their use in general.

In economics we distinguish between uncertainty and risk. This demarcation is denoted *Knightian uncertainty* after Frank Knight (1921):

> *Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated.... The essential fact is that 'risk' means in some cases a quantity susceptible of measurement, while at other times it is something distinctly not of this character; and there are far-reaching and crucial differences in the bearings of the phenomena depending on which of the two is really present and operating.... It will appear that a measurable uncertainty, or 'risk' proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all.*

The practical definitions of Knight's perspectives can briefly be summarized as follows:

- **Risk** means that both the consequences (payoffs) and the probabilities are known by decision makers.
- **Uncertainty** means that the consequences (payoffs) or the probabilities are unknown by decision makers.

A simple example of risk may make things a bit more clear. Let us assume that two possible and mutually excluding outcomes W_P (**P**oor) and W_R (**R**ich) measured in wealth with the respective probabilities ρ_P and ρ_R such that $\rho_P+\rho_R=1$. Then the expected wealth $\bar{W}$ is given by:

$$\bar{W}=\rho_P W_P+\rho_R W_R \qquad [1]$$

Now, suppose [1] is a result of an investment of the size *I,* and let the probabilities ρ_P and ρ_R be unknown. That does not stop necessarily stop an investor from investing. He or she will merely replace the known probabilities with his or her subjective estimates of these probabilities. This gives the following reformulation of [1] where we add the investment into the formula assuming payoffs are immediate (so we do not need to discount the payoffs):

1 For a further discussion on the foundations for decision analysis, see for instance Bunn (1984).

$$\hat{W}=\hat{\rho}_P W_P+\hat{\rho}_R W_R-I \qquad [2]$$

It is tempting to conclude that if $\hat{W}>W_0$, where W_0 is initial wealth, the investor would invest. That conclusion premature as it leaves out the issues of uncertainty and the investor's risk preferences. To better address this issue, we need to move look at risk preferences and expected utility theory (in particular Figure 2 in section 4.1).

3. Risk preferences

Decision makers have different attitudes towards risk. Savage (1954) postulated that each decision maker has his/her own utility function in money income, $U_n(y_n)$, where y_n is the income of decision maker *n*. In the remaining exposition I drop the index *n* for simplicity. Generally this utility function is continuous and twice differentiable, i.e., the first and second derivatives exist:

$$U'(y)=\frac{\partial U(y)}{\partial y} \qquad [3]$$

$$U''(y)=\frac{\partial^2 U(y)}{\partial y^2} \qquad [4]$$

Consistent with the "more is preferred to less" starting point in economics, $U'(y)>0$, i.e., utility increases with increasing income.

Using this foundation Pratt (1964) formulated his measure for risk preferences (attitudes). According to Pratt's risk measure, *r*, a decision maker is:

risk neutral when: $r=\frac{U''(y)}{\partial U'(y)}=0 \Rightarrow U''(y)=0 | U'(y)>0$ [5.1]

risk averse when: $r=\frac{U''(y)}{\partial U'(y)}<0 \Rightarrow U''(y)<0 | U'(y)>0$ [5.2]

risk loving when: $r=\frac{U''(y)}{\partial U'(y)}>0 \Rightarrow U''(y)>0 | U'(y)>0$ [5.3]

Figure 1 illustrates these three different risk preferences:

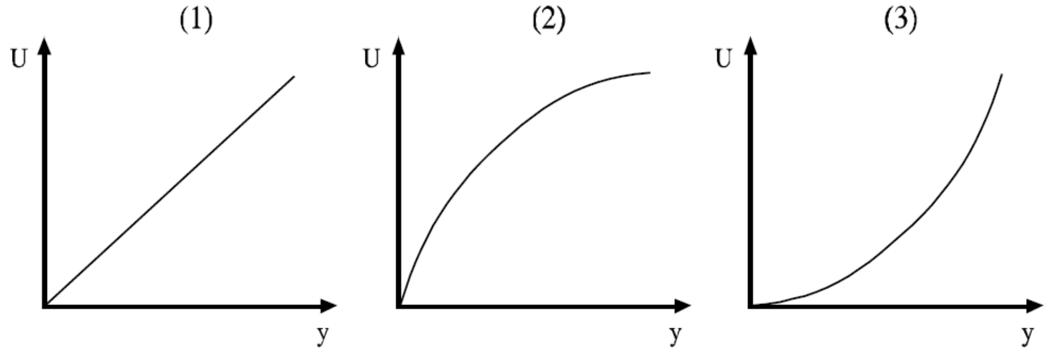

Figure 1: Risk preferences for $U(y)$
(1) Risk neutral, (2) Risk averse, and (3) Risk loving

Note that risk aversion implies that the utility function is concave, while risk loving behavior implies that the utility function is convex.

