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A COST-RISK-BENEFIT ANALYSIS OF TOXIC SUBSTANCES[1]

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ABSTRACT

Hundreds of new toxic substances are produced each year to satisfy consumer demand, but many of them also enter the environment as risks to the exposed population and to ecosystems. The most logical criterion for their control is a net comparison of all product gains and risk losses from using these substances, with the objective of maximizing the overall welfare of society. The operational framework presented here attempts to synthesize cost-benefit and risk information into a decision-making setting for the purpose of identifying the optimal control level. Both quantitative and qualitative value systems are merged into a single framework, and sequential stages of the analysis are outlined in detail. Several decision-making approaches are recommended, the appropriate choice depending upon the extent of risk-benefit data available as well as the preference for monetary versus non-monetary values. Uncertainty in the data base complicates the assessment since its inclusion requires the application of special statistical measures of confidence.

Introduction

As a result of rapid technological changes and industrial development, a large and increasing number of toxic and hazardous substances enters the environment or appears in consumer products each year. Because so many of these elements are generated without stringent regulations, or perhaps with no controls at all, man and nature have been involuntarily exposed to their effects. Some toxic substances cause known potential hazards to human health or ecological

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habitats, but the majority is not well understood and thus introduces uncertain risks to the environment.

In view of these informational deficiencies, policymakers face the complex task of setting optimal standards on product content and environmental quality. This problem becomes particularly acute with early warning systems, designed to recognize potential dangers from harmful chemicals and organisms. The limited time horizon for early warning precludes an extensive, detailed analysis of risks and benefits. Yet regulation, to be effective over the long run, cannot rest simply on intuitive decisions or arbitrary preferences. Inherent values and needs of society must be identified and, if possible, quantified in a framework that reveals the major welfare impacts of regulation. There is consequently a need for the development of methods to assess the cost-risk-benefit tradeoffs of alternative decisions.

In the National Academy of Engineering's colloquium on benefit-risk perspectives, Lind [1] emphasized the importance of quantitative approaches. He was "disturbed by the absence of an understanding of the basic principles and methodology of decision analysis and benefit-cost analysis . . . ." He further stated, "Some people will contend that it is impossible to quantify the outcomes of many social programs. To this I would answer that without quantification of the most basic nature it is impossible to specify a rational criterion for the evaluation of any program."

Echoing this observation, the President's Science Advisory Committee [2] argued that the absence of quantitative information is likely to bias regulations toward the over-protection of health and ecology. While risk avoidance is a necessary consideration, its value to society should be contrasted with that of products generating or containing toxic elements. The cost of incomplete information could have serious outcomes, as the Committee recognized: "Regulatory decisions in the name of protection of health and environmental integrity often have expensive consequences. They typically obligate large expenditures of money, they are meant to remain in effect over long periods of time, and they typically re-arrange large areas of our lives. Given the large impact of these consequences, the decisions producing them deserve the best foundation possible. Errors in regulatory judgments can be extraordinarily expensive, in human and monetary terms."

This study presents a conceptual framework for a cost-risk-benefit analysis, hereafter called a CRB analysis. Operational stages of analysis are identified as they contribute to the optimal decision of maximizing social welfare. The utilitarian value of the method is limited by inadequacy of data, particularly on the risks from toxic substances. However, a methodological framework is important even prior to application. By outlining data requirements, it results in the selective processing of information. Otherwise, the decision-maker could become enmeshed in an unmanageable, largely valueless data bank.

Traditional cost-benefit analysis translates all impacts into economic magnitudes. Obviously, the use of a common denominator, such as the current dollar value, simplifies the task of selecting that control level at which toxic substances yield the highest net benefits to society. Unfortunately, many risks and benefits cannot be easily quantified in economic terms.

Muehlhause [3], for example, claims that risks cannot be valued simply as the product of their cost times the probability of their occurrence. There is also a "non-pecuniary type of boundary condition," which governs the behavior of populations at risk. A much broader concept than that of the traditional analysis is thus recommended. The framework presented here can apply to either conceptual approach–the pure economic–or the more comprehensive analysis.

Conceptual Framework

The term, cost-risk-benefit analysis, implies that decisions on toxic substances are based on some sort of accounting scheme of desirable versus undesirable outcomes. Almost every decision involves elements of risk in addition to benefits, and their assessment is often subjective and based on uncertainties. At the national level, an error of judgment can have serious repercussions, in the future if not at present. The outcome can affect a large segment of society and can disrupt or perturb economic growth. Notably in the protection of health and safety, the public is demanding more than ever that strong legislation be enacted to enhance the overall welfare of society. With hundreds of new toxic chemicals manufactured each year, this demand becomes more challenging. As a result, legislators are confronted with the difficult evaluation of risks and damages (both immediate and probable) and balancing them against social benefits of using toxic substances.

