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The Need to Account for Uncertainty in Public Decision Making Related to Technological Change

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ABSTRACT

In the extreme, there are two opposing approaches to technological development: The *empirical iterative approach* (also called "trial and error") versus the *deterministic predictive approach* (*also called "design"*). In scientific terms, the first is based on association and the latter is based on causality. In Europe, the latter developed as a consequence of the Renaissance, based on a combination of induction (data) and deduction (theory). The "success" of the Western world is based on the design approach. In contrast, China developed the empirical approach to perfection, in which respect they scored much better than the Western world. During the last century there have been an increasing number of environmental "surprises" as a consequence of economic development in the Western world. Many of these detrimental impacts on the environment have occurred due to disregarded knowledge or ignorance with respect to the causality (cause-effect relationship) between the pressures on the environment and consequences to the environment. The precautionary principle has been introduced as a means of dealing with uncertainty and ignorance in decision making. There is need for a change of paradigm from an elitist, narrow approach to an approach that recognises how far we may be from the ability to predict accurately the consequences of technological changes. This uncertainty has to be accounted for in order to prevent surprises. In case of recognised ignorance, solutions have to be flexible and robust, especially in situations involving irreversibility of the consequences of the decision. When recognising uncertainty and ignorance, the empirical iterative approach has its virtue as adaptive management.

Keywords: environment, risk, prediction, design, cause-effect, uncertainty, ignorance, management.

1. INTRODUCTION

This paper puts the role of science and practice into a historical perspective in order to understand the positivistic perception of the scientific approach to engineering during the development of the industrial society. This prevailing perception has been challenged during the past 40 years due to scientific surprises, not the least due to unforeseen impacts on the environment. The concept of uncertainty in its full spectrum from determinism (know all) to ignorance (know nothing) is highlighted as an overture to the introduction of the precautionary principle. The principle is interpreted on the basis of a historical account of selected case studies presented in a book from The European Environmental Agency [1] and [2]. The paper introduces the need for new paradigms of post-modern thinking and participatory approaches to environmental decision making.

The development of Western society can be illustrated using many indicators, most of which are characteristics of success. However, during the 1960s the glory of positivism and modernity was challenged, and since then these philosophies have been in decline as the undisputed basis for the virtue of growth, progress and prosperity.

One of the important indicators of human well-being is health which may be illustrated by life expectancy. It has been in steady ascent in the Western world due to improved nutrition, prophylactic public health measures and hospital care, better domestic environment and improved social circumstances. However, life expectancy is stalling, even declining, due to over- and malnutrition, smoking and stress – and potentially due to a new set of environmental factors with subtle detrimental effects. While the latter is not entirely well documented, still it is a widespread perception of the public and therefore a "real" issue.

The challenge to the established Western mode of society is even more pronounced with respect to the impact on the external environment. The damage has been widespread and is well documented over a wide range of problems, such as eutrophication, acid rain, ozone layer depletion, and chemical contaminants (PCB, TBT, ...). During the last

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century there have been too many "surprises" – situations in which detrimental impacts on the environment occurred due to either disregarded knowledge or outright ignorance with respect to the cause-effect relationship between the pressures on the environment and the consequences to society. This development of concern for the failure of predictability in design of progress is compounded by the revolution in scientific thinking introduced by the concept of "indeterminacy." It is the notion that complex systems, like nature and society, are inherently unpredictable, not only as a shortcoming of our knowledge or skills, but also as a built-in feature, never to be overcome even with the best of science.

The carpet has been pulled under the self-assurance of the Western culture. Modernity is challenged; post-modernity is in. This not only applies to the environmental issues addressed here, but the whole concept of progress and development is under scrutiny. A new morality is taking shape. This paper introduces the historic reasons for that development and sketches the implications of such a change of paradigm. The main thrust of the argumentation is to incorporate "uncertainty" as an operational feature of integrated environmental assessment and management.

2. ENGINEERING APPROACHES

There are two approaches to engineering design and operation of technology:

- The **empirical iterative approach**, also called "trial and error."
- The **deterministic predictive approach**, also called "design."