4. Risk and welfare

In economics risk and welfare is closely related to expected utility theory, which is the method most economists prefer when ranking risky prospects. This section will also briefly present other ways of ranking risky projects.

4.1. Welfare and expected utility theory[2]

Most people are risk averse, i.e., to undertake an action that involves (large) risk, they need to be compensated. For the investor facing an uncertain investment, the payoff of the risky investment must exceed the alternative risk-free payoff that he or she could get from investing I in the bank.

This is consistent with our earlier perspective that this individual has a concave utility of income, $U(Y)$, or wealth, $U(W)$, that is everywhere increasing at a decreasing rate as depicted in equation [5.2].

Figure 2 illustrates why risk averse individual (decision maker) would be willing to buy insurance against the bad outcome that lowers wealth from W_R (**R**ich) to W_P (**P**oor).

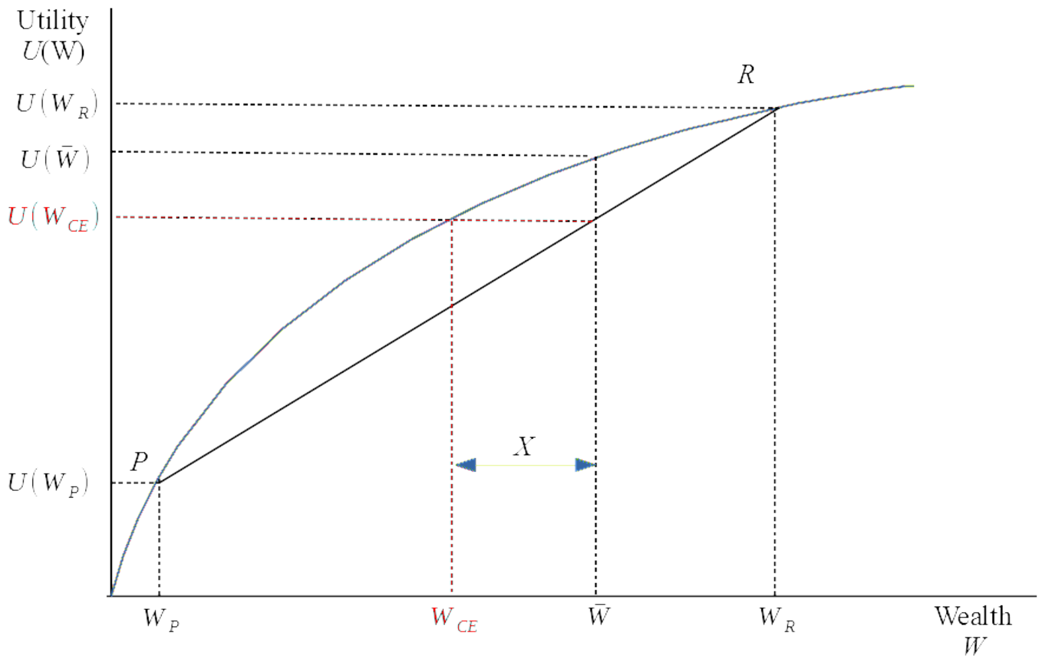

Figure 2: A risk averse individual's willingness to pay for insurance.

In Figure 2, we assume that the initial wealth is W_R, and that the individual faces the possibility of an unforeseen bad event occurring (like loss of your home due to fire) reducing wealth to W_P. The mean wealth of this person given the possibility of the bad event would then still be given by [1]: $\bar{W}=\rho_P W_P+\rho_R W_R$, while the mean utility if the bad event occurs would be the probability weighted sum of utilities from the poor and rich wealth outcomes (that lies along the line PR):

$$U(W_{CE})=\rho_P U(W_P)+\rho_R U(W_R) \quad [4]$$

2 Expected utility theory builds on the seminal work by von Neumann and Morgenstern (1944), which was used by the allied forces to analyze risks of the invasion in Normandy on D-day (June 6, 1944).