Risk-benefit assessments have evolved into a comprehensive, systems framework in order to compare a variety of welfare tradeoffs [4]. To develop and utilize this framework requires multi-disciplinary expertise. Economists have contributed methods and theory for the measurement of social welfare impacts based on market prices or personal willingness-to-pay [5]. Statisticians have derived confidence intervals and other probabilistic measures to assess the degree of risk or benefit uncertainty [6, 7]. Ecologists and health experts have conducted various experiments and research to test animal (and less frequently human) responses to specific toxic materials [2, 8]. But most of these tests have been confined to acute, rather than low-level or long-run, exposures. To utilize this information on risks and benefits, operations research analysts have devised methods of determining socially optimal decisions for toxic and other substances. Some of these techniques are designed especially to handle risk uncertainty [e.g., 9].

Figure 1 abstracts the operational framework for an evaluation of environmental quality. Although the analysis pertains to the control of toxic substances, it can be generalized to other objectives, such as the assessment of

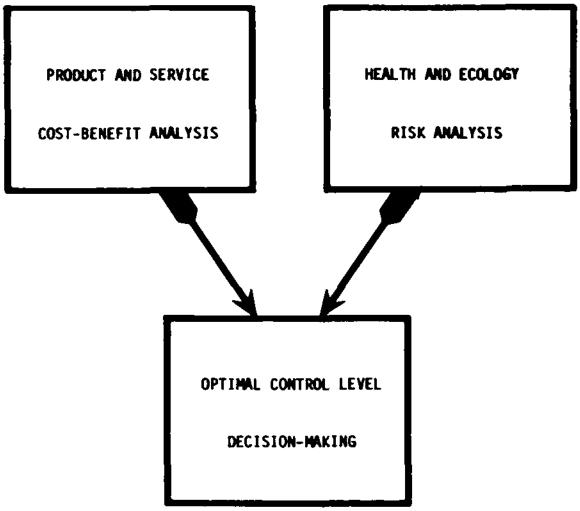

Figure 1. Broad conceptual framework for impact analysis of toxic substance controls.

competing energy sources. Both economic and non-economic factors are represented. Product and service benefits can usually be measured in monetary units. But many social and ecological risks defy quantification and currently are not well understood. To neglect the latter effects in a CRB analysis would yield a partial, and probably misleading, solution of welfare optimization.

According to this diagram, the analysis of toxic substance controls is delineated into three components. First, the cost-benefit assessment pertains to net economic losses attributable to changing consumer demand and supply for products or services subject to controls. Costs can include the treatment of toxic effluents, the substitution of non-toxic for toxic products, and process modifications to alter toxic input requirements or product composition. Benefits respond to each person's willingness-to-pay for the consumption or use of items containing toxic substances or generating them as waste residuals. Net benefit losses can be expected when productive resources are shifted from manufacturing or service sectors into toxicity control programs.

Less amenable to monetary evaluation are risks to human health and ecological systems. The risk analysis attempts to translate these probabilistic states, wherever possible, into expected damages or welfare losses. For some risk categories, quantification is currently infeasible. By controlling toxic substances, risks are avoided, thereby enhancing the safety and welfare of society and preserving environmental amenities.

Both the cost-benefit and risk analyses provide input data for the decision-making component. Here, economic and ecological consequences of various toxicity control levels are compared, and the best solution is found via one of several optimization techniques. The choice of a technique to identify this level is influenced by the type and extent of available benefit-risk information. In the case of early warning systems, only a shortened version of the complete CRB evaluation is feasible because of time constraints on the collection and analysis of data.

Cost-Benefit Analysis

The operational elements of a cost-benefit analysis are outlined in Figure 2. Arrows in the diagram portray the flow of information among sequential steps. The first step entails the pre-selection of all benefit categories, $\alpha_1, \alpha_2, \ldots$, which depend on the direct or indirect utilization and consumption of toxic substances. An example is the demand for pulp and paper, whose production generates mercury-containing residuals. Effluent controls on these residuals

