Critical Approach of the Use of Economic Models in Precautionary Risk Management

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In this article a synthesis of formal models for the economic interpretation of the precautionary principle is presented, with their virtualities, limitations and measures to overcome them.

The concept of precaution has great relevance in environmental regulation in the European Union. On the one hand, and despite the somewhat vague nature of legislation, the interpretation of the precautionary principle has seen recent progress with the development of some economic models and their application. There is, however, a need for a regulatory framework for the implementation of this principle in environmental decision-making, i.e., to clarify concepts and management procedures that are appropriate to the nature of environmental risks.

It is therefore important to know the most relevant economic approaches and models with the aim of identifying their contribution to the debate on precaution in the context of environmental risk management and discuss their practical relevance in public decision-making.

I. Introduction

The concept of precaution has great relevance in environmental regulation in the European Union. Despite the somewhat vague nature of the legislation, the precautionary principle has received some recent development within frameworks and models of economic interpretation and their application.

A significant part of the literature on the subject highlights the need for regulatory frameworks for the operational implementation of the precautionary principle in public decision-making. Concepts and management procedures appropriate to the nature of environmental risks need to be clarified.

It is therefore important to know the economic approaches and models that are most relevant for the debate on precaution and to discuss their practical relevance for public decision.

In this paper a synthesis of formal models of interpretation of the precautionary principle is presented, with its main virtues and limitations in the context of environmental risk management.

In order to contribute to the debate on the operational implementation of the precautionary principle some actions to overcome some of the limitations resulting from the analysis of the models are also identified.

The paper is structured as follows. Section 2 introduces the concept and main elements of the precautionary principle. Section 3 presents a brief description of the most relevant economic models for the interpretation of this principle. The analysis of the relevance and of the limitations of formal models for precautionary decision-making is also included. Section 4 presents a set of initiatives that may contribute to overcome some of the limitations of formal models for precautionary decision-making. Finally, Section 5 concludes.

II. The precautionary principle: concept and key elements

The precautionary principle is currently a fundamental principle of environmental regulation in the European Union.

Enshrined in the Treaty of Maastricht (1992)[1], in article 130 R, nr. 2[2] and referred at the level of the

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1 Maastricht Treaty, 31 *International Legal Materials*, *American Society of International Law* (2004) pp. 247-286.

Member States (at national, regional and local legislation) and of the European Commission (in Action Programmes, directives, declarations and recommendations), it is expressly mentioned in many conferences and international treaties such as the UN Conference on Environment and Development (Rio Summit) (1992)[3] and the Convention on Biodiversity (2000)[4] and other instruments of international law.

In existing publications and international declarations and treaties different definitions for precaution can be found, with different levels of demand for intervention, more optional in some cases (such as in the Rio Declaration) and more binding in others (e.g., the European Commission Communication[5])

One of the most representative definitions is the Rio Declaration, in principle 15: 'In order to protect the environment, the precautionary principle should be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage on the environment, lack of full scientific certainty should not be used as a reason for postponing cost - effective measures to prevent environmental degradation'[6].

Much has been published on the interpretation and practical implementation of the precautionary principle[7]. Despite some ambiguity of the different discourses on precaution, most definitions have common key elements and the scientific community and policy makers do not differ essentially in the identification of the main issues to consider when implementing precaution in practice, namely[8]:

- The duty to act in advance to protect the environment and public health when dealing with suspected risks (uncertain), especially if they are potentially serious or irreversible;
- The demand for more and better scientific information for the assessment of hazards and risks;
- The consideration of a broad set of options for action;
- The analysis and assessment, as complete as possible, of costs and benefits of policy alternatives, including the analysis of their distribution among the different actors;
- The continuous monitoring and review of the adopted precautionary measures taking into account the development of information and of scientific knowledge.

The precautionary situations correspond generally to risk scenarios where an element of the causal chain that goes from the hazard to the final effects is uncertain, in the sense that the cause - effect relation can not be established or rejected. Examples are electromagnetic fields (mobile phones and antennas) and its relation with certain cancers, and nanomaterials and their specific and massive effects on populations. Effective measures of protection are possible in the case of mobile phones, and surveillance and experimentation measures in the case of mobile antennas[9].

The precautionary principle has gained relevance in recent decades with the emergence of technologi-

2 Current Article 191, paragraph 2, of the Treaty on the Functioning of the European Union. The only explicit reference to the precautionary principle is: 'European Union policy on the environment shall aim at a high level of protection, (…). It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay'. In this article, paragraph 1 states the objectives of the environmental policy of the European Union: 'preserving, protecting and improving the quality of the environment; protecting human health; prudent and rational utilisation of natural resources; promoting measures at international level to deal with regional or worldwide environmental problems, and in particular combating climate change.' Paragraph 3 states that 'In preparing its policy on the environment, the Union shall take account of: available scientific and technical data, environmental conditions in the various regions of the Union, the potential benefits and costs of action or lack of action, the economic and social development of the Union as a whole and the balanced development of its regions'.

