RM-78-64

A GAME THEORETIC FRAMEWORK FOR DYNAMIC STANDARD SETTING PROCEDURES

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December 1978

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Prepared for the Stiftung Volkswagenwerk

PREFACE

Standard setting is one of the most commonly used regulatory tools to limit detrimental effects of technologies on human health, safety, and psychological well-being. Standards also work as major constraints on technological development, particularly in the field of energy. The trade-offs to be made between economic, engineering, environmental, and political objectives, the high uncertainty about environmental effects, and the conflicting interests of groups involved in standard setting, make the regulatory task exceedingly difficult.

Realizing this difficulty, the Volkswagen Foundation sponsored a research subtask in IIASA's Energy Systems Program on *Procedures for the Establishment of Standards*. The objectives of this research are to analyze existing procedures for standard setting and to develop new techniques to improve the regulatory decision making process. The research performed under this project include:

- i) policy analyses of the institutional aspects of standard setting and comparisons with other regulatory tools;
- ii) case studies of ongoing or past standard setting processes (e.g. oil discharge standards or noise standards);
- iii) development of formal methods for standard setting based on decision and game theory;
- iv) applications of these methods to real world standard setting problems.

The present Research Memorandum is one in a series of papers dealing with the development and application of decision theoretic methods to standard setting. It presents the formal basis for multistage game theoretic analyses of standard setting problems as well as some illustrative examples.

Wolf Häfele

ABSTRACT

This paper presents a game-theoretic approach to modeling environmental standard setting procedures under specific consideration of the dynamic conflict situation in environmental decisions. Three idealized decision units are considered, the regulator, producer and impactee units: The regulator has to fix the standard. This standard causes a financial burden to the producer, who releases pollutants to the environment. By means of the standard the impactee has to be protected against this pollution.

The starting point is a multistage model for a non-cooperative three person game. After the description of this model the range of its application is indicated by the cases of North-Sea oil, sulphur dioxide, carbon dioxide, and noise. Since any game-theoretic analysis includes the choice of a solution concept, a class of concepts is discussed. The last part of the paper contains a brief survey of the results of two multistage cases where the relevance of the solution concepts is demonstrated.

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INTRODUCTION

Since the end of the 1960s environmental agencies have been set up all over the world establishing guidelines and regulations that should help to limit effects of modern technologies that may be detrimental to the environment. New organizations, regulatory tools, standards, incentives, and procedures were rapidly introduced which often had a substantial impact on the industrial investment and operating costs as well as on the speed at which new technologies were introduced. After an initial period of zealous environmental decision making the time has come now to reflect on this development. Questions such as the following are raised both by environmental researchers and decision makers: How good are our procedures for assessing impacts on the environment? How well do we take uncertainties into account when making regulatory decisions? Are long-term environmental and economic effects of our decision making properly taken into account?

Researchers and experts of environmental agencies began to realize that the difficulties in environmental decision making often lead to decisions that are less rational than one would wish. The problem areas most often mentioned are the vast uncertainties that exist about the environmental effects of pollutants, the difficulty in assessing risks of accidents of scales never encountered before, the conflicting interests of groups involved in and affected by regulatory decision making, and the difficulty in assessing long-term environmental and economic effects. These problems call for new institutional and methodological approaches to environmental decision making (see National Academy of Sciences, 1975, National Research Council, 1977).

This paper presents a game-theoretic approach to the modeling of environmental standard setting decisions, considering specifically the dynamic conflict situation in environmental decisions.

Three decision-making units are considered in the game theoretic model: the regulator, producer, and impactee units; such a structure has in fact also been proposed in connection with risk analysis (H. Otway, P. Pahner, 1976). The *regulator*, who may consist of a regulatory agency where various administrative units and experts interact, has to fix a standard. This standard usually causes a financial burden to the *producer*, who may consist of several energy producers emitting gaseous pollutants, or any other enterprise polluting the environment. The standard serves to protect the *impactee* consisting of the population affected by the pollution.

Under special assumptions about the parties involved one arrives at a conflict among several people that belongs to the class of problems treated by game theory. The assumptions are essentially two: "Each individual has a utility-function that he strives to maximize;" and "Each individual is able to perceive the gaming situation." These two are often subsumed under the phrase "The theory assumes rational players" (R.D. Luce, H. Raiffa, 1957, ch. 1). The problem of how to arrive at utility functions from given preference patterns is dealt with by decision theory (see e.g. D. v. Winterfeldt, 1978, 1), and will not be discussed in this paper. Instead the purpose of this paper is to provide an appropriate game-theoretic framework for standard setting, and to discuss the value of the game-theoretic results for the problem.