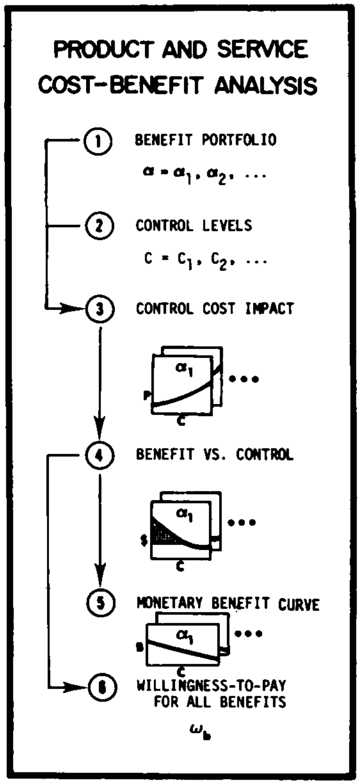

Figure 2. Sequential stages of cost-benefit analysis.

could be so stringent as to aggravate price hikes. Increased costs of control are thus eventually passed on to the consumer, who disbenefits either by paying more per unit of product or by discontinuing his purchase.

For increasing control levels, $C_1, C_2, \ldots$, as defined in Step 2, prices respond in corresponding fashion. Step 3 depicts a typical consumer response, also illustrated in more detail in Figure 3. At control level C_1, the price of product (or service) α_1 is $P_{1\alpha}$; while at C_2 it becomes $P_{2\alpha}$.

A price hike ordinarily implies welfare losses to the consumer of that product. This impact is derived in Step 4 (of Figure 2). As shown more fully in Figure 4, the equilibrium price moves up the demand curve with increasing controls. From welfare economic theory, total benefits are measured as the area under this curve but above the price line. That is, benefits to each consumer equal the difference between the actual price and what he is willing to pay. Some individuals will pay as much as U, while marginal consumers will pay no more than the current price $P_{1\alpha}$. If the unit price increases to $P_{2\alpha}$, the marginal consumer (at $P_{1\alpha}$) is no longer willing to buy the product or service. Benefit losses from decreased demand are then estimated by the area, $XP_{1\alpha}P_{2\alpha}$. Additional disbenefits are incurred by the remaining consumers, who pay an additional $P_{1\alpha} - P_{2\alpha}$ per unit. Welfare losses for these individuals equal the rectangular area, $XYZP_{2\alpha}$. Total disbenefits to society are thus estimated as $XYZP_{2\alpha}P_{1\alpha}$.

These losses are based not on the direct use of toxic substances, but rather on their effect on the price of directly consumable items. Provenzano [10] argued similarly that the value-in-use of such inputs can be measured in terms of the

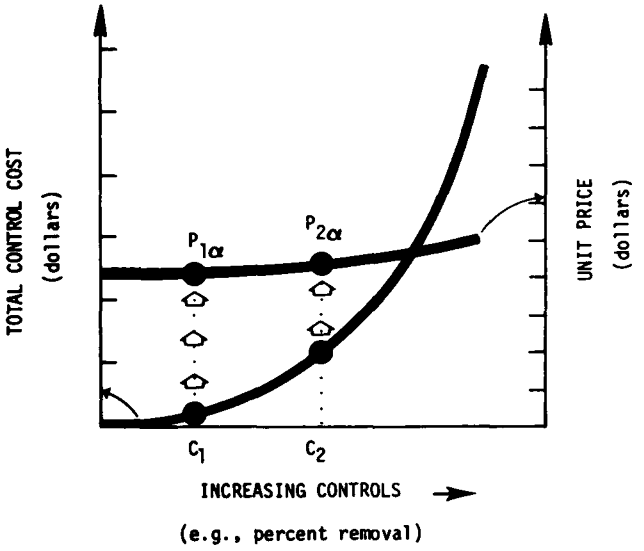

Figure 3. Impact of various control levels on product or service prices.

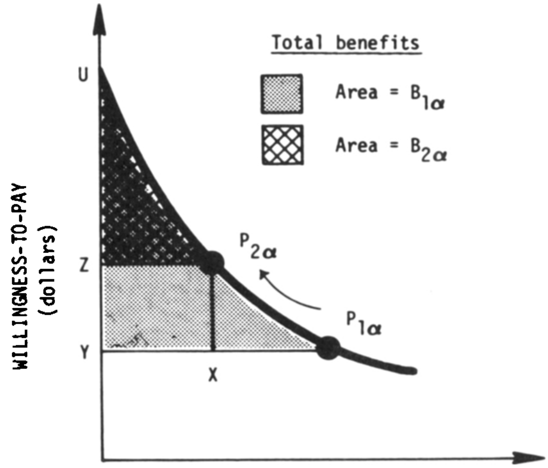

Figure 4. Estimation of product or service benefits for various control levels.

generated output. But he also contended that in cases where this value cannot be isolated for the input in question, benefits must be measured by an alternative method. If the producer must substitute another input, then the appropriate estimate is the additional cost of doing so, also called "the opportunity cost of not being able to use the original input."