3 United Nations Conference on Environment and Development (UNCED) (1992), Jun 14, 31 ILM 874, 879.

4 Cartagena Protocol on Biosafety to the Convention on Biological Diversity: text and annexes. Secretariat of the Convention on Biological Diversity Montreal, Canada.

5 EC – Communication on the Precautionary Principle, COM (2000) – 1, European Comission (2000), Bruss (UNCED)els.

6 UNCED, supra note 3.

7 Such as the following: C. Raffensperger and J. Tickner eds., *Protecting Public Health & the Environment*: *Implementing the Precautionary Principle* (Island Press, Washington DC 1999); P. Harremoes, D. Gee, M. MacGarvin, A. Stirling, J. Keys, B. Wynne and S. Vaz eds., *The Precautionary Principle in the 20th Century: Late Lessons from Early Warnings* (Earthscan Publications, London 2002); EC, *supra* note 5; J. A. Tickner ed., *Precaution: Environmental Science and Preventive Public Policy* (Washington, DC, Island Press 2003); UNESCO, *Le Principe de Précaution* (Commission mondiale d'éthique des connaissances scientifiques et des technologies, Paris 2005); N. Myers and C. Raffensperger, *Precautionary tools for reshapping environmental policy* (Island Press, Washington 2005); E. Fisher, J. Jones and R. von Schomberg, R., *The Precautionary Principle and Public Policy Decision Making: a prospective analysis of the role of the Precautionary Principle for emerging science and technology* (Cheltenham: Edward Elgar 2006). The particular case of the EC Communication on the Precautionary Principle must be emphasized. It aims to provide guidance for the application of this principle in the Member-States.

8 V. Gonçalves "O Princípio da Precaução e a Avaliação de Projectos: Uma Interpretação Económica e de Gestão", PhD thesis in Management (on file at ISCTE-IUL, Lisboa, 2008).

9 CPP (2010), *La Décision Publique Face à l'Incertitude Clarifier les Règles, Améliorer les Outils* (Comité de la Précaution et de la Prévention, Ministère de l´Ecologie, de l´Energie, du Développement Durable et de la Mer. Mars. Paris 2010).

cal or environmental 'new risks', generally characterized by limited and uncertain scientific knowledge, by a collective and involuntary nature, and by low probability but potentially or even irreversible high damage. This applies, for example, to climate change, biodiversity loss, radiological exposure, the effects of chemicals, food safety, biotechnology, nanotechnology and waste management[10].

However, the current formulation of this principle has no clear and practical content and it is insufficient as a guideline for the design of regulatory policies. Multiple controversies have arisen about the level of environmental risk that is required to apply the principle, the role of economic and social consequences and the level of severity of precautionary measures.

The responsibility for defining the configuration of this principle is based on political (or juridical) entities, and regulatory frameworks are needed for its the operational implementation.

III. Economic models for the interpretation of the precautionary principle

Frameworks and models of economic interpretation of the precautionary principle can be grouped into two paradigms: rational - instrumental and deliberative - constitutive[11].

The first considers the theory of choice under uncertainty, involving economics but also concepts of psychology and of statistical decision theory[12]. Given the characteristics of the precautionary principle that are investigated, the formal analysis within this paradigm have been based on two main streams.

The first is the theory of expected utility and also the effect of irreversibility and learning, initiated by Arrow and Fisher (1974)[13] and Henry (1974)[14] and developed by Gollier *et al.*[15] and Gollier and Treich[16]. The decision-maker maximizes expected utility, based on the estimated costs and benefits of different options and alternatives. He also has the expectation to get better information in the future and be able to perform alternative sequential decisions on different dates. The context is that of the irreversibility of investment expenditures for environmental control and of potential environmental damage. There are also models that generalize the expected utility theory, allowing to place non linear weights on probabilities and to introduce subjective probabilities.

The second is an answer to the limitations of expected utility frameworks in situations of divergent expectations about uncertainty by different individuals. The models, referred to as 'ambiguity models', consider imprecise and multiple probabilities and use decision criteria based on individual attitudes towards risk.

In turn, the deliberative-constitutive paradigm considers multicriteria frameworks and models, which include multiple objectives (environmental, economic, social, etc.) in decision-making and enable the integration of deliberative and participative processes.

1. Model description

a. Using the classic framework of expected utility

In its economic dimension, the precautionary principle is best considered in relation to the standard prescription of normative theories of choice under uncertainty namely to choose the course of action that yields the highest expected (net) benefits. Thus, the application of the precautionary principle can be regarded as a comparative analysis of costs and benefits in the study of alternative options with higher or lower risk or uncertainty.