Remarkable engineering accomplishments have been achieved by the **empirical iterative approach**: Roman aqueducts still standing, drainage in ancient Athens, Medieval Gothic cathedrals and many other famous structures. Many mistakes paved the road to these successes: the tower in Pisa is still (just) standing. The bridge over the St. Lawrence River in Quebec was designed by scaling up the bridge in Scotland across the river Forth, but columns cannot be scaled up proportionally and the bridge fell down! The empirical iterative approach is still a valid approach. Those favouring this approach tend to pride themselves by calling themselves "practitioners."

At the other end of the scale is the **deterministic predictive approach**, which favours developing an understanding of all elements in the structure, so that the performance of the structure can be predicted. On that basis, the structure can be designed to meet predetermined requirements. We will call the enthusiasts of this approach "theoretists."

There has always been a schism between the practitioners and the theoretists, frequently in relation to international conferences, at which it is difficult to satisfy both. The fact is that there is little justification for this schism, because there is need for both, e.g. expressed by the joke: "There is nothing more practical than a good theory."

The schism between the two approaches can also be illustrated by the development of engineering education, which has become more theoretical still – leaving the student to achieve know-how from practise after graduation. It is a valid question to pose, whether it is a good tendency to educate by exemplified application of models. Do the students get a basic understanding of theory and/or practise, or do they get entangled in the mechanisms of futile handling of hardware and software, which will be obsolete by the time the students graduate from the university?

3. THE CHINESE HERITAGE COMPARED TO THE EUROPEAN

As an illustration of the difference between *the empirical iterative approach* and *the deterministic predictive approach*, it is interesting to compare the Chinese heritage with that of the European with respect to technology and science.

The Chinese developed technology to perfection both earlier and better than in Europe. The connection between the two cultures was by all accounts marginal and presumably insignificant to the development of technology. The only connection was the trade along the Silk Route, which was so long and had so many stations that little information was transmitted along with the goods. Alexander the Great met a Chinese army in Afghanistan, but they never engaged each other. Chinese and European ships met only occasionally in Indian waters with no effect with respect to information, except wild stories. The interpretation that China and Europe developed virtually independently of each other is confirmed by the fact that Marco Polo (1254–1324) was met with scepticism upon return to Venice from his visit to China due to his fantastic stories which few believed.

Chinese technology was centuries ahead of European technology [3, 4]. The examples are legion: The production of porcelain, called "china" for that very reason, was an unknown technology in Europe until imported and the technology copied for local production. China had cast iron long before Europe. Pumping by the piston principle, but made with bamboo, was known centuries before, and so on, over the whole spectrum of technology. It is manifest that technological development was far advanced compared to cultural development parallel in Europe. In this context, the heritage of technology as interpreted in connection with Chinese philosophy was based on *association* rather than *causation*.

Association is defined philosophically as an interpretation of an interrelationship between phenomena, determined by observation on a purely empirical basis, without an interpretation of the relationship as an expression of a specific law of nature with a universality beyond mere observation – in other words, without ontological interpretations. The Chinese used the empirical iterative approach. They were masters of "trial and error," and on that basis they scored far better than the Europeans.

The European development of philosophy dates from the Greeks: Socrates, Plato, Aristotle and many more from the ancient Greek culture. What is outstanding was the unique suggestion that there is another world with features that can be interpreted as a reality in a separate, ideal world. The ontology (the concept of being) as a concept was born. That other world can be described accurately, like in geometry, and it may have a reality more real than what we experience (Socrates). The epistemology of the world is just an imperfection of reality as we perceive it. Accordingly, laws of nature are solid reality to which our experience is just an imperfect approximation.

This concept did not survive the dogmas of the Christian Church up through the Middle Ages, but survived via the Arab cultures of North Africa and was transferred with the Moors via Spain to reach central Europe in time for the Renaissance. It is interesting that the scientific revolution of the Renaissance dealt with something as heavenly and apparently useless as the movement of the sun, the earth and the stars. Copernicus (1473–1543; *De revolutionibus orbium coelestium* 1543), Kepler (1571–1630; *Mysterium Cosmographicum*, 1596; *Astronomia Nova*, 1609), Galilei (1564–1642; *Dialogo sopra i due massime sistemi mondo, tolemaico e copernicano, 1632*) described the motion of the planets and claimed the sun to be the centre as a consequence to the interpretation of laws of nature. This would have failed (and almost did) due to conflicts with the Church. However, the Church was weak at the time and could not suppress the new ideas. Newton (1642–1727; *Philosophiæ Naturalis Principia Mathematica*, 1687) made a quantum leap forward, followed up by subsequent contributors to classical physics, chemistry and biology. Laws of nature became the basis for understanding it. Models of nature became the basic concept and the instruments for the development of natural sciences and engineering. This developed simultaneously with new approaches to experimentation. Ontology and epistemology worked in harmony.