Here W_{CE} is the certainty equivalent wealth that makes the individual indifferent between facing the risky situation associated with the decline in wealth from W_R to W_P .

Now suppose that this individual with mean wealth $\bar{W}$ from [1] could get full insurance against the bad outcome giving wealth W_P , i.e., completely remove the uncertainty. In that case the individual would with full certainty have the mean wealth $\bar{W}$ less the costs of insurance, *X*. Let *X* be the insurance costs that makes the individual indifferent between buying insurance or not. Now, note that $U(\bar{W}-X)=U(W_{CE})$. The difference between mean wealth and the certainty equivalent wealth, $X=\bar{W}-W_{CE}$, is this individual's maximum willingness to pay for insurance (also called the *risk premium*).

The maximum willingness to pay for insurance is most familiar in risk analysis from the finance literature. In general economics the we may think of this as the *cost of risk bearing* (CORB) which would entail the least costly way to minimize risk. Insurance could be part of a comprehensive strategy to reduce risk (see Perman *et al*. 2011,section 13.1.2 for a slightly different exposition to this decision problem).

Some further remarks on expected utility and :

1. If this individual had risk neutral preferences, i.e., the utility function was a straight line, the willingness to pay for insurance would be zero because the utility function would then lie on the line PR.
2. Increased risk aversion means that the utility function $U(W)$ becomes more curved and the difference $\bar{W}-W_{CE}$ increases, i.e., the welfare enhancing CORB also increases.

Is the concave form of the utility function reasonable? Economists think yes. There are two main reasons for this. First, most people buy insurance – which implies risk aversion. Second, consider a person who either could be poor (wealth W_P) or rich (wealth W_P). The marginal utility of wealth (= the slope of the utility function evaluated at wealth, $U'(W)$) is higher if this individual were poor than rich, i.e., $U'(W_P)>U'(W_R)$. This is also consistent with what we observe from consumer behavior: poor people with few funds available for consumption (tight budget constraint) prioritize their purchases of consumption goods more than rich people (less tight budget constraint).

4.2. Some implications of expected utility for sustainability and economic policy

These insights have some important implications for environmental policy: Uncertainty about the impacts of environmental degradation or resource depletion is not an argument against taking precautionary measures, it is an argument in favor or such measures if have similar risk reducing impacts as buying insurance in Figure 2.

Chichilnisky and Heal (1993) deal with a related international insurance situation. Their argument is as follows: As the US in 1993 was less concerned about global climate change than the EU, the price on this insurance should be lower than the EU's willingness-to-pay for this insurance. This "trade" would therefore be welfare enhancing for both the US and the EU.

4.3. Other methods of ranking risky alternatives

Expected utility is the economists' preferred way of ranking risky alternatives as economic agents who behave according to the axioms underlying expected utility[3], and robustness to a wide variety of probability distributions (Machina, 1987). There are several other ways of ranking risky alternatives. The ensuing sub-sections will discuss two of these approaches (not exam curriculum in ECN 275/375). Stochastic dominance (Bunn 1984), an extension of dominance from matrix methods, regret theory (Loomes and Sugden 1982), and prospect theory (Kahneman and Tversky 1979) are not presented.

4.3.1. The "mean-variance" method

As the name *mean-variance* suggests, this method works particularly well when the probability distributions describing the risky scenarios in question, is captured by the mean (1st moment of the probability distribution) and the variance (2nd moment). Figure 3 captures the preference ordering for the three types of risk preferences.