The prevailing framework for the economic analysis of such choices is that of the expected utility theory, developed by von Neumann and Morgenstern

10 F. Ewald, *Aux Risques d'Innover. Les Enterprises Face au Príncipe de Précaution* (Editions Autrement, Paris 2009); SEHN, *Advancing the Precautionary Agenda* (Science & Environmental Health Network, Feb 2009); M. D. Rogers, "Risk Management and the Record of the Precautionary Principle in EU Case Law", 14 (4) *Journal of Risk Research* (Abril 2011), pp. 467–484.

11 Fisher *et al.*, *supra* note 7

12 N. Moreau and D. Rivaud-Danset, L'Incertitude dans les Théories Économiques (Repères, La Découverte, Paris 2004).

13 K. J. Arrow and A. C. Fisher, "Environmental Preservation, Uncertainty and Irreversibility", 88 *Quarterly Journal of Economics* (1974), pp. 312–319.

14 C. Henry, "Investment Decisions Under Uncertainty: the Irreversibility Effect", 64 (6) *American Economic Review* (1974), pp. 1006–1012.

15 C. Gollier, L. Jullien and N. Treich, "Scientific Progress and Irreversibility: An Economic Interpretation of the Precautionary Principle", 75 *Journal of Public Economics*, pp. 229–253.

16 C. Gollier and N. Treich, "Decision-Making Under Scientific Uncertainty: the Economics of the Precautionary Principle", 27 (1) *Journal of Risk and Uncertainty*, pp. 77–103.

(1944)[17].This model supposes a complete identification of the possible states of the world accompanied by a probability distribution and a precise forecast of the consequences of all the actions envisageable in all the possible states. Probabilities can be inferred from objective information, such as previous observations of the frequency of particular outcomes.

b. The role of irreversibility and learning

Another type of models includes two new elements that allow to capture important dimensions of technological and environmental 'new risks': decisions involve the existence of irreversibilities (in investment expenditures and environmental damage) and uncertainty about the future consequences of a decision will be reduced, at least partially, due to the gradual acquisition of new scientific information[18].

Authors such as Gollier *et al.*[19], Kolstad[20], Ulph and Ulph[21], and Fisher *et al.*[22], based on the economic model of climate change[23], searched for an economic justification for the precautionary principle considering strategies of sequential decision making, where the expectation of reducing uncertainty with the progress of knowledge allows early decisions of higher consumption. The results obtained show that the attitude of decision-makers towards risk and the type of payoff function are instrumental to those choices. The main results of empirical models also demonstrate that the verification of the precautionary principle is very dependent on data and, in particular, on the decision-maker expectations[24]. Thus, these models only allow a very general interpretation of the precautionary behavior and of potential risks for society.

c. Nonlinear weights on probabilities

Empirical evidence indicates that, when facing uncertainty, people quite often seem to find low-probability events with extreme outcomes more noticeable, expressing a kind of pessimistic or optimistic behavior, and pay less attention to the intermediate outcomes. Prominent examples, based on experiments, are given by Allais[25], Ellsberg[26] and Kahneman and Tversky[27].

This led to the development of a wide range of alternatives to, and generalizations of expect utility theory. Of these, one of the most significant and widely-used has been rank-dependent utility models[28],[29]. The central insight underlying these approaches is that individuals can distort somewhat the likelihood of an extreme result or not assign the same utility to intermediate results with the same probability[30].

Bargiacci[31] examines the relationship between rank-dependent utility and the precautionary principle, with specific application to climate change. With pessimistic preferences, displaying overweighting of adverse low-probability events, the evaluation of

17 J. Von Neumann and O. Morgenstern, *Theory of Games and Economic Behaviour* (Princeton: Princeton University Press, 1944).

18 In these models, scientific uncertainty (or not proven risk), which characterises precautionary situations, differs from risk (proven risk), which characterises prevention situations, mainly due to its possible reduction with time.

19 Gollier *et al.*,*supra* note 15

20 C. D. Kolstad, "Fundamental Irreversibilities in Stock Externalities", 60 *Journal of Public Economics* (1996), pp. 221-233.

21 A. Ulph and D. Ulph, "Global Warming, Irreversibility and Learning", 107 *Economic Journal* (1997), pp. 636-649.

22 A. Fisher, M. Hanemann and U. Narain, "The Temporal Resolution of Uncertainty" (University of California, Berkeley 2004).

23 In the global warming model, measures should be taken to limit emissions of greenhouse gases, without knowing with certainty the consequences of its accumulation in the atmosphere (see reports of the IPCC-Intergovernmental Panel on Climate Change (IPCC, *Climate Change 1995: Economic and Social Dimensions of Climate Change* (Cambridge University Press 1996); IPCC, *Climate Change 2001: the Scientific Basis* (Cambridge University Press 2001).

