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DECISION CRITERIA FOR INNOVATION

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The classic definition of an innovation is "the setting up of a new production function".[1] Implicit in the definition, but often unstressed, is the fact that an innovation entails a decision made under uncertainty as distinct from risk. To set up a new production function and have objective probabilities or be certain about the result is logically impossible. The possession of such information would imply that the action was an imitation and not an innovation for the given environment.

This article examines innovations in the light of the principal mathematical criteria for decision-making under uncertainty that have been elaborated in recent years. It attempts to deepen the analytic base for investigating the phenomenon of innovation. The analysis shows that for many proposed innovations it is possible to formulate a decision function. This function, whose explicit form depends on the decision-maker's state of mind, indicates whether the proposed innovation should be implemented in full or in experimental fashion or whether a "wait and see" policy of not innovating should be followed.

A simple model of an innovation will be considered first.

Assume that for the proposed innovation the only element of uncertainty is whether it will succeed or fail, it being known beforehand what the total monetary gain or loss will be. More specifically, let the possible discounted net gain be η units and the possible loss be one unit. Should the innovation be adopted, the payoff vector is therefore $(\eta, -1)$. If the innovation is not implemented, there will be zero gain or loss regardless of whether the innovation would have succeeded or failed. The payoff vector for non-adoption is thus $(0, 0)$.

Except in the case of "all or nothing" innovations, there is one other alternative available to the entrepreneur. He may experiment. Experimentation is specified as having a possible loss of θ where θ is greater than zero but less than one and is a function of the degree of experimentation relative to full implementation of the innovation. Assuming constant returns, this function is linear, continuous and has positive slope. Hence the possible gain from experimentation is $\theta\eta$. The payoff vector for experimentation is thus $(\theta\eta, -\theta)$. This payoff vector takes no account of the information obtained from experimentation. Such information only has a potential value to the decision-maker; by itself it puts no money in his pocket. To realise this potential value he has to make and act out another decision as to what he will do. For this decision he has four alternatives—the three previous ones plus (perhaps) the chance of selling his experimental information. The intrinsic

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[1] Schumpeter, J. A., *Business Cycles*. Volume 1. McGraw-Hill, New York. 1939. p. 87.

value of information to him is that he can make this latter decision under conditions of risk, whereas in the initial decision problem he had to act under uncertainty.[2] Risk conditions are attained since from the results of his experimentation he can attach objective probabilities to success or failure.

The experimentation alternative need not necessarily consist of a single experiment. It may encompass a number of simultaneous experiments for which the total possible loss is θ. In fact, if experimentation is the strategy selected, the best procedure would be to conduct a large number of extremely small experiments. The larger the number of experiments, the greater the reliance that can be placed on the information obtained. Should the experimental information be regarded as inconclusive, a decision to experiment further may be made. As noted already, this would involve problems of risk and not uncertainty. No doubt an astute entrepreneur whose initial decision was to experiment would follow some such sequential procedure.[3] If the idea behind the innovation was public knowledge, he could not experiment indefinitely without running the risk of others adopting the innovation first, so reducing his possible gain if the innovation turned out to be successful.

The payoff matrix for the simple model may be set up as follows:

Decision-Maker's Alternatives	*Nature's Alternatives*	
	Success	*Failure*
Adoption	η	-1
Experimentation	$\theta\eta$	$-\theta$
Non-adoption	0	0

This matrix depicts a decision problem under uncertainty because the "true" state of Nature, i.e., success or failure of the innovation, is completely unknown to the entrepreneur at the time he has to decide between his three alternatives. The matrix is read as follows: If the decision is made to experiment, then the decision-maker receives $\theta\eta$ if the innovation is successful and receives $-\theta$ (or loses θ) if it fails. A noteworthy feature of this decision problem is that only pure strategies can be followed. Mixed strategies are impossible since the alternatives are mutually exclusive.

Four basic methods of resolving decision problems under uncertainty have been developed. They are explained briefly here.[4] Each assumes that the elements of the payoff matrix are in terms of utility.