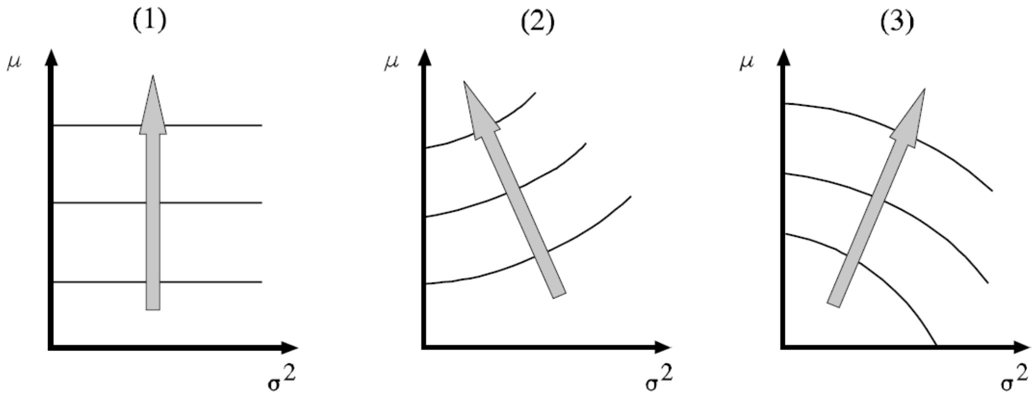

Figure 3: Indifference curves and preference direction for the mean variance method. (1) Risk neutral, (2) Risk averse, and (3) Risk loving.

A risk neutral decision maker (panel 1) only cares about the expected payoff (μ). Consequently, the indifference curves are parallel to the variance (σ^2) axis. A risk averse decision maker (panel 2) needs to be compensated with an increased expected payoff (μ) as uncertainty captured by the variance (σ^2), increases. Finally, a risk loving decision maker needs to be compensated with an increase in the expected payoff (μ) as uncertainty captured by the variance (σ^2), decreases.

A major advantage with the mean-variance method is that it makes the mean-variance trade-offs transparent compared to the expected utility model where this is "hidden" in the utility function.

4.3.2. Matrix methods

Matrix methods are more suited for analyzing cases where probabilities of outcomes (states) are not known. They come in multiple formats. The basic format is to remove action alternatives (***a***) in the table below that are dominated for all states (***s***) for at least one action. Table 1 gives an illustration.

3 The six axioms behind VNM expected utlility theory: (1) connexity, (2) transitivity, (3) monotonicity ("more is preferred to less"), (4) continuity, (5) compound probability and (6)independence. For detals on their significance, see Machina (1987). Knowledge on the axioms is not required for ECN 275/375 exams.

Table 1: Removal of dominated strategies (a=1 dominates a=2).

Outcome	Action:		
	a = 1	a = 2	a = 3
s = 1	6	6	8
s = 2	5	5	2
s = 3	7	5	3

In Table 1, the outcome of action a=1, is strictly preferred for s=3 or indifferent for s=1 and s=2. Hence, a=1 dominates a=2, and the table is simplified by removing the column a=2. The general principle for a strictly dominant strategy is that the dominant action (a) has higher payoffs for at least one outcome (s) and equal payoffs for the other outcomes.

Mini-max is a variant of matrix methods where the decision maker chooses the action that has the highest payoff of the actions that have the lowest payoff. Table 2 provides an illustration.

Table 2: Mini-max illustration.

Outcome	Action:	
	a = 1	a = 2
s = 1	31	32
s = 2	10 001	34
Expected *	516	33

Remark: * Equal probabilities of states 1 and 2

In Table 2 the decision maker compares the values of the worst outcome (s=1), and chooses the action with the most preferred payoff (a=2) as 34 > 31. Mini-max decisions are rarely optimal (Bunn, 1984), and reflect extreme loss aversion. To see this latter point suppose there are equal probabilities for s=1 and s=2 occurring. Then the expected value of a=1 is 516 while the expected value of a=2 is 33. That hardly looks like a decision rule likely to maximize well-being.

In the history of decision theory, the main contribution of the matrix methods is their focus on dominant strategies to simplify the decision problem. The dominance of certain actions can be extended to probability distributions into stochastic dominance. As previously mentioned, that is not dicsussed in this overview note.

5. Presenting risky alternatives

Matrix methods is one way of presenting the risks associated with certain actions. *Decision trees* is another commonly used approach. Consider a situation where somebody considers cheating on the taxes. If this person decides *action=cheat*, the avoided tax payment is t. However, if the person is audited, there is a penalty, $s > t$. If this person decides *action=comply* (not cheat), the tax payment is t independent on being audited or not. Table 3 shows the decision matrix with an extra added row for the expected value of the two actions when the probability of being audited is ρ.