The starting point is a multistage model for a game between the three players: regulator, producer, and impactee. It is hoped that the model is general enough to embrace some essential features of most problems of standard setting. Furthermore it should permit parameter analysis in a way that crucial uncertainties about health effects and economic development as well as about utility functions can be identified. This parameter analysis seems to be indispensable especially for the regulator's utility function, since his utility function should reflect both general economic considerations and detrimental effects of pollution on the population, the weights on both being highly arbitrary. Though essentially descriptive, these models should help the regulating authority structure the standard setting task, including such problems as whether and what research program to start, e.g. on health effects, in order to reduce crucial uncertainties. Furthermore they allow one to look at cases where technical or physical parameters dominate such that for all reasonable utility functions and existing uncertainties nearly the same results are obtained.

The models concentrate on long-term aspects or dynamic problems and rather neglect distribution and bargaining problems (see, e.g., Organization for Economic Co-operation and Development, 1976, and J.C. Harsanyi, 1977) although these can be included in principle.

The paper is organized as follows. First the model description is given. Then the range of applications is illustrated by cases such as North Sea oil, sulphur dioxide, carbon dioxide, and noise. The North Sea oil problem was treated as a detailed one-stage game model, and multistage models were developed for carbon dioxide and noise (D. v. Winterfeldt, 1978), (E. Höpfinger, D. v. Winterfeldt, 1978). The multistage cases are sketched thereafter.

Since there is a variety of different solution concepts for n-person games ($n \geq 2$), any game-theoretic analysis includes the choice of a solution concept. That is why a class of appropriate solution concepts are discussed: the equilibrium point for noncooperative games, Pareto-optimal points for essentially cooperative games, the "minimal distance from bliss-point" concept, and the Nash solution. Furthermore a hierarchical solution concept is given for cases where first the regulator announces his strategy and thereafter the producer. This two-level leadership concept may be regarded as normative.

At the end a brief survey is given of the results of the two multistage cases demonstrating the relevance of the solution concepts.

MODEL DESCRIPTION

The dynamic or multistage models developed below are *three-person games in extensive form.* The definition of such games is rather involved and, since the authors hope that the following description is sufficiently self-contained for a general definition of games in extensive form, they only refer to (J.C.C. McKinsey, 1952) and (G. Owen, 1968).

The Time-Discrete Game

It is assumed that only time periods or stages have to be considered instead of a time-continuum. Thus a game is played at each stage, and the player's strategies control not only the payoff but also the transition probabilities governing the game to be played at the next stage. Each component game is determined by the states of the play. For example s can contain the relevant physical state of the world, e.g., the amount of oil in the water, of sulphur dioxide in the air, and their distribution; or the relevant economic state. Other than with the more usual games where players make simultaneous and independent choices, *perfect information* is assumed for the component game by the following structure: At each stage the regulator makes his choice first, then the producer is informed about the regulator's choice and makes his choice, and finally the impactee learns about the other choices and makes his choice.

The play proceeds from component game to component game with the transition probabilities jointly controlled by the players. Since the transition probabilities are often not exactly known, subjective transition probabilities are admitted for the players which may differ from each other. The process of the play can be sketched as in Figure 1.

Let S denote the set of possible states. For each $s \in S$ the set of the regulator's choices or measures is denoted by $M_R(s)$. Let $M_P(s,m_R)$ denote the set of producer's measures or choices in the case of state s and the regulator's choice m_R. If the

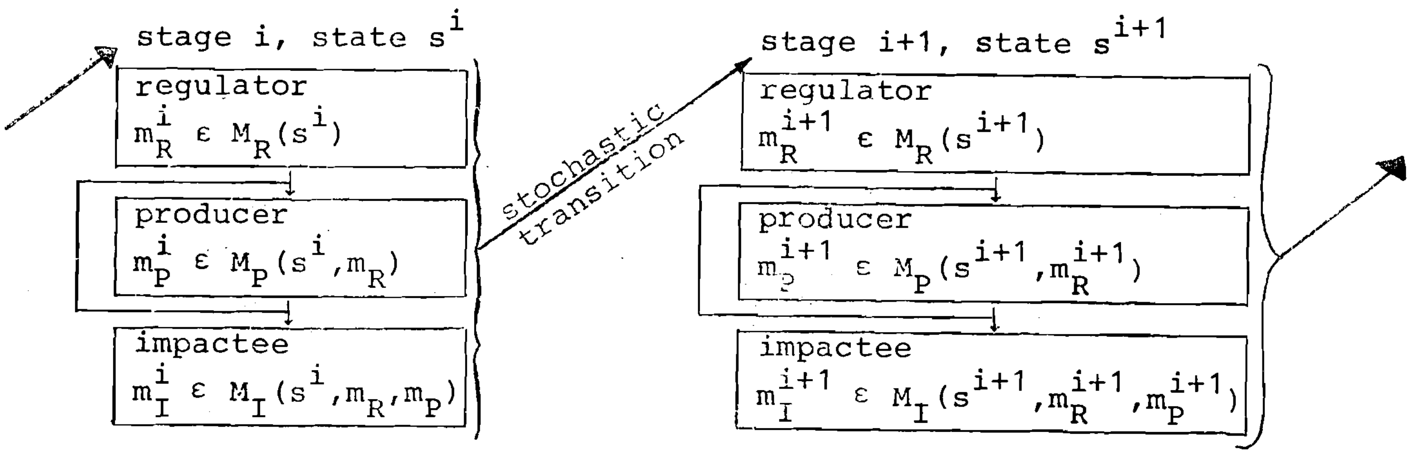


Figure 1. Transition from stage i to stage i+1.