The Wald or maximin criterion treats the matrix as if it were a two-person zero-sum game, the best selection being the alternative which has the maximum minimum payoff. Nature being passive, this method is extremely conservative.

[2] For decision making under risk conditions see Luce, R. D., and Raiffa, H., *Games and Decisions.* John Wiley and Sons, New York. 1957. pp. 277-278.

[3] Extreme astuteness would result from familiarity with A. Wald's *Statistical Decision Functions.* John Wiley and Sons, New York. 1950.

[4] For a more detailed discussion see Luce and Raiffa, *op. cit.,* pp. 278-298.

Laplace's principle of insufficient reason says that since the probabilities attached to the various states of Nature are unknown, they are best regarded as equally likely; that alternative giving the highest average expected utility over all of Nature's states should then be chosen.

Selection of the alternative which has the minimum maximum regret is suggested by the Savage or minimax regret criterion. To facilitate this choice a regret matrix is calculated from the payoff matrix by subtracting the expected payoff from the maximum payoff in the same column.

Lastly, Hurwicz's pessimism-optimism criterion takes account of the best and worst payoffs for each of the decision-maker's alternatives. With an index of pessimism, α, lying between 0 and 1, the value of α times the minimum payoff plus $(1-\alpha)$ times the maximum payoff is calculated for each alternative. The preferred alternative is the one for which this function has the largest value.[5]

Each of these criteria is based on different assumptions about the axioms an optimal decision should fulfil. Hence each may lead to a different choice. There are no *a priori* theoretical grounds for prescribing one method of solution instead of another. Which is the preferred method depends on the frame of mind of the decision-maker. Hence it is possible for different people to choose different solutions for a given decision problem under uncertainty and yet for each to be acting quite rationally.

Now consider the application of these criteria to the payoff matrix above. To do this it must be assumed that the decision-maker's utility, *ceteris paribus,* increases monotonically with his money income and that the proposed innovation has no effects that cannot be measured in money terms. The former assumption is not unreasonable.[6] However, the latter may be. For instance, for some people, innovation may be a source of utility in itself.[7]

By letting the possible loss under adoption be one unit, the matrix has been normalised. This reduces the number of variables that must be considered to two, η and θ. The range of these variables is known, viz., $-1 \leqslant \eta \leqslant \infty$ and $0 < \theta < 1$. The following analysis shows that the absolute and relative sizes of these variables determine the choice that should be made.

Consider first the case when $0 < \eta < 1$. This is the situation if the possible gain is positive but less than the absolute value of the possible loss. For the benefit of readers unfamiliar with the application of the relevant decision criteria, the examination of this case will be given in detail.

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[5] A more general formulation of this criterion, which includes the above principle and the Wald criterion as special cases, is possible. See Radner, R., and Marschak, J., "Note on Some Proposed Decision Criteria." *Decision Processes.* John Wiley and Sons, New York. 1954. p. 62.

[6] See Halter, A. N., "Measuring Utility of Wealth among Farm Managers." *Journal of Farm Economics,* forthcoming.

[7] In such cases it would be possible to derive a specific set of subjective probabilities for Nature's alternatives such that the decision-maker could maximise his expected utility by treating the problem as a subjective risk problem—See Koofmans, T. C., *Three Essays on the State of Economic Science.* John Wiley and Sons, New York. 1958. pp. 157-159.

The alternative with the maximum minimum payoff is optimal under the Wald criterion. This particular payoff is associated with the non-adoption alternative in the given matrix. Hence, following the Wald criterion, the best choice is non-adoption.

For the Laplace criterion both success and failure have a probability of one-half. The expected payoff for adoption is thus $[(.5)\eta - (.5)]$ and, since $\eta < 1$, this is negative. Likewise the expected value for experimentation, $[(.5)\theta\eta - (.5)\theta]$, is negative since $0 < \theta < 1$. Both are, therefore, less than the expected value for non-adoption, which is zero. Hence, non-adoption is the optimal strategy under these conditions.