Table 3: Tax cheating decision matrix in net payoff form.

Outcome	Action:	
	cheat	*comply*
audited	$-t-s$	$-t$
not audited	0	$-t$
Expected	$\rho(-t-s)$	$(1-\rho)(-t)$

Ranking of the state (outcome) contingent pay-offs from highest to lowes: 0 (cheat, not audited), *-t* (comply, audited or not audited), and *- t - s* (cheat, audited). Figure 4 shows the decision tree for this decision problem for three different ways of illustrating the value of outcomes.

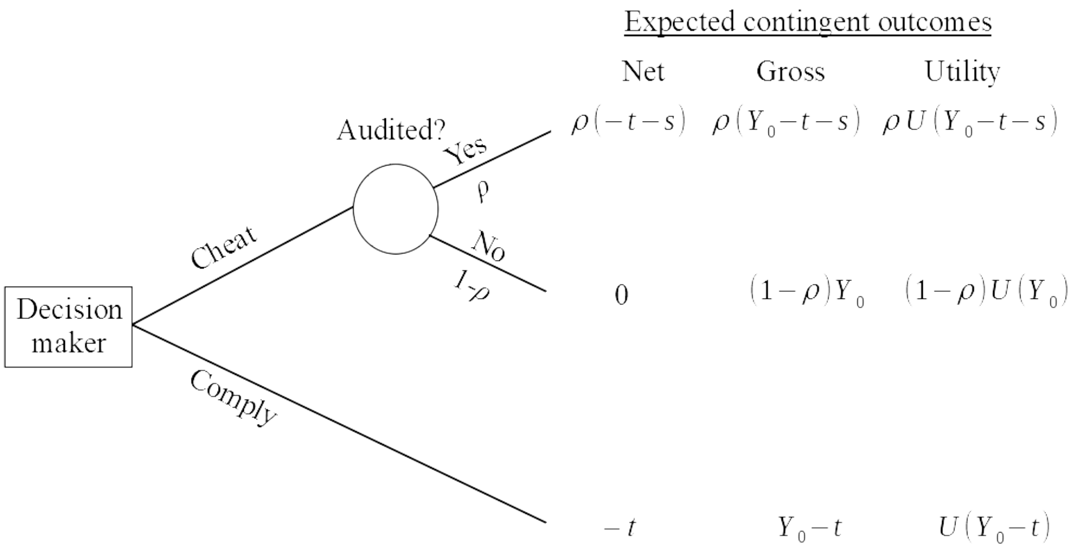

Figure 4: Decision tree for the tax cheating problem.

The net and gross formulations are equivalent. To see this, compare the indifference condition for cheating or not cheating, starting with the gross formulation [5a] that transforms to the net formulation [5c]:

$$\rho(Y_0-t-s)+(1-\rho)Y_0=Y_0-t \qquad [5a]$$

$$\rho Y_0+\rho(-t-s)+Y_0-\rho Y_0=Y_0-t \qquad [5b]$$

where the red and blue terms cancel out to give

$$\rho(-t-s)=-t \qquad [5c]$$

The same does not hold when we add the utilities of the outcomes as the risk premium (the maximum willingness to pay for insurance against an audit in the language used for Figure 2) differs depending on the size of the initial income, Y_0. Hence, for the utility formulation we need to add initial income into the utility function as done in Figure 4 above.[4]

4 Another and formal mathematical way of seeing this is that $\rho U(Y_0-t-s)\neq\rho U(Y_0)+\rho U(-t-s)$ except for linear utility functions.

6. Irreversibility and risk issues

The possibilities of an action's irreversible consequences or consequences that are expensive to correct for is another side of risk considerations. This section deals with these issues.

6.1. Irreversibility

Definition Irreversibility: Any decision *made now* which commits resources or generates costs that cannot subsequently recovered or reversed is an irreversible decision (OECD 2018:257).

An example of this would be loss of a species due to certain actions or events. With modern gene technology, we cannot rule out that it would be possible to "recreate" this species, but that possibility hinges on several factors like our possibility to regenerate the genome of lost species. Most likely, such actions would be quite costly. This implies that society may be better off preventing for example species loss if the costs of securing existence of the species is not too high. One way of securing existence is to collect and preserve species. This is the basic idea behind the Svalbard Seed Vault (*https://www.seedvault.no/*), where potentially useful seeds are stored.