producer chooses $m_P \in M_P(s,m_R)$, then $M_I(S^i,m_R,m_P)$ denotes the set of choices or measures possible for the impactee. Hence M_R is a map on S; M_P a map on $\{(s,m_R)|s\in S, m_R \in M_R(s)\}$; and M_I a map on $\{(s,m_R,m_P)|s\in S,m_R\in M_R(s),m_P\in M_P(s,m_R)\}$. Then $P_j(.|s,m_R,m_P,m_I)$ (j=R,P,I) denotes the subjective probability for the next state given state s and choices m_R,m_P,m_I. Strictly speaking $P_j(.|s,m_R,m_P,m_I)$ is a probability measure on the measurable space (S,∂), where ∂ is an appropriate σ-algebra that depends only on the last state and choices neglecting all previous states and choices. For each component game a utility function is given for each player:

$$U_j : \{(s,m_R,m_P,m_I)|s\in S,m_R\in M_R(s),m_P\in M_P(s,m_R),m_I\in M_I(s,m_R,m_P)\}\to R \quad ,$$

where $U_j(s,m_R,m_P,m_I)$ denotes the payoff to player j (j=R,P,I).

Games which may stop after finitely many stages can be included such that a permanent state is reached providing only one choice for each player and zero payoff for each. This is important in case one tries to approximate infinite stage games by finite stage games.

A play of the game is given by an infinite sequence $(s^1,m_R^1,m_P^1,m_I^1;\ s^2,m_R^2,m_P^2,m_I^2;\ \ldots)$ of states and decisions. Then one possibility for the payoff functions is given by

$$\underline{U}_j(\pi) := \sum_{i=1}^{\infty} \rho_j^i U_j(s^i, m_R^i, m_P^i, m_I^i) \qquad (j = R,P,I) \quad ,$$

where $0 < \rho_j \leq 1$ is a *discount factor* for player j. A second one is given by

$$\lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} U_j(s^i, m_R^i, m_P^i, m_I^i) \quad .$$

Since the latter suppresses the payoff of the first stages we shall only use the first. The discount factor ρ_j is the larger the more the future is regarded as important. In general, $\underline{U}_j(\pi)$ is well defined if $\rho_j < 1$. For special cases, however, $\underline{U}_j(\pi)$ is well defined for $\rho_j = 1$ because technical constraints such as limited resources of fuel limit the summation

$$\sum_i U_j(s^i, m_R^i, m_P^i, m_I^i) \quad .$$

In order to arrive at games that are not too complicated only stationary strategies have been considered. Thus a strategy σ_R of the regulator is a function of S providing always the same choice $\sigma_R(s) \varepsilon M_R(s)$ as soon as $s \varepsilon S$ occurs; a strategy σ_P of the producer is a function on $\{(s,m_R) | s\varepsilon S, m_R \varepsilon M_R(s)\}$ providing always the same choice $\sigma_P(s,m_R) \varepsilon M_P(s,m_R)$ as soon as (s,m_R) occurs; and analogously the impactee's strategy σ_I is a function on

$$\{(s,m_R,m_P) | s\varepsilon S, m_R \varepsilon M_R(s), m_P \varepsilon M_P(s,m_R)\} \quad ,$$

such that

$$\sigma_I(s,m_R m_P) \varepsilon M_I(s,m_R,m_P) \quad .$$

Given a strategy tuple $(\sigma_R,\sigma_P,\sigma_I)$, a subjective probability $P_j(.|\sigma_R,\sigma_P,\sigma_I)$ over the space of possible plays is determined for each player. Under measurability conditions not specified each player can expect a payoff given by

$$V_j(\sigma_R,\sigma_P,\sigma_I) = \int \underline{U}_j(\pi) dP_j(\pi|\sigma_R,\sigma_P,\sigma_I) \qquad (j = R,P,I) \quad ,$$

where $U_j(\pi)$ denotes the payoff in the case of play π.

Except for a solution concept and except for a mathematical discussion of the assumptions necessary for the well-behavior of the mathematical terms above, the model description is complete.

So far the population affected by pollution has been represented as a rational player with a utility function. This is no self-evident approach. Another possibility would be to represent the population by a *response function* based on its perception of the effects of pollution. But this can be done within the game-theoretic model given above in that the choice sets $M_I(s,m_R,m_P)$ contain one element only. If the impactee's payoff is not of interest one can drop the impactee and only consider the transition probabilities of regulator and producer. However, it is not easy in general to formulate a response function adequately describing the reactions of the population. One result of a three-person game-theoretic model may therefore consist in response functions that are special strategies of the impactee and are considered with some solution of the game.