The regret matrix for the Savage criterion is:

	Success	*Failure*
Adoption	0	1
Experimentation	$\eta - \theta\eta$	θ
Non-adoption	η	0

For adoption and non-adoption the maximum regret is 1 and η respectively. If $0 < \eta < \theta$, then $(\eta - \theta\eta) < \theta$ and the maximum regret for experimentation is θ. Since $\eta < \theta < 1$, the non-adoption strategy should be followed for it has the minimum maximum regret. If $\theta < \eta < 1$, then the maximum regret for experimentation is less than that for adoption or non-adoption so that experimentation is the optimal choice. If $\theta = \eta$, then $(\eta - \theta\eta) < \theta$. Since $\eta = \theta < 1$, either the experimentation or non-adoption strategies are optimal.

Only the Hurwicz pessimism-optimism criterion remains to be considered. With an index of pessimism α, the value of $(1 - \alpha)$ times the maximum payoff plus α times the minimum payoff for each alternative is as follows:

Adoption: $(1 - \alpha)\eta - \alpha$
Experimentation: $\theta[(1 - \alpha)\eta - \alpha]$
Non-adoption: 0

The best alternative is that for which this value is a maximum.
If $(1 - \alpha)\eta - \alpha > 0$
then $(1 - \alpha)\eta - \alpha > \theta[(1 - \alpha)\eta - \alpha] > 0$,
since $0 < \theta < 1$,

and the innovation should be adopted. Equivalently, if $\eta > \frac{\alpha}{1-\alpha}$, adoption is the best alternative under the Hurwicz criterion. But if $\eta < \frac{\alpha}{1-\alpha}$, which implies

$$(1 - \alpha)\eta - \alpha < 0,$$

then non-adoption is the correct strategy. If the above relationship should have an equal sign so that $\eta = \frac{\alpha}{1-\alpha}$, then any of the three alternatives is optimal since the Hurwicz value of each is zero.

The cases remaining to be considered are those when $-1 < \eta \leqslant 0$, $\eta = 1$ and $\eta > 1$. There is no need to follow these cases through in detail. The procedure is the same as for $0 < \eta < 1$. The results of such calculations are presented in Table 1, which shows the relevant selection for each criterion under each pertinent range of η values. Where an additional decision rule is involved it is also shown. The selection is indicated thus: A for adoption, E for experimentation and N for non-adoption.

As would be hoped, each criterion completely rejects the proposed innovation when the possible gain is negative, i.e., when $\eta < 0$. When $\eta = 0$ the only exception to a non-adoption strategy choice occurs under the Hurwicz criterion for the special case when the decision-maker is 100 per cent. optimistic so that α is zero. He may then rationally follow any of the three alternatives. This, of course, is quite logical for a person with no pessimism.

The Wald criterion always selects non-adoption. This is not unexpected since this criterion assumes that the worst will invariably occur. Such an assumption is reasonable in a true game where the opponent is striving to defeat the decision-maker but not here where the opponent, Nature, is passive.

For the Laplace criterion the dividing line between adoption and non-adoption is when $\eta = 1$. At this value of η the possible gain is equal to the possible loss. If the possible loss is equal to the investment in the innovation, then the innovation should be implemented only if the possible total discounted return over time on the investment is at least 100 per cent. Taking into account possible indirect costs that may arise through upsetting the over-all production programme, the return on the investment would have to be greater than 100 per cent. for adoption to be optimal.

Table 1. Optimal Strategies for a Proposed Innovation

Criterion	$-1 < \eta \leqslant 0$	$0 < \eta < 1$	$\eta = 1$	$\eta > 1$
Walc	N	N	N	N
Laplace	N	N	A or E or N	A
Savage	N	N if $\eta < \theta$ N or E if $\eta = \theta$ E if $\eta > \theta$	E	E if $\eta < \frac{1}{1-\theta}$ A or E if $\eta = \frac{1}{1-\theta}$ A if $\eta > \frac{1}{1-\theta}$
Hurwicz	N if $\eta < 0$ N or E or A if $\eta = \alpha = 0$	N if $\eta < \frac{\alpha}{1-\alpha}$ N or E or A if $\eta = \frac{\alpha}{1-\alpha}$ A if $\eta > \frac{\alpha}{1-\alpha}$		