24 A. Ingham and A. Ulph, "Uncertainty, Irreversibility, Precaution, and the Social Cost of Carbon", in D. Helm (ed.), *Climate Change and Policy Response* (Oxford: Oxford University Press 2005); S. Peterson, "Uncertainty and Economic Analysis of Climate Change: A Survey of Approaches and Findings", 11 *Environmental Modeling and Assessment* (2006), pp. 1–17.

25 Allais, M. (1953), "Le comportement de l'homme rationnel devant le risque: critique des postulats et axiomes de l'école américaine". Econometrica 21, 503-546.

26 D. Ellsberg, "Risk, ambiguity and the Savage axioms", 75 (4) *Quarterly Journal of Economics* (1961), pp. 643-69.

27 D. Kahneman and A. Tversky, A., "Prospect theory: an Analysis of Decision Under Risk", 47 (2) *Econometrica,* (1979), pp. 263–91.

28 J. Quiggin, "Risk Perception and Risk Aversion Among Australian Farmers", 25 *Australian Journal of Agricultural Economics* (1981), pp. 160-9; J. Quiggin, "A Theory of Anticipated Utility", 3 Journal of Economic Behavior and Organisation (1982), pp. 323-43; D. Schmeidler, "Subjective Probability and Expected Utility Without Additivity". 57 Econometrica (1989), pp. 571–87.

29 Another framework is 'prospect theory' (Kahneman and Tversky, *supra* note 27). The two frameworks have been combined in 'cumulative prospect theory' (A. Tversky, P. Slovic and D. Kahneman, "The Causes of Preference Reversal", 80 (1) *The American Economic Review* (1990), pp. 204-217.

30 E. Diecidue and P. Wakker, "On the Intuition of Rank-Dependent Utility", 23 (3) *The Journal of Risk and Uncertainty* (2001); pp. 281-298

31 R. Bargiacci, "Climate Change Scenarios and the Precautionary Principle", in J. Wesseler, H.-P. Weikard and R. Weaver (eds.), *Risk and Uncertainty in Environmental and Natural Resource Economics* (Cheltenham: Edward Elgar, 2004).

risky outcomes is less favorable than under expected utility with the same utility function. He also concludes that impacts are ambiguous, and depend on model specifications and parameter values, though the general tendency is for less favorable evaluation of risky outcomes.

d. Subjective probabilities

In the presence of scientific uncertainty, and with no objective basis for the choice of a probability distribution, Savage (1954)[32] showed that it is as if individuals take their decisions referring to subjective expectations, that are mental representations about external objective facts, based on their extensive experience of judging problems of a given kind. He referred to that particular probability distribution as 'subjective'. This supposes that individuals must have a very precise knowledge of the risk situation.

Savage axiomatised rational behavior under uncertainty with appropriate consistency properties within the framework of the von Neumann and Morgenstern model, but with subjective probabilities[33].

e. Ambiguity models

When faced with complex or unfamiliar problems and without precise information, the preferences of individuals are often not consistent with a single (objective or subjective) probability distribution as usually assumed by the theory of expected utility. Ranges of probabilities (or "multiple priors") can then reflect the intuitive notion that a decision-maker might feel more confident in some beliefs than in others. This situation is described in decision theory as one of "ambiguity". Climate change policy is a classical example where predictions are derived from different models whose results are often presented as a range of probabilities for a single event.

Consistent with these observations, Gilboa and Schmeidler (1989)[34] consider a framework in which the decision-maker acts as if holding a set of beliefs (probability distributions) meriting consideration and assesses the utility of each action by calculating the minimum expected utility that can be obtained with respect to all the probability distributions being considered. This represents a focus on the worst case scenario, which corresponds to the least favourable outcomes. Then, he opts for the action offering the maximum expected utility. Thus, the model is using the "maximin" decision criterium.

This criterium can be used as a conceptual framework for designing management rules which adhere to the precautionary principle. If we consider that the emergence of a worst case scenario could lead to an irreversible change, then, to prevent it, a precautionary approach should be taken, which implies that the decision rule should be based on the worst case scenario[35]

f. Multi-criteria analysis

Multi-criteria analysis was designed as an evaluation tool in order to address complex problems with multiple dimensions and objectives (environmental, economic, social,...) and involving quantitative and qualitative issues[36].

The alternative options to consider should be diversified to reflect different scenarios and incorporate multiple perspectives and values. The definition of criteria for evaluating options and their weighting should reflect the relative importance of the main issues involved in decision-making and include some form of public participation[37]. Multicriteria models allow the incorporation of participative and deliberative methods in decision-making processes[38]. Thus, a multi-criteria framework may be suitable for precautionary decision-making, which involves the adoption of long-term, holistic and inclusive perspectives in environmental protection[39].