Step 5 of Figure 2 translates the consumer surplus estimates (Figure 4) into a benefit curve, as shown in Figure 5. There are numerous sources of uncertainty in these estimates, which account for the wide confidence bands around expected values. For example, only a subset of the entire population is sampled in deriving demand curves. Biases in willingness-to-pay surveys are another source of error. If the respondent believes that his answer will affect prices, he may purposely give a lower estimate. Or perhaps he is unsure of the value and thus gives different answers, depending on the time at which he is interviewed.

It must be noted that benefit losses for product α_1 represent only one impact of consumer demand. If there is a close substitute for this item, then its benefit losses will be partially negated by increased consumption and hence greater benefits for the alternate product or service. To account for net benefit changes thus requires the identification of all significant impacts, whether they are direct or indirect, competing or complementary, short-term or (discounted) long-term. Added together, the individual product and service benefits provide an estimate of total social impacts.

An alternate method of estimating net benefits is to derive a willingness-to-pay curve (Step 6) representing all impacts simultaneously. By means of survey techniques, individuals are asked to estimate the amount that

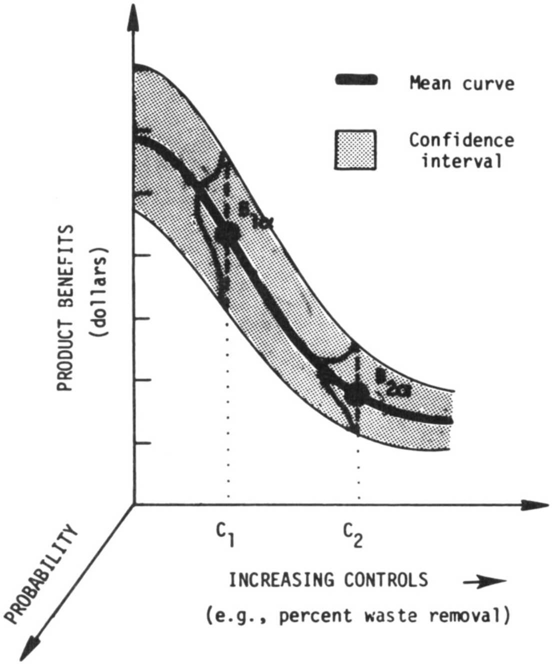

Figure 5. Formulation of product or service benefit curve.

would represent sufficient compensation (excluding risks) for reducing current use of toxic substances. Their answers are then plotted against various toxicity control levels, and a benefit curve ω_b is then fitted through these sample observations.

Theoretically, this curve should be equivalent to the net sum of all single product and service benefit curves derived in Step 5. But this assumes that each individual is perfectly knowledgeable about the totality of benefits. In practice, willingness-to-pay values are more likely to reflect a narrow, self- rather than society-oriented perspective. Biases in these values can thus be anticipated. For instance, an individual will be conservative if he fears that his answer might affect his tax base, while an overestimate is probable if he suspects that other members of society will be responsible for payment.

Risk Analysis

Risks to human health and ecological systems constitute the second component of the conceptual framework. As toxic substances are removed from the environment or the food chain, risks should decline correspondingly. Social benefits from such action include an improvement in the health, safety, and general welfare of the exposed population.

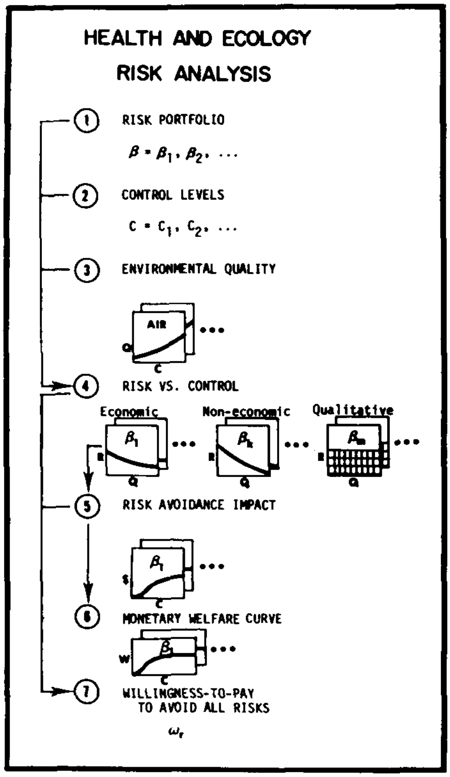

Figure 6. Sequential stages of risk analysis.