This truncated and too brief account of European science is highlighted only to show the unique influence the interpretation of nature had on the development of technology and engineering in Europe. Development became a combination of the empirical iterative approach and the deterministic predictive approach. The laws of nature allowed the development of a structure of understanding, which together with data and experience made modelling of nature, technology and engineering possible. This symbiosis was the basis for the quantum leap forward and the rate of development of technology as the basis for the industrial society.

However, faith in the infallibility of deterministic interpretation of laws of nature is declining for many reasons. Among the reasons is that many mistakes were made with respect to risks to human health and to the environment during the second half of the last century. In addition, basic physics – the centre of deterministic success – developed beyond Newtonian physics into quantum mechanics, in which stochastic elements overshadow deterministic predictability, which raised basic questions related to the adequacy of determinism. This development carried on into other disciplines, such as chemistry, biology, economics and social sciences, which are characterised by increasing complexity.

The need for integrated analysis of systems is becoming overwhelming due to too many mistakes and surprises with simple approximations to complex problems during the past half century. However, the complexity of integrated systems [5] gives rise to fundamental concerns regarding the combination of empirical information with known model structures. Similarly, a number of theoretical developments, such as chaos theories (e.g., [6]), theories of self-organisation [7] and catastrophe theories cast doubt on the wisdom of retaining determinism as anything but an unattainable ideal for positivism.

Europe overtook China in technology by a long distance, but the concept on which this advance was based is losing its magic. It may be time to consult Asian concepts of holism [8], e.g., by addressing the Vedas, forgetting about the sections on rites, and concentrating on the more philosophical section: The Upanishads [9]. Similarly, Taoisms may be worth analysing, as nuclear physicists discovered some time ago [10]. Such a development might enlighten university engineering education, which is based mostly on experience (data) combined with information (associations), sometimes with knowledge (causation), but seldom with wisdom.

4. DETERMINISM VERSUS UNCERTAINTY

How predictable is the performance of technologies? How well can scientific understanding and/or experience provide sufficient assurance of reliability?

In the development of the natural sciences since Copernicus, Kepler, Galilei, Newton, etc., the deterministic description of cause-effect relationships has been the core of development. It is axiomatically assumed that there is a unique relationship between the action taken and the effects (e.g., in the environment or on human health). However, during the second half of last century it has been realised that there are both inherited and practical uncertainties associated with cause-effect relationships and more recently questions have been raised as to whether, in reality, there is such an identifiable, unique relationship at all, also called post-modernism.

The cause-effect relationship may be written as follows:

$$e = f(i_1, i_2, \ldots, i_n;\ p_1, p_2, \ldots, p_n) + \varepsilon$$

Where

e is the effect
f is a functional relationship
i are input variables
p are parameters
ε is the uncertainty ("error term")

The functional relationship may be empirical in the form of correlations (association) or theoretical (causation) in the form of generic relationships, based on a-priori knowledge of the phenomena involved. In relation to environmental cause-effect relationships, the phenomena are physical, chemical, and biological, but integrated assessment includes social and economic relationships.

The functional relationship is frequently described as a model. Such models are framed within a context that is essential to identify with clarity. The framework consists of the model structure, which is the functional relationship proper, the inputs, which are driving forces associated with natural phenomena and anthropocentric pressures on the environment, and the parameters, which characterise the functional relationship. In some cases such parameters are well known from a-priori scientific knowledge, in many cases they have to be determined in each individual case by experiments and analysis of the phenomena involved. The final results from the model are the outcomes of interest (the effects), to which the uncertainty is associated.