32 L. Savage, *The Foundations of Statistics* (1954), revised and enlarged edition (1972) Dover, New York.
33 Thus, this model would remove the distinction between uncertainty and risk, and, hence, between precaution and prevention (where the probabilities are objective).
34 I. Gilboa and D. Schmeidler, "Maximin Expected Utility with a Non Unique Prior", 18 *Journal of Mathematical Economics* (1989), pp. 141-153.
35 A. Lange and N. Treich, "Uncertainty, Learning and Ambiguity in Economic Models on Climate Policy: Some Classical Results and New Directions", 89 (1-2)*Climatic Change*, pp 7-21.
36 G. Gamboa and G. Munda, "The Problem of Wind-Park Location: a Social Multi-Criteria Evaluation Framework". 35 (3) *Energy Policy* (2007), pp. 1564-1583.
37 Such as of representatives of economic activities and public interest groups, scientists and government consultants.
38 G. Munda, *Social Multi-Criteria Evaluation for a Sustainable Economy* (Springer-Verlag New York 2008).
39 A. Stirling and S. Mayer, "Confronting Risk and Precaution: a Multi-Criteria Mapping of a GM Crop" in M. Getzner (ed.), *Developing Alternatives for Valuing Nature* (Routledge, London 2005).

2. Advantages and limitations of models

a. Advantages

All formal models that translate the precautionary principle in economic terms help to clarify the concept of precaution and decision-making. They frame a decision problem concerning the prevention and management of risks and they perform an economic analysis of the impact of risks on individual and collective welfare.

Despite the many simplifications that theoretical models involve, in general terms, they seek to represent interactions of multiple parts of a complex systemwith compelling axiomatic foundations. Thus they reveal a number of implementation challenges and problems to solve and they contribute to a better understanding of the behaviour of important system parameters.

i. They reveal a number of implementation challenges

Formal models reveal a number of implementation challenges and problems such as the incorporation of the nature of attitudes towards risk, the identification of the type and scope of the information to be integrated, and the selection of decision rules which can provide an appropriate way to describe economic choices.

Thus, models based on expected utility consider decision-maker preferences based on his expectations concerning dangers with known and objective (or subjective, in the Savage model) probabilities. The Gollier *et al.* model considers these expectations also regarding the progress of scientific knowledge about risks. In ambiguity models, the attitude of the decision maker facing imprecision is explicitly considered in the decision criterion for choosing one among the admissible decisions.

The type and scope of information to be considered depends on the specification of models and scenarios defined for the consequences of decisions. In particular, Gollier *et al.* model includes scenarios that consider the possibility of reviewing the decision-maker's expectations with the improvement of scientific knowledge. In ambiguity models, the consequences of each decision can be evaluated taking into account multiple probability distributions, which allow to represent the existence of different scientific theories, and thus, the opinion of all experts. Finally, multicriteria analysis allows the inclusion of qualitative and multidimensional information and the inclusion and weighting of possible conflicts of interest.

In the different models within the framework of expected utility theory, with their different payoff functions, the decision rule considers the principle of the maximization of a social welfare function by the public decision-maker. Ambiguity models consider decision criteria under uncertainty such as the 'maximin' criterion, which reflect the decision maker's attitude towards uncertainty. Finally, multicriteria models use functions that weight the multiple criteria considered.

ii. They contribute to a better understanding of the system behaviour

Although each one in its particular way, the theoretical models contribute to a better clarification of the phenomena and of the logic of individual and collective choices and their effects. Thus, they contribute to the understanding of the behavior of important parameters, such as risk perceptions, impacts and associated economic costs, and the level of protection required .

The Gollier *et al.* model, for example, establishes the rational nature of precautionary behaviour, understood as additional-saving behaviour, in the context of dynamic risk management. In ambiguity models a choice is carried out among a set of possible actions based on a set of divergent expectations about risk scenarios. Multicriteria analysis allows to monitor more closely the interests of the various entities involved in decision making.

The different models also allow to study the impacts and the economic costs associated with different scenarios of consumption, production or pollutant emissions and, thus, to study precautionary strategies.

b. Limitations

But formal models have some important limitations related to the fact that they are more conceptual than practical oriented.

The use of models also raises the problem of obtaining relevant data and information to characterize the socio - political context and the space of events and results associated with risk emergence. These

problems, and the conceptual and theoretical difficulties, have limited the practical application and the political relevance of precautionary decision tools[40].

Formal models present some important theoretical difficulties, that are considered below.

i. Each model is only applicable to certain kinds of risks

As they apply only to certain kinds of risks, the different models are not of general application, and the selection of models to be used must be based on the nature of risks. This will also clarify the nature of precautionary analyses.

Thus, for example, expected utility models are perfectly appropriate where risks are well-characterized but not in the controversial context of the 'new risks', where the true underlying probability distributions that should be used to take the expectations are either unknown or unknowable. In such situations, multiple probabilities and ambiguity models may be preferred.

The models that incorporate the role of irreversibility and learning apply better to the management of phenomena with reliable prospects of improved future information and of arriving at confirmed risks, such as the greenhouse gas emissions or the ozone layer protection, but not to others, such as GMO crops, which could have an unacceptable human and social cost[41].