The assessment of these impacts is described in Figure 6. Step 1 enumerates specific categories of either known or suspected risks. If control levels (Step 2) refer to emission loads, they must be transformed into ambient concentrations of toxic substances to which the population at risk is exposed. Step 3 shows a typical model, whereby effluent loads are translated into ambient conditions by a waste diffusion process. Other examples may be more complicated to predict, such as the accumulation of mercury derivatives in fish.

Risk levels are then related to environmental quality according to Step 4. This step is very crucial to the analysis, as it involves the assessment of risks, either probabilistic or deterministic, over a range of quality (or control) levels. Three types of risk are differentiated. Some risks can be monetized, e.g., medical costs and lost wages from illness. Others can be also quantified, such as pollution tolerance levels of fish species, but their translation into economic values is questionable. Either the item at risk has no price in the marketplace, e.g., seagulls, or else it indirectly supports commercial products but is not demanded in itself, e.g., phytoplankton in the food chain culminating with commercial fish.

Still other risks currently defy any numerical or physical quantification, but are described in qualitative fashion. The preservation of environmental intangibles such as aesthetics falls within this domain.

Because risks are probabilistic and must usually be assessed without adequate data, their mean values serve limited objectives. Instead, a stochastic interpretation of each risk level is more relevant. According to Figure 7, this interval is bounded along the lower border but not along the upper one. This distinction occurs for at least two reasons. First, in addition to typically mild cases of exposures, there may be isolated reports of serious episodes, e.g., human fatalities, caused by extended exposure to toxic substances. These observations could fall far above the typical or mean risk curve. Second, but more importantly, there are unknown or as yet undiscovered risks whose recognition would either shift the mean curve upward or extend the confidence range far above the mean. Because early warning systems must weigh such uncertainties, the confidence band should reflect the likelihood of future problems. Thus, unlike the balanced Gaussian distribution underlying most confidence measures, this band would be skewed toward high risk values. Note that this function ranges over the original control level, which is derived from ambient quality according to the diffusion model in Step 3.

The sixth step results in the transformation of risk avoidance into an expected economic return. As the risk of human accidents, sickness, or fatalities

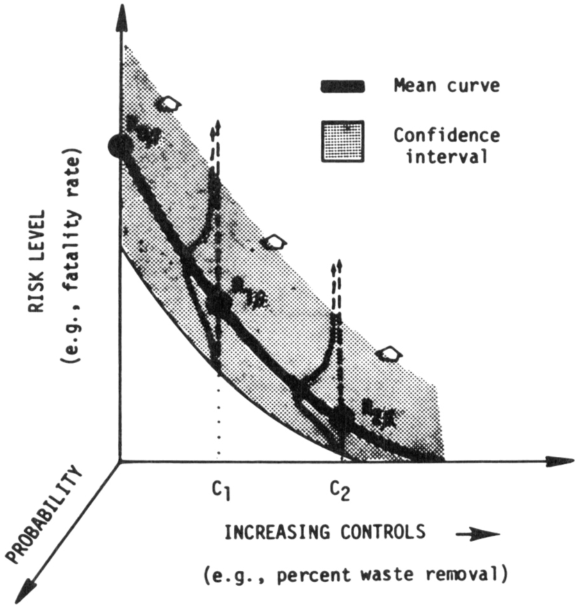

Figure 7. Estimation of risks at various control levels.

declines, savings can be anticipated in terms of lower medical costs, higher wages from reduced absenteeism at work, etc. An expected value of these savings is depicted by the upward sloping curve.

Finally, to circumvent the task of developing individual risk curves, willingness-to-pay surveys can be conducted to derive an aggregate welfare index. Analogous to that derived in the cost-benefit analysis, the function ω_r (Step 7) depicts total economic gains of reducing all risks simultaneously, as controls on toxic substances become more stringent.

In Figure 8, a typical welfare function is derived from increasing risk avoidance levels. An S-shaped form is illustrated, with a horizontal asymptote defining maximal expected welfare. This limit is necessary since each individual, with a finite income, can afford only a limited insurance premium to protect his health from unknown events. The S-shape has been empirically justified in a survey [11] of the amount, ω, that people are willing to pay to reduce their probability, ρ, of heart attacks and premature death. Mathematically, this function is written as,