The error term, which is equal to the uncertainty, describes the extent to which it has not been possible to simulate the effect on the basis of a deterministic functional relationship. This term is conventionally interpreted within the framework of classical statistical uncertainty. However, the interpretation has been expanded over the past decade into ''postnormal science,'' introduced by Funtowicz and Ravetz [11] and Morgan and Henrion [12]. It includes the uncertainty associated with not knowing the essential phenomena, lack of data, poor calibration, ambiguous contextual definitions, and conflicting interpretations due to different perspectives, which all contribute to the level of uncertainty [13, 14]. The significance of uncertainty has been acknowledged widely, including in the discipline of integrated environmental assessment [15].

Uncertainty is defined as any deviation from determinism. The level of uncertainty may be expressed by using the full range from *determinism, statistical uncertainty, scenario uncertainty, recognised ignorance, indeterminacy to absolute ignorance.* A much more elaborate presentation of a typology of uncertainty is described in [16].

Determinism is an ideal that is never achieved. However, history has demonstrated beyond any doubt that determinism is worth striving for. Even with the best of determinism, the output variables show statistical uncertainty. However, we have statistical instruments with which to handle variations in the output data. Risk expressed statistically is a rational approach to the description of variation. There is always statistical uncertainty involved, due to the mere fact that all relationships have to be calibrated with data. With a well-known functional relationship and an adequate combination of parameters plus number and character of data, statistical uncertainty can be expressed and incorporated in a risk analysis. That is the core basis for the established discipline of risk management, including prevention.

Scenario uncertainty is experienced when we have some ideas about the range of outcomes, but not their statistics. We can use scenarios as an approach to analysis, because we can describe a set of plausible outcomes, but we cannot associate probabilities with them.

Recognised ignorance applies when we do not know how to describe essential functional relationships [17], but the issue has been recognised. Ignorance can be personal and can be overcome by education. Ignorance may apply to everybody and then we talk about communal ignorance, the situation where nobody knows. The relationships may become known later due to research and development, but the relationships may not be known at the time, when far-reaching decisions have to be made.

Indeterminacy is the situation where we know that we cannot know. Indeterminacy is in fact knowledge about the fact that we do not know and will not be able to know. *Practical indeterminacy* is the situation where the functional relationships are so complicated and the number of parameters so large that neither determinism nor stochasticity is within reach. The functions and the parameters become unidentifiable. *Theoretical indeterminacy* is the situation where the relationships are inherently unidentifiable, e.g., due to chaotic properties that make predictions impossible [6].

5. MODELLING, CALIBRATION AND VERIFICATION

Models have become the preferred tools to predict performance, in accordance with the deterministic predictive approach. However, there are many loopholes in the approach. Deterministic models may appear to be accurate, but that may be the veil behind which the uncertainty is hidden. This can be exemplified by the established practise of relating a model to reality through data – e.g., discussed in relation to urban hydrology by Harremoës and Madsen [18].

A striking example is the interpretation given by Lomborg [19] to the results derived from Nordhaus' [20–22] economic models of climate change. The model simulations 100 years into the future are interpreted down to differences of less than one percent in order to demonstrate that the Kyoto-protocol is not an economically sound proposition. Far-reaching conclusions are drawn from ''best-guess'' results, in spite of a highly qualified sensitivity and uncertainty analysis by Nordhaus [20], from which Nordhaus himself derives the conclusion that the most appropriate proposition due to uncertainty is a trial and error approach. That situation of uncertainty has not been diminished appreciably by further reductionistic elaborations (regional aggregation and time-varying discounting) on the same model approaches.

The universality of a hypothesis is the basis on which predictions are made. However, such a hypothesis in an open system can never be proven, but confidence in its universality may be improved by induction, i.e., experience [23]. On the other hand, a hypothesis can be falsified. It takes just one example to prove it wrong. These philosophical facts are worth remembering in a situation where the reality of models is routinely postulated on the basis of calibration and verification based on data from past performance. The practise is to use half of an available time series for calibration (fitting the parameters of the model) and to use the other half of the time series for verification (showing that the model performed well). There are two important points to be made in this context:

1. The universality of the calibrated/verified model does not go beyond the universality of the data series used for the analysis in question – unless the model structure and the parameters that were not calibrated/verified by the time series in question have a universality indicated by induction, i.e., experience from other time series.