Juridical procedures can be formalized within this framework at least by representing a court sentence as a transition from one state into another. Research programs on health effects and the impactee's attitude can reduce the range of M_I and make the transition law more exact, reducing, for example, the variance of a distribution relating to the transition.

Extensions

If the game has only finitely many stages and the sets of states and measures of all the players are finite, the game always has an equilibrium point in "pure" (nonstationary) strategies (see, for example, J. Rosenmüller, 1977), i.e. no random choices are necessary. This is due to the property of full information for all players. Nevertheless one may ask whether other orders of succession among the players' choices are appropriate. Firstly, this approach seems a suitable one since the regulator is often regarded as the most powerful player who usually is the first announcing his choices. Citizen groups usually only react to the regulator's or producer's decision. Secondly, an alternative order of succession can be included by introducing dummy choices and enlarging the state space by the players' last choices. Of course, this might yield a cumbersome model.

One arrives at much more complicated games if one considers strategies like "reduction by 20 percent of emission of a pollutant over five years" if there is no major change of economic or technical conditions. Due to a lack of time such a model has not been developed. Due to the stationary property of strategies, however, this model can increase the probability of emission reduction by 20 percent over five years thus reflecting a "mixed" strategy.

Bargaining of the players can be included (J.C. Harsanyi, 1977). Bargaining among the groups that are represented by the three players is not a major point of the game-theoretic model. Instead we rather start from the assumption that the groups have reached agreements. Thus, for example, an analysis like the one of (W. Richter, 1978) of the location of a public utility has not been carried over to detrimental facilities like nuclear plants using cooperative game theory where the players are the affected individuals. In the case of global pollution and local regulators, producers, and citizen groups, however, the local models are the basis for modeling the conflict situation among the groups of regulators.

RANGE OF APPLICATIONS

The following description of cases serves as an introduction into the variety of problems that can be treated within the framework outlined above.

North Sea Oil

Due to oil haulage in the North Sea there is now, even during normal operation, pollution by chronic oil discharges in addition to accidental oil spills.

Components of state: distribution of polluting oil in the North Sea, amount of oil raised in the previous year, amount of fish caught in the last previous year, recreation index of the coast, equipment and organization of the three players.

Choices:

a) Regulator: maximal amount of oil pollution, monitoring systems together with basic juridical measures (taxes), research programs on effects of pollution;

b) Producer: amount of oil to be raised during the next period, treatment, equipment, violation of standard;

c) Impactee: no action, aggression against oil company, changes of political leaders, fishermen drop their jobs, tourists avoid coasts.

Consequences, costs, and benefits: satisfication of standards of other nations, increase of gross national product, better balance-of-payments, decreased water quality, reduction of fishing and tourism.

Sulphur Dioxide

Regional pollution by burning fossil fuel.

Components of state: distribution of sulphur dioxide in the air, number of ills effected by sulphur dioxide, amount of sulphur dioxide produced in the previous year, distribution of population, attractivity factor of landscape, percentage of unemployed, gross national product,...

Choices:

a) Regulator: maximal amount of emitted SO_2 (including juridical basis), (taxes), monitoring, removal of producers, initiate research program on health effects, improvement of medical systems, help for migration of population, ...;

b) Energy producer: installation of filters, reduction of energy production, combustion of other fuels;

c) Impactee: migration, aggression against government or energy producer, civil action, vote to suspend government, reducing his own consumption of energy.

Consequences, costs, and benefits: employment, large gross national product, lung diseases, ultimately death.

Carbon Dioxide

Global pollution manifested as increased amount of carbon dioxide in the atmosphere.

Components of state: amount of atmospheric CO_2, temperature, high temperature catastrophe.

Choices:

a) Regulator: maximal amount of emitted CO_2 (including juridical basis);

b) Producer: amount of production of CO_2;

c) Impactee: aggression against energy producer or government, vote to suspend government, reduce energy consumption.

Consequences, costs, and benefits: employment, large gross national products, catastrophe.

Noise

A lot of industrial activities impose a noise problem on their environment. This description relates to the fast Shinkhansen train in Japan.

Components of state: maximum quantity of noise near the railway line, settlement in the vicinity of the railway line, layout of soundwalls, upper bound for speed of trains.

Choices:

a) Regulator: maximal quantity of speed or noise, order to build sound walls;

b) Producer (of noise): sound walls, reduced speed, dislocation of neighbors;

c) Impactee: complaints, petition to regulator, legal action against railway company.

Consequences, costs, and benefits: increased or decreased gross national product, dislocation of residents, health effects on residents.

EXAMPLES

The North Sea Oil problem as yet has only been treated as a detailed one-stage model by D. v. Winterfeld, (1978, 2). The study contains considerations that are difficult to handle within a genuine multistage model and is not discussed here further. It has turned out that the sulphur dioxide problem can only be treated adequately within a regional model including several pollutors, input-output analysis, and migration problems. Considering the lack of solutions and in the understanding of the basic structures of simpler cases, this problem has been postponed. In the short period of time available only studies on carbon dioxide and noise as dynamic games were carried out that are briefly outlined in this paper. Detailed descriptions can be found in (E. Höpfinger, 1978, 1) and (E. Höpfinger, D. v. Winterfeldt, 1978).