$$\omega = e^{a-b/\rho},$$

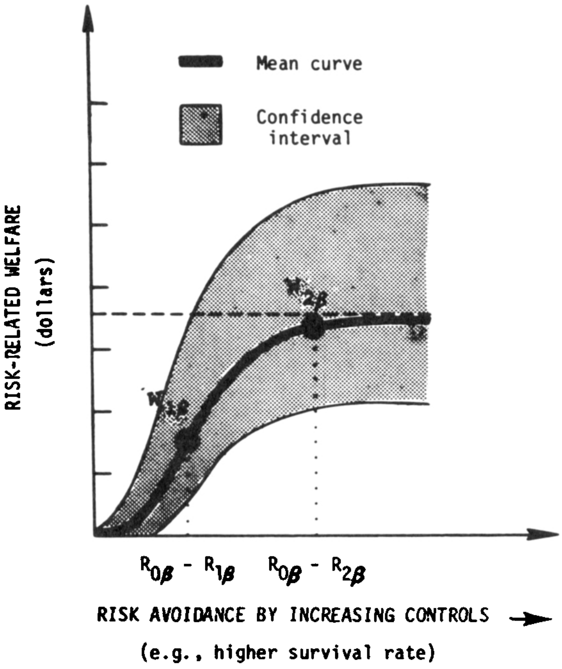

Figure 8. Estimation of risk reduction-welfare impacts at various control levels.

where a and b are regression coefficients. Typical confidence bands for this regression show the variation of people's perception of welfare. The distribution of family incomes influences this variation, with wealthier respondents generally willing (and able) to contribute more dollars [12].

In addition to purely monetary values, there has recently been concern about the "nonpecuniary demand for safety" [3]. Irrespective of monetary welfare impacts, this consideration could lead a consumer to reject a toxic substance-bearing product for a number of personal reasons, including the following: ". . . his talent and ability to manage the operation of the product in question, his past experience and success of similar undertakings, and his natural propensity or aversion for assuming risks." To compensate for this nonpecuniary impact, the welfare curve is multiplied over its entire risk avoidance range by a factor exceeding unity. Although this factor has been described in theory, it has never been measured empirically, and therefore remains subject to debate.

Decision Analysis

After risks and cost-benefit impacts are evaluated, the decision-maker can compare them for the purpose of setting optimal control levels. The objective is to set standards so as to maximize social welfare, mathematically stated as the present discounted value of all product and service benefits plus total risk avoidance gains. Figure 9 depicts four alternate approaches to optimization. The selection of an approach depends not only on the extent of information but on the extent of monetary data. The economic analysis, which relies completely on dollar values, can proceed as a complete or partial assessment. The former relates total willingness-to-pay to changing levels of toxic substance use. By superimposing the benefit and risk avoidance functions, ω_b and ω_r, respectively, a social welfare curve is derived as their sum. Figure 10 illustrates the manner in which the best decision is identified. From differential calculus, the social optimum C_* is that point at which the derivative of the social welfare curve vanishes. (In cases where there are several local optima, the decision-maker must choose the best solution.)

The optimal solution is not so obvious as this simplified graph indicates. Willingness-to-pay curves for each benefit or risk (see Figures 5 and 8) reveal that uncertainties play a fundamental role in the analysis. Consequently, the social welfare function becomes a confidence band surrounding the mean curve. The optimum is translated into an interval of likely values with a derived probability distribution, rather than a single value. The decision-maker is most likely to select the mean value or a higher one, if he is risk averse [13].

To be meaningful, willingness-to-pay curves should reflect the totality of benefit impacts. However, no individual has a clear perception and understanding of all market and economic factors. Moreover, there are inequity issues underlying one's ability to pay. Family income levels will affect the