   This point is highly relevant to environmental issues, in particular to extreme events and to predictions far into the future. Data series seldom incorporate extreme events – and if they do, very few data are of an extreme character. The calibration/verification of models is rarely related to the extreme events to which the models are applied. The reality of the extrapolation is that it is based entirely on theoretical considerations based on induction (experience) from rare sets of data – if any. Similarly, predictions regarding environmental impacts are uncertain due to alterations in the system that are not incorporated in the model structure, e.g., model parameters for the biota in lakes and rivers calibrated from data before the impact may not apply after the impact. Other examples are extreme events, abrupt change in behaviour, and catastrophes, e.g., due to instability. In climate change, the scare scenario is instability of the Gulf Stream [24].

   The scientist has only two options: (1) Use the best theoretical knowledge by which to make a prediction – and refrain from a claim that the model has been verified, or (2) shift to the empirical iterative approach.

2. Calibration/verification of a model for use in practise to a particular problem is seldom based on data series of such comprehensiveness that it permits calibration/verification of other than a few local characteristics. In fact, many of the parameters of the model are not identifiable for the simple reason that the time series in question does not contain the information required to determine the parameters.

   The loophole of calibration/validation in relation to complex models is that good fits can be achieved with different sets of parameters – leaving the ‘‘calibrator’’ with a false sense of certainty. That mistake has been made repeatedly. In some cases, the model incorporates certain combinations of parameters that can only be calibrated as a combination – unless very elaborate scientific investigations are undertaken. The key question is: Does this reality call for simple models or complicated models in which certain features are taken for granted and not subject to calibration/verification? So far, the experience is that the approach should be tailored to the situation in question.

   Uncertainty and ignorance should be given more emphasis – otherwise the modelling approaches to prediction will lose credibility.

6. THE PRECAUTIONARY PRINCIPLE

The precautionary principle is a framework of thinking in situations that governs the use of foresight and demands an ethical stance in situations characterised by uncertainty and ignorance and where there are potentially large pros and cons of both regulatory action and inaction. The key is the lack of knowledge. It is best illustrated by comparison with prevention, which is an action taken in situations where the detrimental effects and the likelihood of their occurrence are fairly well known. The precautionary principle has been introduced to formulate an approach to situations in which ignorance and indeterminacy dominate the cause-effect relationships.

The importance of the precautionary principle is due to the realisation that many of the cause-effect relationships between the pressures from development of society and the environmental impacts are less than well known, and that the lack of knowledge ought to affect decision making. Even worse, the lack of knowledge about the fact that we do not know may give a false sense of assurance and establish the basis for ‘‘surprises.’’ It may cause pretensions that we do know, when in fact we do not. Generally, it is considered incompetent to admit ignorance – it is not considered appropriate for experts to express advice with statements of uncertainty. The fact is that it requires a high degree of competence to identify ignorance and courage to declare it.

The European Environmental Agency [1] and Harremoës et al. [2] have published reports looking into the history of scientific surprises, derived from ignorance or lack of attention to existing knowledge in environmental decision making. The list of cases examined are: *Antibiotic as animal growth promoters, Hormones as animal growth promoters, BSE, Mad Cow Disease, Hormones in fertility treatment, Spectrum of persistent pollutants, Asbestos, SO_2 and acid rain, CFCs and the ozone layer, PCBs, Benzene, MTBE as a substitute anti-knocking agent, Radiation, Marine overfishing and TBT.*

Each case study is analyzed historically with respect to the decisions taken (or not taken) at any particular time versus the knowledge or lack of knowledge at that time. The aim has been to learn from the case studies. The case studies are characterized by a history of failure in performance in relation to the environment. The attempt is to extract from the history experiences that can be used to interpret the potential use of the precautionary principle.