A Multistage Model for the Atmospheric Carbon Dioxide Problem

The effects of increased shares of carbon dioxide in the atmosphere are not well known. The conjectures that exist at present are rather contradictory. This model is based on the assumption that a continuous increase of CO_2 in the atmosphere beyond an unknown critical value, caused by the burning of fossil fuel, will lead to irreversible and large changes in the climate of the earth that are to be regarded as catastrophic. The regulator is assumed to be an international agency, and the group of all emitters of CO_2 as the producer.

The states of the game are

$$\{(C,L)\,|\,C\geq 0, L\geq 0\} \cup \{k\geq 0\}$$

where

C is the amount of carbon dioxide in the atmosphere;
L is the upper bound of emission of CO_2 during the period;
k is the critical value of the atmospheric CO_2-content.
Since the true critical value is unknown one has to consider the set of all possible critical values.

Let (C^1, L^1) denote the first state. The choices of the players in case of state (C,L) are the following:

The regulator chooses $0 \leq l \leq L$, with l denoting the upper bound of carbon dioxide emitted by the producer. The producer chooses $0 \leq a \leq l$, the amount of CO_2 to be emitted. The producer chooses the degree of pressure $0 \leq p \leq 1$ he wants to exert on the regulator. With probability $\bar{p}v$ the bound L is replaced by $\frac{L}{2}$, where $0 < v < 1$ is a fixed number.

For state k the choices of the players are $l = 0$, $a = 0$, $p = 0$.

By assumption the critical value is not known and further information is not available. Hence all three players may have different conjectures denoted by C_I, C_P, and C_R. For simplicity C_P denotes the maximal amount of carbon dioxide in the atmosphere if all fossil fuel is burnt.

Given state (C,L) and the choices (l,a,p) the following states are possible at the next stage:

$$(C+\beta a, L), \quad (C+\beta a, \tfrac{L}{2}), \quad \{k\geq C\},$$

with βa denoting that part of the carbon dioxide emitted remains in the air. β is assumed to be constant. The subjective probabilities P_R, P_P, P_I for the new states are:

New State	P_R	P_P	P_I
$(C+\beta a, L)$	0 if $C \le C_R < C+\beta a$ 1-pv if $C+\beta a \le C_R$	1-pv	0 if $C \le C_I < C+\beta a$ 1-pv if $C+\beta a \le C_I$
$(C+\beta a, \frac{L}{a})$	0 if $C \le C_R < C+\beta a$ pv if $C+\beta a \le C_R$	pv	0 if $C \le C_I < C+\beta a$ pv if $C+\beta a \le C_I$
C_R	1 if $C \le C_R < C+\beta a$		
C_I			1 if $C \le C_I < C+\beta a$

State k cannot be changed.

The transition from state s to state t has the utility

$U_j'(s;l,a,p,;t)$ for player j=R,P,I.

$$U_j'(C,L;l,a,p;C+\beta a,M) = c_1 l + c_2 a + c_3 p \quad (M=L,\tfrac{L}{2})$$
$$U_R'(C,L;l,a,p;k) = c_1 l + c_2 \frac{k-C}{\beta} + c_3 p + c_R$$
$$U_R'(k;o,o,o;k) = 0$$
$$U_P'(C,L;l,a,p;C+\beta a,M) = c_4 a \quad (M=L,\tfrac{L}{2})$$
$$U_P'(C,L;l,a,p;k) = c_4 \frac{k-C}{\beta} + c_P$$
$$U_P'(k;o,o,o;k) = 0$$
$$U_I'(C,L;l,a,p;C+\beta a,M) = c_5 a + c_6 p \quad (M=L,\tfrac{L}{2})$$
$$U_I'(C,L;l,a,p;k) = c_5 \frac{k-C}{\beta} + c_6 p + c_I$$
$$U_I'(k;o,o,o;k) = 0$$

Because of $U_j(s,l,a,p) = \int U_j'(s,l.a.p,t)dP_j(t|s,l,a,p)$ $(j=R,P,I)$, i.e. U_j is the subjective expected utility of the utility of the payoff:

$$U_j(k,o,o,o) = U_j(k,o,o,o,k) = 0 \quad (j = R,P,I) \quad ,$$

since the conditional probability $P_j(k|k,o,o,o)$ the transition from state k to state k occurs is one.

$$U_R(C,L,l,a,p) = \begin{cases} c_1 l+c_2 a+c_3 p, & \text{if } C+\beta a \leq C_R \text{ or } C_R<C; \\ c_1 l+c_2 \frac{C_R-C}{\beta} + c_3 p+c_R, & \text{if } C \leq C_R\ C+\beta a; \end{cases}$$

$$U_P(C,L,l,a,p) = c_4 a;$$

$$U_I(C,L,l,a,p) = \begin{cases} c_5 a+c_6 p, & \text{if } C+\beta a \leq C_I \text{ or } C_I<C; \\ c_5 \frac{C_I-C}{\beta} + c_6 p+c_I, & \text{if } C \leq C_I < C+\beta a \ . \end{cases}$$