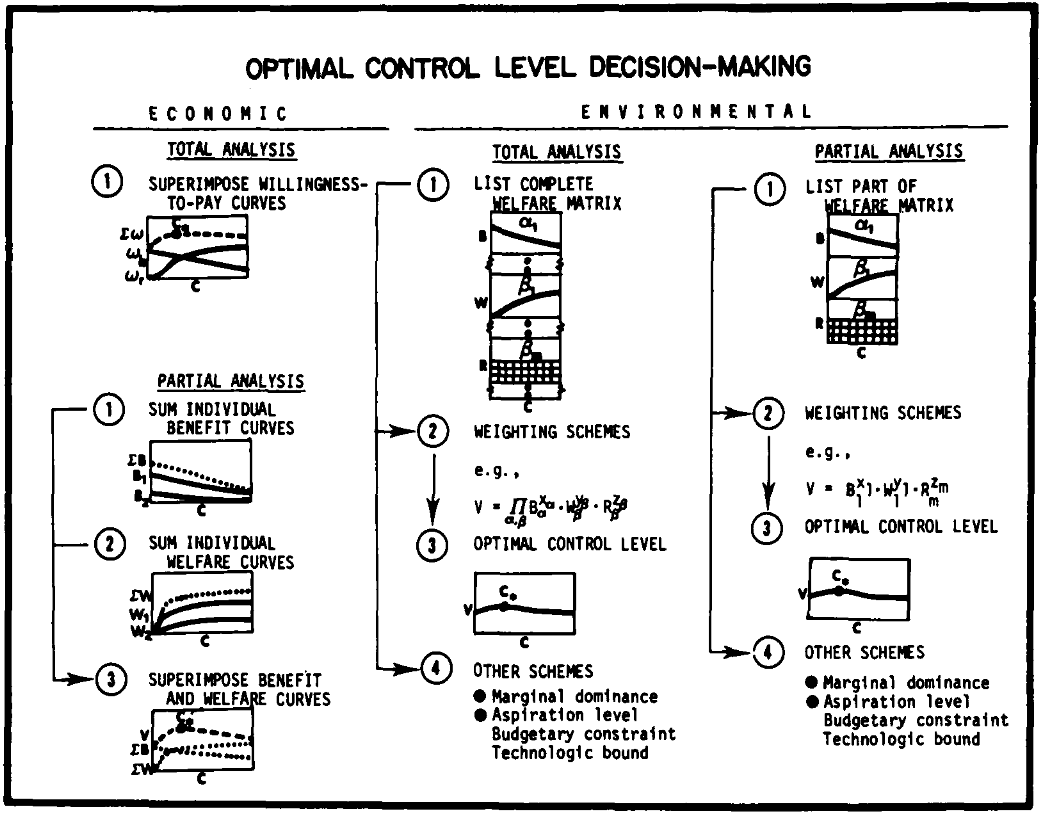

Figure 9. Sequential stages of optimal decision-making strategies.

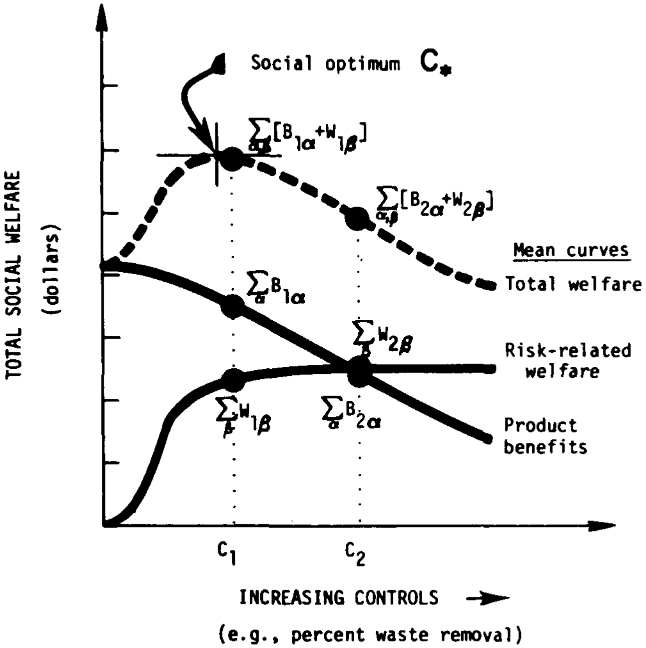

Figure 10. Selection of optimal control level in risk-benefit analysis of toxic substances.

magnitude of his response. In at least one empirical study [12], willingness-to-pay was found to increase significantly with rising incomes. At very high incomes (exceeding $50,000) this trend tapers off and even dips slightly. Because of such distributional questions, willingness-to-pay values are not widely accepted in measuring economic impacts.

Another approach based solely on monetary trade-offs is a partial assessment. Several important benefit and risk avoidance functions are summed together to derive a social welfare function, after which the optimal control point (or interval) is determined. Provided that the economically most significant curves are chosen, this partial approach should provide a reasonable approximation to the actual (total impact) solution.

The above optimization strategies rely on monetary values. Obviously, there are non-quantifiable aspects of the environment as well. The remaining strategies in Figure 9 are called "comprehensive" since they include non-economic and economic data. In the complete analysis, all risk and benefit portfolios are enumerated (Step 1). To permit comparability of these values for policy-making purposes, all risk-benefit impacts must be determined over the same range of control levels.

This one-to-one correspondence makes it possible to compare marginal impacts by sight, and thus to quickly identify those control levels likely to yield the greatest overall changes in risks and benefits. The next three steps describe methods of selecting the best policy. First, a weighting scheme can be applied, such that magnitudes of risks and benefits are substituted into a "value function." This function can be exponential (as shown) or some other form, whose value V rises as individual benefits increase or risks decline. Values are thus calculated over all control options, and a maximal level C_* is found (Step 3).