In addition to the nature of the risks, it is very important to clarify all the requirements of the precautionary principle in the specific context of each particular case, since the result of precautionary decision (whether or not to recommend conservation) is also dependent on other factors. Thus, a "rational" precautionary measure such as, for example, the required extent to which to collect information about future possibilities before acting, varies with the circumstances[42].

ii. Single dimensional assessment is insufficient

Controversies regarding the application of the precautionary principle are often disputes about how to obtain some balance between competing interests in a context of high uncertainty where it is not possible to have a clear technical solution. In this situation, the evaluation and the weighting of factors and interests, technical, ecological, economic, social, ethical and political, interacting in a complex system, and the management of any conflicts often becomes necessary[43].

Thus, the single-dimensional evaluation in most models is insufficient, in particular in models within the theory of expected utility, which look mainly for cost-benefit analysis with efficient choices according to preference levels of decision-makers. In these models, the level of risk that should be borne by society as a whole is decided by a single decision maker. The multicriteria models are more suitable to address multidimensionality but they do not separate scientific and political factors. Furthermore, they imply 'incommensurability of values'[44], and this may lead to operational constraints. Thus, these models must be applied with great objectivity and transparency, especially in areas of great complexity and controversy.

In the context of multidimensionality and of the analysis of the consequences of the options considered, precautionary measures should be proportionate to the risks and to their potential effects.

iii. Poor connection between individual and collective values

The analysis of public decisions involving collective risks requires the definition of reasonable levels of risk that are accepted by society.

In this regard, Gollier *et al.* revealed a weakly intuitive individual saving behaviour in response to the various ways of envisaging the future that is a very broad interpretation of the potential risks to the community. In the context of subjective probabilities, the risks perceived by the decision-maker can be in accord with risk assessments calculated by the scientific community, but the conditions for the validity of the value judgements for collective decision-makingremain unidentified.

Ambiguity models, which represente the existence of divergent expectations about hazards, seem to allow the transparence of the procedure for consulta-

40 R. Kast, "Calcul Économique et Mise en Pratique du Principe de Précaution", 21 (2) *Économie publique* (2007).

41 O. Beaumais, *Économie de l'Environnement: Méthodes et Débats* (La Documentation Française, Paris 2002).

42 C. A. Tisdell, *Economics of Environmental Conservation* (Edward Elgar 2005).

43 R. Cooney, *Biodiversity and the Precautionary Principle: Risk and Uncertainty in Conservation and Sustainable Use* (Earthscan, London 2005).

44 'Incommensurability of values', i.e., "the absence of a common unit of measure for plural values" as defined by Martinez-Alier *et al.* (J. Martinez-Alier, G. Munda and J. O'Neill, "Weak Comparability of Values as a Foundation for Ecological Economics", 26 *Ecological Economics*, pp. 277-286.

tion of stakeholders and the possibility of reaching an agreement on a possible consensus expectation[45]. However, the criterion they put forward for collective management is inappropriate to the proportionate nature that precautionary measures should have.

Thus, the limitations of the models in linking individual and collective values raises the problem of the definition of institutional procedures for determining collective choices.

iv. Unique solutions inadequate

In formal models decision responds generally with a definition of the exact action to be undertaken. In some models, it is based on a decision-maker utility maximization function, which represents the aggregation of interpersonal preferences. In other models, it is based on a decision criteria that reflects the adoption of a particular attitude of the decision-maker facing uncertainty. However, although the precautionary principle can be understood as a search for a minimum security level, a priori it does not require adopting extreme uncertainty aversion. The precautionary principle in the broadest sense of the term must be understood to mean that it is necessary to act under uncertainty assuming reasoned risk-taking and leading to reasonable decisions[46].

In addition, the proportionate nature of the measures to be taken, a key component of the precautionary principle, should be considered. Proportionality requires the definition of the specific nature of the risks to be managed and the expected level of security, and taking into account the opportunity costs associated to precautionary measures[47].

IV. Practices to consider in precautionary decision-making

The preparation of public decisions related to environmental hazards is often limited, in particular because of the insufficient characterization of environmental and also of social and economic impacts, in the short and in the long term. Another difficulty is the insufficient identification and integration of agents for the institutional support to the decision-maker in the dialogue process and in the decision instruction.

Therefore, it is clear the lack of mechanisms and of generally accepted operational frameworks to guide the implementation of the precautionary principle. The conditions of application of this principle have, thus, been much conditioned by factors such as the decision-makers' objectives, their attitudes towards risk and uncertainty and the rules and decision criteria they use.