The parameters are assumed to have the following signs $c_1 \geq o$, $c_2>o$, $c_3<o$, $c_4>o$, $c_5>o$, $c_6>o$ whereas c_R, c_P, c_I are large negative payoffs. $c_1 \geq O$ reflects the regulator's internal difficulties to set small standards, $c_2>o$, $c_4>o$, $c_5>o$ the benefits of energy production, $c_3<o$ the damage of pressure, and $c_6<o$ the burden of organization. It turns out that these assumptions already determine the shape of the range of the payoffs.

A Multistage Model for Noise Problems

Since the opening of the fast railway line Shinkansen in 1964, complaints about noise and vibration have never ceased. Up to now the Japanese National Railways have been reluctant to take steps towards noise reduction such as building soundwalls, dislocation of neighbors, and slowing down trains. So far the impactee's mearsures have gone through all the possible stages: complaints, petition to the government, organization of citizens for negotiations with Japanese National Railways and the government, and legal proceedings. The regulator consists of various institutions (like the Environmental Agency, for example) with expert committees and subcommittees, local government, and national government. For a better understanding of the basic structure, the institutional aspects are neglected and the regulator is formalized as one player. The impactee is characterized by a response function.

The states of the game are a subset of

$$\{(L,i) \mid \underline{n} \leq I \leq \bar{n},\ i = 1,2,\ldots 7\} \quad ,$$

where L denotes an upper bound for an admitted noise level, $\bar{n}$ the maximum value of noise produced by the train operated only under economic considerations, and $\underline{n}>O$ the minimum value of noise under which the train can be run under economic considerations. (L,1) is the first state after construction of the railway line.

Hence $(L,1) = (\bar{n},1)$. State $(L,2)$ indicates that a petition has been filed. $(L,3)$ states that the population affected by noise has organized itself to negotiate with the government for a low noise standard. If negotiations fail the impactee can start a lawsuit, which is indicated by $(L,4)$. $(L,4)$ can be followed by states of type $(L,5)$, $(L,6)$, or $(L,7)$. $(L,5)$ denotes that a permanent compromise has been achieved with upper bound L for noise: $(L,6)$ that the lawsuit was decided in a neutral or positive way for the Japanese National Railways and the government; and $(L,7)$ that the lawsuit was decided in favor of the impactee. $(L,5)$, $(L,6)$, and $(L,7)$ are final or absorbing states.

For each class of states the component game and the transition probability are given separately.

It is assumed that the costs and benefits of the train have aggregated such that the utility of the regulator is given as a function on the values of noise:

$$u_R : [\underline{n},\bar{n}] \rightarrow \mathbb{R} ,$$

as long as there is no action on part of the population. u_R is assumed to be unimodal, i.e. it is strictly increasing on $[\underline{n},L^+]$ and strictly decreasing on $[L^+,\bar{n}]$ where $L^+ \varepsilon [\underline{n},\bar{n}]$. u_R reflects a compromise among the economic importance of the train and the detrimental effect on the neighboring residents. As long as there is no regulation the (noise-) producer's utility is specified by the strictly increasing function

$$u_P : [\underline{n},\bar{n}] \rightarrow \mathbb{R} ,$$

based completely on economic considerations.

In the case of the first state $(L,1) = (\bar{n},1)$ the sets of choices are specified by

$$M_R(\bar{n},1) = \{l \mid \underline{n} \leq l \leq \bar{n}\} ;$$

$$M_P(\bar{n},1,l) = \{n \mid \underline{n} \leq n \leq l\} ;$$

where l denotes the utmost level of noise allowed to the producer, and n the value of noise generated by railway operation. The impactee's choices are not specified since the impactee is formalized by a response function resulting in special transition probabilities.

Given state $(\bar{n},1)$ only states $(\bar{n},1)$ and $(\bar{n},2)$ can succeed. A critical noise level $n_I \varepsilon [\underline{n},\bar{n}]$ is assumed for the impactee such that noise is regarded as a substantial impact if and only if its value is greater than n_I. The subjective transition probabilities are specified by

$$P((\bar{n},2)\ \bar{n},1,l,n) = \begin{cases} 0 & \text{if } n \leq n_I \ ; \\ p_2 & \text{if } n > n_I \ ; \end{cases}$$

$$P((\bar{n},1)\ \bar{n},1,l,n) = \begin{cases} 1 & \text{if } n \leq n_I \ ; \\ 1-p_2 & \text{if } n > n_I \ . \end{cases}$$

Indices j = R,P for the subjective probabilities are omitted since this model assumes that regulator and producer consult the same experts. $p_2>0$ represents the experts subjective probability that the impactee will prefer a petition. The utilities are given by

$$U_R(\bar{n},1,l,n) = u_R(n) \ ; \qquad (\underline{n} \leq n \leq \bar{n})$$
$$U_P(\bar{n},1,l,n) = u_P(n) \ .$$