Although weighting functions have been used in actual studies [e.g., 14], they lack general popularity. Since relative weights must be assigned, such functions explicitly trade-off monetary and non-monetary impacts. Of course, any decision-maker is ultimately faced with this problem in designing policy; but to explicitly interrelate such impacts raises objections among ecologists, many of whom claim that environmental quality cannot be described in dollar terms. Another objection is that all dependent variables in the weighting function must assume numerical values, thus conflicting with the meaning of non-quantitative risks.

The simplest, and perhaps most popular, solution is to promote "zero tolerance" of toxic elements. That is, their use is completely banned, in an effort to minimize health risks. From a social welfare point of view, this aspiration level is probably inefficient since it fails to consider the benefits side.

Of greater appeal to environmentalists and economists alike is a quasi-optimization approach called "marginal dominance." The decision-maker inspects risks and benefit curves individually, and identifies those control levels at which marginal (changing) impacts are extreme. From previous remarks on willingness-to-pay, these marginal conditions may indicate the optimal solution. But when there is a large number of such impacts, numerous control levels will be identified. Consequently, the problem then reduces to choosing one optimum. This choice depends on the implicit ranking of marginal risks and benefits by the decision-maker. Thus, a value system must still be applied, but at least it is not so obvious as to be repugnant to many environmentalists. Of course, all control decisions are restricted within budgetary and technological feasibility bounds.

Conclusion

Policies on toxic substance control should not be derived from subjective opinion. If welfare of society is to be optimally enhanced, a quantitative analysis of benefits and risks is the most promising approach. Recently, in fact, scientists have strongly advocated the development of methods to assess competing impacts of product benefits versus risks from exposure to toxic elements.

An operational framework is presented here for the purpose of assessing welfare impacts of product or service benefits, health or ecological risks, and then utilizing them in a decision-making analysis. There are several approaches to selecting the optimal control level, each appealing to a distinct audience and having specific advantages. Economic approaches are simplistic in that they assume only monetary values. Willingness-to-pay surveys provide a quick method of assessing the total value of risks and benefits, but their plausibility is frequently questioned. Individual risks and benefits can be listed in a partial assessment, but the adequacy of this list may be difficult to ascertain. Moreover, a large number of these categories may be necessary to cover a substantial portion of total effects.

To the non-economist, complete dependence on monetary values is frequently unacceptable. There are intangible or non-economic aspects of the environment that should also be assessed. To comply with their value system, a more comprehensive approach is developed. Here, as with the pure economics approach, the amount of risk-benefit data available determines whether a total or partial assessment is appropriate. The latter is more likely in view of the limited time horizon over which controls on toxic substances must be established.

Because risks and benefits are not necessarily translated into the same units, e.g., dollars, the optimization procedure is not straightforward. A weighting function can be derived by assigning relative values to impacts at various control levels, but this technique implies a direct comparison of monetary and non-monetary impacts. An alternative method is to apply marginal dominance, whereby the greatest changes in specific risks and benefits are identified as controls become more stringent. These changes will indicate the most likely policies for welfare optimization.

On the risk side, there are several unresolved problems of assessment. One involves the role of uncertainty of the data base. A CRB analysis based on currently available information is likely to underestimate total impacts. As more knowledge about potential risks is discovered, the public seems more willing to pay to avoid these risks. An example is asbestos, which was of no concern fifty years ago but is now under intensive investigation because of recent findings on illnesses of asbestos plant workers [15].

Another problem concerns the protection of any natural ecosystem or even a single species. While species fatality curves must be known, risks also pertain to changes in metabolic rates, reproduction rates, and modifications of the food chain. Complex linkages and survival dependencies within an ecosystem make this analysis particularly challenging. Moreover the accumulation and synergistic effects of toxic elements pose still another problem. To segregate the effects with respect to each element may be impossible.

The complexity of risk-benefit analyses is accented by the need to evaluate risks and benefits over the same range of control levels. This requires the translation of ambient exposure control levels (for risks) into control standards on emissions or product content. Provided that controls pertain uniformly to one industry or product, the analysis presented here is applicable. But if more than one generating source of toxic substances is involved, the control variable is multi-dimensional rather than single-valued (see Figure 3). In this case, the control parameter C is equivalent to a vector.

As shown here, the operational framework for a CRB analysis consists of numerous steps. In theory, however, the procedure can be explained more simply [3]. But the gap between conceptual models and their empirical application is surprisingly wide. The CRB analysis may be simplified to some extent by minimizing costs of controlling toxic substances, subject to the avoidance of certain risks. But this objective neglects the (often high) value of products containing or generating toxic elements. Instead, this study assumes that the control costs are eventually paid by the consumer in the form of higher prices, and hence that product benefit changes reflect these costs.

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