6.2. Option option value

Definition Option value: The willingness to pay for maintaining or preserving a public asset or service even if there is little or no likelihood of the individual actually ever using it (Wikipedia 2019).[5 6]

The *option value* is therefore a value measure for the possibility of deriving utility from a specified activity. If the net expected benefits from this activity exceeds the costs of securing this possibility, it would be potentially welfare enhancing to ensure this possibility. Safe minimum standards is another approach of securing possibilility of future use. See Nævdal (2013) for a non-technical overview. For further details on the option value, see Perman *et al.* 2011, section 13.2.1).

6.3. Quasi-option value

Definition Quasi-option value: The value of reduced uncertainty by gathering information through delaying an irreversible decision (modified after OECD, 2018:256).

The key issue in the above definition is that by waiting to commit resource use now to some later time, we could learn more. An example from OECD (ibid.:259-60) on developing or waiting to develop a potential valuable natural site illustrates this. Assume that:

- The current value of developing the site is D_0 today (t = 0) with certainty, and that future expected discounted values of developing are D_1 (from t = 1 and onwards).
- The estimated current conservation value is V_0, but that future discounted conservation value is either high, V_{high} with probability ρ, or low, V_{low} with probability 1-ρ.

Figure 5 (next page) gives the decision tree for committing or wait to develop.

5 Wikipedia is normally not considered an authoritative or valid reference, but it is often a good place for finding key references.

6 This Wiki reference also provides links to the finance literature and its use of the term *option value*, *options*, and *real options*.

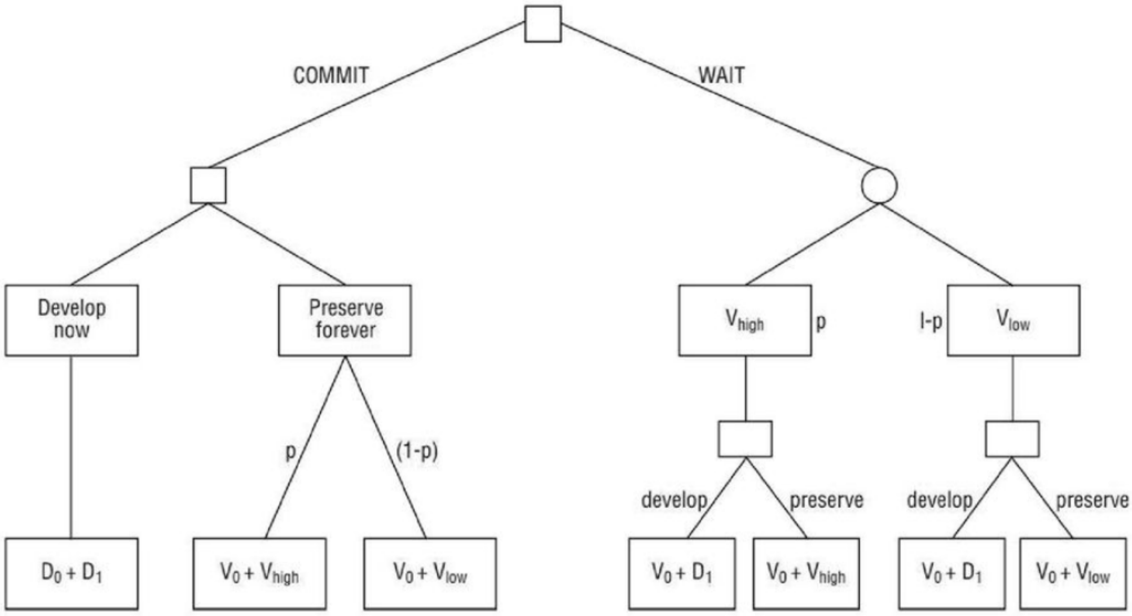

Figure 5: Decision tree for committing or wait to develop (OECD, 2018:258).