Given state $(\bar{n},2)$ the set of measures are

$$M_R(\bar{n},2) = \{l \mid \underline{n} \leq l \leq \bar{n}\} \ ;$$

$$M_P(\bar{n},2,l) = \{n \mid \underline{n} \leq n \leq l\} \ .$$

Then $(\bar{n},2)$ can only be replaced by $(\bar{n},3)$ denoting the formation of an organization. We assume the following subjective transition probabilities:

$$P((\bar{n},3)|\bar{n},2,l,n) = \begin{cases} 0 & \text{if } n \leq n_I \ ; \\ p_3 & \text{if } n > n_I \ ; \end{cases}$$

$$P((\bar{n},2)|\bar{n},2,l,n) = \begin{cases} 1 & \text{if } n \leq n_I \ ; \\ 1-p_3 & \text{if } n > n_I \ ; \end{cases}$$

where $p_3>0$. The idea is that $n \leq n_I$ is conceived as giving in by either the regulator by $l \leq n_I$ or by the producer in the case of $n \leq n_I < l$. The payoffs are specified by

$$U_R(\bar{n},2;l,n) = u_R(n) \ ; \qquad (\underline{n} \leq n \leq l)$$
$$U_P(\bar{n},2;l,n) = u_P(n) \ .$$

If an organization is formed (which is denoted by $\bar{n}$,3) it is the impactee's objective to have the regulator give in.

Let

$$M_R(\bar{n},3) \quad := \{l \mid \underline{n} \leq l \leq \bar{n}\} \quad ;$$

$$M_P(\bar{n},3,l) := \{n \mid \underline{n} \leq n \leq l\} \quad ;$$

then

$$P((\bar{n},4)|\bar{n},3,l,n) = \begin{cases} 0 & \text{if } l \leq n_I \; ; \\ p_4 & \text{if } l > n_I \; ; \end{cases}$$

$$P((\bar{n},3)|\bar{n},3,l,n) = \begin{cases} 1 & \text{if } l \leq n_I \; ; \\ 1-p_4 & \text{if } l > n_I \; ; \end{cases}$$

where $p_4 > 0$ and $(\bar{n},4)$ denotes the start of a lawsuit. Let

$$U_j(\bar{n},3,l,n) := u_j(n) \qquad (j = R,P; \;\; \underline{n} \leq n \leq \bar{n})$$

Three outcomes of a lawsuit are considered. There is a compromise (L,5) suspending the lawsuit, or a sentence in favor of regulator and producer (L,6), or a sentence in favor of the impactee (L,7). Let

$$M_R(\bar{n},4) \quad = \{l \mid \underline{n} \leq l \leq \bar{n}\} \cup \{(l,\Lambda) \mid \underline{n} \leq l \leq \Lambda \leq \bar{n}\} \quad ;$$

$$M_P(\bar{n},4,l) = M_P(\bar{n},4,l,\Lambda) := \{n \mid \underline{n} \leq n \leq l\} \cup \{(n,N) \mid \underline{n} \leq n \;\; \varepsilon\; N < \bar{n},\; n \leq l\} \; .$$

Let

$$M_C := \{(l,\Lambda;m_P) \mid (l,\Lambda) \in M_R(\bar{n},4),\; \Lambda \leq n_I,\; m_P \in M_P)\bar{n},4,l)\}$$
$$\cup \{(m_R;n,N) \mid m_R \in M_R(\bar{n},4),\; (n,N) \in M_P(\bar{n},4,m_R),\; N \leq n_I\}$$

be called the set compromise pairs of choices. Then we assume

$$P((L,5)|\bar{n},4,m_R,m_P,) = \begin{cases} 1 & \text{if } (m_R,m_P) \in M_C \text{ and } L = \min(\Lambda,N), \\ & \text{where } \Lambda := +\infty \text{ or } N := +\infty \text{ unless} \\ & \text{defined previously;} \\ 0 & \text{else;} \end{cases}$$

$$P((L,6)|\bar{n},4,m_R,m_P) = \begin{cases} p_6 & \text{if } L = n_R \text{ and } (m_R,m_P) \notin M_C; \\ 0 & \text{else;} \end{cases}$$

$$P((L,7)|\bar{n},4,m_R,m_P) = \begin{cases} p_7 & \text{if } L = n_I \text{ and } (m_R,m_P) \notin M_C; \\ 0 & \text{else;} \end{cases}$$

where $\underline{n} \leq n_I \leq n_R \leq \bar{n}$ for the maximal noise level n_R fixed by the court is in favor of the producer, $0 \leq p_6+p_7 \leq 1$. Hence

$$P((\bar{n},4)|\bar{n},4,m_R,m_P) = \begin{cases} 0 & \text{if } (m_R,m_P) \in M_C \quad ; \\ 1-p_6-p_7 & \text{if } (m_R,m_P) \notin M_C \quad . \end{cases}$$

The payoffs are specified by

$$\begin{aligned} U_R(\bar{n},4,m_R,n) &= U_R(\bar{n},4,m_R,n,N) = u_R(n) \\ U_P(\bar{n},4,m_R,n) &= U_P(\bar{n},4,m_R,n,N) = u_P(n) \end{aligned} \qquad (\underline{n} \leq n \leq l) \quad .$$

State (L,5) means that either the regulator has agreed to take $L \leq n_I$ as the maximal noise level or that the producer has bound himself to noise levels not higher than $L \leq n_I$.