In this situation, the need for a methodological reflection to clarify the issues and procedures of public decision under uncertainty, particularly when it concerns the precautionary principle, have been highlighted in several national and international forums. A recent example was the public hearing of the parliamentary committee for the evaluation of scientific and technological choices in France concerning the balance of the application of the precautionary principle four years after its constitutionalisation[48]. The need to clarify the situations that are relevant for the application of the precautionary principle was referred, and also the need to provide tools to allow improved choices by the decision-maker and to organize the practical implementation of this principle.

In order to contribute to this debate, and following the analysis presented in the previous sections, some practical actions that should be implemented have been identified in this paper. The opportunity of these actions, which aim to overcome the limitations mentioned in the previous section, was, thus, revealed by the formal models analysis. These actions should also be incorporated in a common procedural framework. This framework is referred to at the end of this section.

1. Comprehensive treatment of information and knowledge

The practical implementation of the precautionary principle does not involve a uniform and satisfactory decision criterion: decision-makers should take in-

45 M. Matheu, *La Décision Publique Face aux Risques*(La Documentation française, Paris 2002).

46 P. Boucard, "Does the Decision Theory in Economics Shed Light on the Application of the Precautionary Principle ?", presentation held at European Association of Environmental and Resource Economists, 16th Annual Conference (2008).

47 O. Godard, "Le Principe de Précaution Comme Norme de l'Action Publique, ou la Proportionnalité en Question", 54 (6) *Revue Économique* (Nov 2003), pp. 1245–1276.

48 J.-C. Etienne, "Le Principe de Précaution: Bilan de son Application Quatre Ans Après sa Constitutionnalisation" (Office Parlementaire d´evaluation des choix scientifiques et technologiques, Paris 2009).

to account the potential dangers but any specific action is not imposed and very different measures can be carried out from simple warnings to the ban of some dangerous products or technologies. As a principle, it is not defined as a mechanical measure or application. Different decision criteria can clarify its implementation, but no unambiguous criterion is a translation of the precautionary principle. The key question is how to make an informed judgment of an empirical context for decision-making.

So analyzes based on more contextualized models are needed, adapted to the conditions of uncertainty, irreversibility and learning of specific cases, so that they can "resolve" regulatory issues and data limitations[49].

Therefore, it is important to analyze scenarios with explicit and debated costs and benefits, which are appropriate to each case, in order to help decision-makers to make an appropriate choice in the context of an identification as complete as possible of the existing alternative courses of action.

If the uncertainty is too high making it difficult to forecast scenarios, decision-makers should seek to adjust their analysis of available data, with more cautious processes.

2. Integration of multiple values in decision-making

In solving many situations that involve the application of the precautionary principle it is necessary to evaluate and weight multiple factors and interests, sometimes divergent, in order to identify measures that are proportionate to the seriousness of risks and to their potential consequences.

The decision context and the nature and quality of available data may justify the use of different models and operating methods or the combination and integration of methods in order to obtain more robust and consensual results.

Modelling should only allow the formalisation of the subject of discussion. It would be too ambitious to ask the models the integration of multiple dimensions. All models of decision under uncertainty inevitably omit some relevant factors[50]. The role of the expert should also be limited to providing only the most safe and legitimate expectations.

3. A more democratic decision

In the interpretation and application of risk management measures with the precautionary principle, procedures to be used should gather technical and non-technical information in an interactive social process. The analysis of individual aspirations of people concerned by the risks (experts, laymen, etc.) and of the collective forms of deliberation and justification which govern social situations of risk emergence, will enable to throw light on a reasonable decision which can reconcile collective responsibility and respect for the plurality of aspirations of individuals within a society.

Public authorities must intervene to establish socially acceptable levels of risk for a given hazard, based on procedures for technical and scientific research and on public debates.

4. Defining a range of solutions

In complex situations with rationality limited by the capacity for collecting and processing information and for computation, and also by the difficulty of judging conflicts between divergent interests, the main issues would be better considered in terms of characteristics of choice problems that can be described in general terms, rather than as parametric properties of particular models such as expected utility or other.

The precautionary principle provides general indications on the course to follow in the face of potentially serious risks, but cannot be reduced to a single criterion. Therefore, a good solution would be to validate a nucleus of criteria which could select a limited set of decisions that, in certain circumstances, could serve precautionary purposes[51].

A formal economic analysis of the decision-making problem should then be capable of identifying an area of acceptable solutions that societymight well find acceptable, and not a single solution inadequately considered to be optimal.

49 O. Godard, "Le Principe de Précaution et la Proportionnalité Face à l'Incertitude Scientifique" in Conseil d'État, *Rapport public 2005 – Responsabilité et socialisation du risque* (La Documentation Française, Paris 2005).

50 J. Quiggin, "The Precautionary Principle and the Theory of Choice under Uncertainty" (Working Paper, School of Economics, University of Queensland, Brisbane, 2009).

51 Quiggin, *supra* note 50.

5. Using a common procedural framework

For the assessment of collective risks and the implementation of precautionary measures it is important that public authorities set a common mode of action with precise procedures.