The degree of experimentation, indicated by the size of θ, is the important factor for the Savage method. If $0 < \eta < 1$ then the size of θ relative to η determines whether experimentation should be carried out or a non-adoption strategy followed, no consideration being given to adoption. When $\eta > 1$ no consideration should be given to non-adoption, and the size of $\frac{1}{1-\theta}$ relative to η determines whether a policy of experimentation or adoption should be followed. However, θ is under the control of the decision-maker. Since θ is a continuous variable over the range from 0 to 1, he can, for a given value of η, always find a θ such that he should experiment. Indeed, under the assumptions of constant returns and no indivisibilities, he can calculate the optimum degree of experimentation. It is that which gives the required information with a minimum possible loss. For $0 < \eta < 1$ this is when $\theta = \eta$. It is $\theta = \frac{\eta - 1}{\eta}$ when $\eta > 1$.

Disregarding the trivial case of negative or zero gain, the best choice under the Hurwicz criterion depends on the size of η relative to the fraction $\frac{\alpha}{1-\alpha}$. Whether the possible gain is greater or smaller than the possible loss is not crucial. However, the greater η is for a given α, the greater the possibility of $\eta > \frac{\alpha}{1-a}$ and the more likely that the innovation should be adopted. For a given η, the smaller the ratio of the decision-maker's pessimism to his optimism or, equivalently, the greater his optimism index, the greater the likelihood that the innovation should be adopted.

This completes the analysis of the simple model. Consider now a more realistic model in which success or failure is again uncertain but with the additional uncertainty that only a range of possible gains or losses is known or can be estimated. The assumptions of constant returns and no non-monetary effects are retained. The maximum loss may still be taken as one unit and will occur if the innovation is an utter failure. Let the maximum gain be η units. The payoff under a strategy of adoption will therefore vary continuously from η down to -1 depending on the degree of success of the innovation. Regarding failure as negative success, it is apparent that η is the payoff for maximum success and -1 the payoff for minimum success.

The corresponding payoff range for experimentation is from $\theta\eta$ down to $-\theta$. For non-adoption the payoff will again always be zero regardless of the true state of nature.

For this more realistic model, nature has an infinite number of possible states. It would be possible to make this set finite by partitioning the interval from η to -1 into segments and taking the mean of each segment, but this is not necessary. Only for the Laplace criterion are the intervening values relevant. However, since the experimentation payoff vector is merely a scalar multiple of the adoption payoff vector while the non-adoption vector consists only of zeros, the analysis of Table 1 still holds for the Laplace method. Nor is the previous analysis upset for any of the other three criteria. For the Wald, Hurwicz and Savage criteria the only relevant values are the extreme ones, η, -1, $\theta\eta$, $-\theta$ and 0. The positions of these maximum and minimum values are unchanged relative to the payoff matrix of the original simple model.

While the second model discussed is not completely realistic for all possible innovations, it is not unreasonable that for most innovations the entrepreneur can estimate the possible maximum and minimum success payoffs. Given these estimates, and provided that the mean is the only moment of the probability distribution of the estimate that is taken into account, the above analysis provides a rational framework for the entrepreneur to follow in his decisions about whether or not to innovate.[8] Of course, which of the four decision criteria he follows is purely a matter of his own judgment and personality. Indeed it is not necessary that he follow any of the four criteria explored above. Any number of other algorisms are possible. For a rational selection it is only necessary that the criterion used be well defined.[9] With this restriction, there are no *a priori* theoretical grounds for choosing one criteria instead of another. However, it is doubtful that any more plausible criteria than those listed are available for normative analysis of empirical situations. In fact, the model outlined is so simple that it could hardly be criticised as being beyond the capabilities of real world decision-makers and might therefore bear investigation of its worth as a deceptive model.[10] Thus, those who never innovate may be following some Wald type of "expect the worst" criteria, whilst those who follow an experimentation approach are surely following some Savage type of procedure emphasising regret. It might even be found that some early adopters as well as innovators act as if under uncertainty. Alternatively, some innovators may, by attaching subjective probabilities to nature's alternatives, act as though the situation was a risky one and not the uncertain one that it really is.