7. EXAMPLES

CFC and PCB fall into the category of *absolute ignorance* at the time of introduction (see [25, 26]). CFC was introduced as an inert chemical in refrigeration in exchange for ammonia, which gave rise to severe occupational health problems. The introduction of CFC was a real advantage in this respect. Nobody had any notion of potential harmful effects in the environment. In fact, at the time the inertness of CFC was considered a virtue. It was a scientific coincidence that the potential effects on the ozone layer were discovered, and it was a scientific achievement that the theoretical hypothesis was meticulously pursued. Similarly, PCB was introduced to benefit specific industrial applications, like a dielectric constant fit for application in transformers. Again, its inertness was considered a virtue. Only a meticulous scientific endeavour discovered strange peaks on the chromatograph in eggs from endangered predatory birds that were caused by PCB – and a whole set of harmful effects of PCB were discovered and actions taken to limit its use.

Antibiotics in animal feed is a case of lack of concern for *scenario uncertainty* in the analysis of pros and cons [27]. The worst case scenario is readily identifiable as the accelerating immunisation of bacteria pathogenic to the domestic animals as well to the humans. The probability of this occurrence is not known, and will be hard to predict, even with intensive research [28]. The question is whether it is prudent to obtain a marginal growth benefit with the potential of long-term irreversible immunisation of pathogenic organisms to the antibiotics known today.

MTBE is a case of *interdisciplinary ignorance* [29]. When finally lead in gasoline was phased out due to its recognised poisonous properties, MTBE was introduced as a substitute. All the expertise building up to that decision was based on experts in air pollution, engine design, and oil chemists. It came as a surprise that MTBE leaking into the groundwater could cause severe pollution due to persistency in groundwater and nasty taste and odour problems. These properties of MTBE had been known since the 1960s in scientific publications and since the 1970s in textbooks.

SO_2 and acid rain is a success story about the discovery, acquisition of knowledge and abatement of the unanticipated, long distance, trans-boundary effects of the discharge of acidity through the stacks from power plants [30]. It took time to realise the problem, research the cause-effect relationship, and convince the respective institutions in different countries that money had to be spent to abate the situation. This is still in progress.

The following lessons were identified in the EEA Study [1, 2]:

1. Acknowledge and respond to ignorance, as well as uncertainty and risk, in technology appraisal and public policymaking.
2. Provide adequate long-term environmental and health monitoring and research into early warnings.
3. Identify and work to reduce 'blind spots' and gaps in scientific knowledge.
4. Identify and reduce interdisciplinary obstacles to learning.
5. Ensure that real world conditions are adequately accounted for in regulatory appraisal.
6. Systematically scrutinise the claimed justifications and benefits alongside the potential risks.
7. Evaluate a range of alternative options for meeting needs alongside the option under appraisal, and promote more robust, diverse and adaptable technologies so as to minimise the costs of surprises and maximise the benefits of innovation.
8. Ensure use of 'lay' and local knowledge, as well as relevant specialist expertise in the appraisal.
9. Take full account of the assumptions and values of different social groups.
10. Maintain the regulatory independence of interested parties while retaining an inclusive approach to information and opinion gathering.
11. Identify and reduce institutional obstacles to learning and action.
12. Avoid 'paralysis by analysis' by acting to reduce potential harm when there are reasonable grounds for concern.

8. IMPLEMENTATION OF PRECAUTIONARY PRINCIPLE

The qualitative, normative recommendations outlined above have been expanded into more operational approaches [31] dealing with issues like burden and level of proof interpreted as tools, such as power analysis of the risk of false negatives versus false positives in decision making. In conventional risk assessment, the risk of false negatives and false positives do not play the role such considerations deserve [32–35]. In the established practise of risk assessment, it is not acknowledged that decisions regarding choice of level of proof are ethical issues, not technical or scientific ones [36]. In spite of this fact, it is common practise to require a scientifically-based, stringent level of proof that no harm may occur from a technical development. It is a basic ethical question whether it is fair that members of the public should shoulder the burden of proof at a level of scientific proof against the promoter of a potentially risky technical development. This is, however, how the WTO's regulatory approaches work. We need acknowledgement of the ethical issues and new approaches and tools for integrated environmental assessment and risk management.

In case of ignorance and indeterminacy as described above, the precautionary principle comes in as an approach that emphasises an empirical iterative approach in cases in which a predictive scientific approach fails or suffers from a predominance of uncertainty. In relation to risk assessment, the chemical properties to be concerned with are: persistency in the environment, bio-accumulation in the environment, severity of toxicity, and irreversibility of consequences.