In order to avoid situations of being subject to contradictory pressures for or against immediate action, a regulatory framework is required, which is coherent, proportionate and eficiente, and also suited to the nature of the potential dangers, with common procedures that organize research, expertise and public information and debate.

It is essential to the clarification of the decision process that the different decision elements are clearly distinguished. These are risk and uncertainty assessment, costs and benefits involved and their distribution by population, and actors behavior and their possible impact on risk and on actions implemented to prevent it.

An agreement should be established about the definition of acceptable levels of potential dangers, so that decisions have the support of the population and can be applied in a more effective and democratic way.

As an example of this type of regulatory framework, it is important to refer to a recent study in France that includes a proposal for the formalisation of a step-by-step process of public decision-making under uncertainty, which systematically incorporates elements of expertise and debate taking into account their contributions and their limits[52].

This process includes the following two important phases. In the first phase - preliminary risk assessment - the problem in question is classified as a prevention or as a precaution one, depending on the risk being proven or ambiguous. In the second phase, and in the case of proven risk, prevention measures are chosen as a function of the risk level, whereas in the case of any ambiguity, durable precautionary measures are defined when there is risk evidence or surveillance measures in the absence of evidence.

Other frameworks for the practical implementation of the precautionary principle have been developed. Their most important elements are the potential severity of impacts on the environment or on health, the level of evidence and the degree of precaution required, and the proportionality of precautionary measures to deal with the potential consequences and with risk[53].

V. Conclusions

The analysis of the main approaches and models of economic interpretation of the precautionary principle allows to know their contribution to the debate on precaution in environmental risk management and to discuss their practical relevance.

The formal models presented in this paper help to clarify the concept of precaution and decision-making. They frame the decision problem concerning the economic analysis of the impact of risk on individual and collective welfare and risk management.

Despite many simplifications, they reveal a number of implementation challenges and problems to solve and they contribute to a better understanding of the behaviour of important system parameters. However, models are more conceptual than policy orientated. They have also theoretical difficulties and data collection problems.

Each model applies only to certain kinds of risks. For example, the use of expected utility model assumes objective probabilities to represent decision-makers' expectations, whereas in situations where the precautionary principle is applied, such as in the case of 'new risks', the true underlying probability distributions that should be used are either unknown or unknowable.

In many models, the single-dimensional assessment of the consequences of alternative options is also insufficient and makes them vulnerable in their application to complex problems involving impacts of diverse nature and sometimes difficult to quantify. In this case, a multi-criteria framework may be more suitable for precautionary decision-making.

The link between individual and collective values is also insufficient in most models. The level of risk that should be borne by society is decided by a single decision-maker, except in models that allow for ambiguity aversion. These models represent the existence of multiple perspectives and, thus, seem to allow the transparence of the procedure for consultation of different "stakeholders".

Finally, models lead to unique solutions, and this is not suited to complex and uncertain problems and is ill suited to the proportionate nature of precautionary measures.

52 CPP, *supra* note 9.
53 T. Aven and O. Renn, *Risk Management and Governance. Concepts, Guidelines and Applications* (Heidelberg: Springer, 2010).

Difficulties of obtaining pertinent data and information also limit the applicability of the models.

Therefore, these models only provide a very restricted scope for interpreting precautionary behaviour and are a very general interpretation of potential risks to the community.

In addition, it is clear the lack of generally accepted mechanisms and operational frameworks to guide the implementation of the precautionary principle in an objective, consistent and socially acceptable way.

So, in this paper, some actions to overcome the limitations of formal models are identified seeking to contribute to the debate concerning the clarification of issues and modalities of public precautionary decision.

A first issue is the need to use a very broad treatment of information and knowledge to enable better response to uncertainty. Another issue is the need to integrate in the decision-making process the multiple interests and values involved in the risk situation considered, its potential consequences and the management of potential conflicts.

Moreover, it will be important to seek to reconcile collective responsibility and respect for the plurality of aspirations of people concerned by the risks (experts, laymen, etc.). Public authorities should intervene to establish socially acceptable levels of risk, based on technical and scientific procedures and on public debates. Finally, a formal economic analysis of the decision-making problem should be capable of identifying an area of reasonable solutions which the various components of society might well find acceptable instead of a single solution inadequately considered to be optimal.

Thus, it may be concluded that, given the complexity of problems concerning collective risks, the use of formal models should primarily serve to formalize the subject of discussion, even losing accuracy to gain relevance. Naturally, as a multidisciplinary concept with great social relevance, and for the configuration of which are responsible political (or juridical) entities, the precautionary principle can not be defined solely as an economic model. It will also be essential to have a regulatory framework with clear and precise procedures, appropriate to the nature of risks and socially acceptable for risk assessment and for the evaluation of its potential consequences and the implementation of precautionary measures. Thus, more informed, effective and democratic solutions will be achieved.