An additional possibility, with implications extending beyond the innovation problem, is that some decision-makers may change their approach to the problem as the payoff matrix changes. In other words, the configuration of the payoff matrix may in part determine which general type of decision criteria is used. For instance, the Wald or Laplace criterion might be used when the possible loss is large in absolute terms and the possible gain small. If the absolute value of the possible gain is large and the possible loss small, then Hurwicz or Savage type procedures might be used.

No mention has been made so far of the implications of a Shackle type approach to the innovation decision problem.[11] The justification is that Shackle's theory is descriptive, emphasises psychological variables and allows what would normally be regarded as irrational decisions. In

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[8] See Tintner, G., "A Contribution to the Non-Static Theory of Production." *Studies in Mathematical Economics and Econometrics.* University of Chicago Press, Chicago. 1942. p. 106. Also Dorfman, R., *et al., Linear Programming and Economic Analysis.* McGraw Hill, New York. 1958. pp. 465-469.

[9] Luce and Raiffa, *op. cit.*, p. 278.

[10] See Simon, H. A., *Models of Man.* John Wiley and Sons, New York. 1957. pp. 241-256 and 196-206.

[11] See Shackle, G. L. S., *Time in Economics.* North-Holland, Amsterdam. 1958. Ch. 2.

contrast, the criteria discussed above are essentially mathematical and at least rational to the extent of never giving contradictory solutions to a given problem. However, some comments on the Shackle approach are pertinent. Since there is complete uncertainty about Nature's strategy selection, zero potential surprise must be attached to each of her alternatives. The decision-maker's choice of a strategy would then be based on direct comparisons of the maximum gain-maximum loss pairs, the alternative whose pair lies highest on his gambling indifference system being selected.[12] Thus, for given values θ and η, there is no *a priori* way of determining which alternative a Shackle type decision-maker will select unless his gambling indifference system is known. However, the comparison of maximum gain-maximum loss pairs is suggestive of the Hurwicz criterion. Indeed, Shackle's theory is subsumed under the Radner-Marschak generalisation of the Hurwicz criterion.[13] It should be mentioned though that Shackle would disagree with Radner and Marschak as to the definition of uncertainty. The particular Hurwicz criterion analysed in this paper corresponds to the use of the Shackle theory by a potential innovator whose gambling utility function is of the form

$$U_i = \alpha x_i + (1 - \quad 0 \leqslant \alpha\alpha) y_i, \leqslant 1$$

where x_i is the maximum loss of the i th alternative, y_i the maximum gain of the i th alternative and α is an index of his degree of belief that a loss will occur and not a gain.

In conclusion, while this article has considered innovation only in its economic overtones, recognition must be made of the stimulus it has received from some of the recent work in rural sociology.[14]

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The equation on page 120 should read as follows:—

$$U_i = \alpha x_i + (1 - \alpha) y_i, \quad 0 \leqslant \alpha \leqslant 1$$

Page 119, line 25, should read "descriptive," not "deceptive."

[12] See Shackle, G. L. S., *Uncertainty in Economics.* Cambridge University Press. 1955. pp. 48-55.

[13] *op. cit.* Arrow has already pointed out that the Wald maximin principle is a special case of Shackle's theory. Arrow, K. J., "Alternative Approaches to the Theory of Choice in Risk-Taking Situations." *Econometrica.* 19 : 4 (Oct. 1951). p. 433.

[14] See especially the works of Wilkening, E. A., and Lionberger, H. F., listed in *Research and Writing on Diffusion of Farm and Home Practices: A Bibliography.* National Project in Agricultural Communications, Michigan State University. March, 1956. Also Rogers, E. M., and Beal, G. M., *Reference Group Influence in the Adoption of Agricultural Technology.* Iowa State College, Ames. 1958.