The greater is the suspicion of harmful effects to the environment and/or to human health, the more pre-emptive measures are called for. In view of the level of ignorance and indeterminacy, it is important to take development in the right direction in a stepwise fashion, because the possibility of being wrong must be counter-balanced by the advantages of a new technology or chemical. At the same time, it is urgent to increase monitoring and research on the issues concerned. It is in everybody's interest to improve, where possible, the knowledge of the cause-effect relationship (remove the uncertainty and ignorance) and to decrease the uncertainty (provision of more and better data and establishment of safe procedures for implementation) associated with design and operation of new technologies.

There has to be a much greater attention to irreversibility. In such cases, the primary demand is for thorough investigation of existing knowledge, investigation of potential consequences, analysis of alternatives, assessment of risk perception and intensified monitoring of the environment and initiation of research on identified suspicion. The precautionary approach is not a rationale by which to tighten the regulatory screw on well-known issues. It is an integrated attempt to avoid or minimise the effects of scientific surprises in the future.

In case of great uncertainties, the conclusion is that the empirical iterative approach should take precedence over the more conventional design approach. This is also called "adaptive management," which is in fact an established discipline that has been used in the management of renewable resources for some time [37]. The idea is that many decisions should be considered to be experiments. Consequently, the decisions should be adaptive. The idea is that the decision should be flexible and easily altered without severe consequences in view of new experiences. That apprehension calls for a subsequent monitoring programme and even research dedicated to the task of revealing whether the assumptions on which the decision was taken are still valid, and whether the development in time is in accordance with the predictions. If not, adaptive management comes into play: New decisions are taken in view of the new experiences, and new flexible measures are taken. Presently, in integrated environmental assessment and management we miss the appreciation of this option; the tools by which to implement the adaptive policy should be further developed.

9. NEW PARADIGMS AND CONCLUSION

In the context of scientific development, there is a need for a paradigm change. According to Kuhn [38], science moves in stages. A fundamentally new concept/approach, called a new paradigm, revolutionises science at certain intervals. In the intervening periods "normal science" works to improve knowledge within the frame of the prevailing paradigm. Slowly, the fundamental concept becomes threatened by mismatches with reality. A new paradigm emerges as a fundamentally new approach to the framing, structuring, analysis and interpretation as part of the craftsmanship of science – much to the dislike of the establishment.

We are approaching a paradigm shift where uncertainty will come to play a dominant role in political decision-making. This is illustrated by the advocacy of post-modernism, according to which the complexity of systems gives rise to an inadequacy of the existing approaches. Explanatory models in the deterministic category "are not deemed to be approximations to the underlying (complex) reality. Rather they are a special case, an impoverished mode of description possible and appropriate only for limited situations. The notion of complexity requires us to consider an absence of full predictability" [5]. Among other changes, this introduces a need for cultural factors to be included as ways to cope with uncertainty.

Under the new paradigm, uncertainty (statistical uncertainty, scenario uncertainty, recognised ignorance, and indeterminacy) becomes an accepted fact on both sides of the border between the scientists on one side and the public and the politicians on the other side. This will require a change of attitude on both sides. The politicians will have to accept that fuzzy answers may be the best expression of expertise. The scientists will have to learn that identification of the fuzzy borderline between knowledge and ignorance may be the sign of real competence.

In a much larger context, there is a need for a change of ethics in relation to the knowledge base (or lack of same) for decisions regarding the environment and human health. The whole concept of uncertainty cannot be handled by "command and control" nor "economic" regulation. It requires a basic change of attitude, by industry, agriculture, public institutions, politicians and the public [36]. Political decisions are taken as "designs," assuming that adequate information is available for a once-and-for-all decision. The reality is different. Decisions are frequently made on an uncertain, even ignorant basis. Accordingly, decisions should be considered experiments to be followed up by adequate monitoring and research. Decisions should be diverse, robust, and adaptive with an assumption that they may be modified in view of evidence of failure of assumptions or deviations from expectations. Adaptive management should become a prominent feature in integrated environmental assessment and proper tools should be developed for implementation of the precautionary principle and adaptive management.

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