The left branch of the decision tree shows commit today, which entails to develop or preserve forever where the expected value of "preserve forever" equals $\rho(V_0+V_{high})+(1-\rho)(V_0+V_{low})$. The right branch provides an analysis of the option on "waiting", i.e., delaying the decision one time period and collect more information. A consequence of waiting is forfeiting the benefits of developing today, D_0 (development can at the earliest take place next time period). The quasi-option value (*QOV*) in this case is the difference between the expected value of "wait" and the best decision in "commit", i.e.:

$$QOV = E(\text{wait}) - MAX(\mathit{develop}, \mathit{preserve\ forever}) \quad [6a]$$

or in full mathematical form:

$$QOV = [\rho\, MAX(V_0+D_1, V_0+V_{high}) + (1-\rho) MAX(V_0+D_1, V_0+V_{low})] - MAX[D_0+D_1, \rho(V_0+V_{high}) + (1-\rho)(V_0+V_{low})] \quad [6b]$$

The next period a similar assessment takes place with an updated probability ρ for V_{high}, and V_{low}. A repeated positive quasi-option value (= benefits of waiting > benefits of committing), lead to subsequent periods of waiting, and hence repeats of the assessment in Figure 5.

Note that a decision to commit to "preserve forever" in the left branch in Figure 5 is not an irreversible decision, as development could take place later. However, under "commit" and if the expected net benefits of "preserve forever" is much higher than "develop", "preserve forever" is the optimal decision. A real-life reason for this is that it allows to focus on making other decisions.

The quasi-option value problem may look different for other cases, but the essence is the same: A formulation that compares the benefits of committing or waiting (one more period), with the possibility of repeated waits if the quasi-option value is positive.

Conrad (1980) showed that option values, quasi-option values, and the expected value of perfect information (EVPI) are related. EVPI utilizes Bayes' rule to update the probabilities of various states taking place. Knowledge of EVPI is outside the exam curriculum in this course.

7. Policy implications

Decision models are constructed to enable decision makers make more informed decisions, thereby increasing the likelihood of better outcomes. There are multiple sources of uncertainty in these models. This is particularly the case for environmental and natural resource problems, which involve interaction with complex natural systems where our knowledge is incomplete.

7.1. Risk analysis and decision making

Being aware of the uncertainties involved and the risks associated with decisions could impact social welfare in unforeseen ways, where we are particularly concerned about large "negative surprises". The expected utility framework with risk aversion provides an orderly way of figuring out how much resources we should devote to reducing such risks, where *CORB* (the cost of risk bearing, the economic variant of maximum willingness to pay for insurance) is essential.

Often, the risk picture itself is too complicated for us to see what goes on at first sight. Decision matrices and trees help us to structure the risk picture. While the linkages between actions and probable outcomes may still be incompletely captured, structuring the risk picture may help us to identify what are the most important sources of uncertainty.

Some actions lead to potentially irreversible outcomes or outcomes where the costs of recreating a desirable state are high. The *quasi-option value* framework provides us with a useful tool to analyze the benefits of committing to a decision today with possible irreversible consequences, waiting, or partial implementation while we gather more data to reduce the uncertainties.

This note aims to introduce you to some of these tools. As the course progresses, we will apply these tools onto various environmental and natural resource issues.

7.2. Risk preferences, wealth, and welfare

The Brundtland commission (1987) defined sustainability as:

> *"… development which meets the needs of current generations without compromising the ability of future generations to meet their own needs …"*

This implies non-declining total *consumption opportunities* over time. Consumption opportunities are difficult to measure. A more operational concept of sustainability is *non-declining consumption*. This is in line with economic theory as consumers only derive utility (welfare) from consumption.

The risk analysis tools, in particular the expected utility framework, could also provide us with insights on the linkages between wealth and welfare, and sustainability. Go back to Figure 2 and view the utility function as a reasonable representation of the aggregate utility of wealth or income in a society. It then follows that more equal distribution of wealth or income enables society to reach a higher utility level with less income or wealth, and hence also lower pressures on natural resource use and the environment.

The validity of this claim hinges a concave aggregate utility function. Friedman and Savage (1948) argued that as we observe some individuals who simultaneously buy insurance (risk averse = concave utility function) and engage in gambling (risk lovers = convex utility function), the aggregate utility function cannot be concave. Ongoing work to aims show that their argument is irrelevant.

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