Let

$$M_R(L,5) := \{l|\underline{n} \leq l \leq L\} \quad ,$$

$$M_P(L,5) := \{n|\underline{n} \leq n \leq l\} \quad ,$$

then

$$P((L,5)|L,5,l,n) = 1.$$

The payoffs are specified by

$$U_j(l,5,l,n) = u_j(n) \qquad (j = R,P;\ \underline{n} \leq n \leq l) \quad .$$

State $(n_R,6)$ indicates a sentence unfavorable to the impactee.

Let

$$M_R(n_R,6) = \{l|\underline{n} \leq l \leq n_R\} \quad ,$$

$$M_P(n_R,6,l) = \{n|\underline{n} \leq n \leq l\} \quad ,$$

Then $P((n_R,6)|n_R,6,l,n) = 1 \quad ,$

$$U_j(n_R,6,l,n) = u_j(n) \qquad (j = R,P) \quad .$$

State $(n_I,7)$ signifies a sentence unfavorable to regulator and producer. Let

$$M_R(n_I,7) = \{l|\underline{n} \leq l \leq n_I\},\ M_P(n_I,7,l) = \{n|\underline{n} \leq n \leq l\} \quad .$$

Then

$$P((n_I,7)|n_I,7;1,n) = 1 \quad .$$

The payoffs are given by

$$U_j(n_I,7,1,n) = u_j(n)+c_j \qquad (j = R,P) \quad .$$

c_j 0 expresses the freedom of decisions lost for other industrial activities involving noise since the sentence must be taken into account for the designing of such activities. In the case of $L^+>n_I$, it is assumed that c_j is a negative multiple $-m_j$ of $u_j(L^+) - u_j(n_I)$, i.e.

$$c_j = -m_j(u_j(L^+) - u_j(n_I)) \quad .$$

Since (L,5), $(n_R,6)$, and $(n_I,7)$ are permanent states the payoffs for plays will only exist for proper discount factors $\rho_R<1$ and $\rho_P<1$. ρ_R and ρ_P need not be equal. Sometimes $\rho_P<\rho_R$ seems to be an adequate assessment.

SOLUTION CONCEPTS

Given the strategy-sets Σ_j (j = R,P,I) of the three players and the vector of utilities (V_R,V_P,V_I) defined on the cartesian product $\Sigma_R x \Sigma_P x \Sigma_I$ of the strategy sets, each player faces the problem of selecting a strategy in order to obtain a high utility. Features that have to be considered in the selection of appropriate strategies are precisely formulated as solution concepts. However, except for two-person zero-sum games, there is no unique solution concept for general n-person games (see R.D. Luce, H. Raiffa, 1957), (J.C. Harsanyi, 1977).

In the following we will introduce several familiar solution concepts and discuss their applicability to the problem of procedures for standard setting which depends on the specific structure of the conflict situation, and the purpose of our analysis.

Definition

A three-tuple $(\sigma_R^+,\sigma_P^+,\sigma_I^+) \in \Sigma_R x \Sigma_P x \Sigma_I$ of strategies is called a *weak equilibrium point* if

$$V_R(\sigma_R^+,\sigma_P^+,\sigma_I^+) \geq V_R(\sigma_R,\sigma_P^+,\sigma_I^+) \qquad (\sigma_R \in \Sigma_R) \quad ;$$

$$V_P(\sigma_R^+,\sigma_P^+,\sigma_I^+) \geq V_P(\sigma_R^+,\sigma_P,\sigma_I^+) \qquad (\sigma_P \in \Sigma_P) \quad ;$$

$$V_I(\sigma_R^+,\sigma_P^+,\sigma_I) \geq V_I(\sigma_R^+,\sigma_P^+,\sigma_I) \qquad (\sigma_I \in \Sigma_I) \quad .$$

The three-tuple $(\sigma_R^+, \sigma_P^+, \sigma_I^+)$ is called a *strong equilibrium* point if the left-hand term of an inequality is always larger than the right-hand term.

Discussion

Equilibrium points are points of stability inasmuch as no player can improve his payoff if all the players persist in their equilibrium strategy. There is no statement as to how to arrive at an equilibrium point. In R.D. Luca, H. Raiffa, (1957, p. 91), it is pointed out that it is advantageous in such a situation to disclose one's strategy first and to have a reputation for inflexibility. A further complication is that several equilibrium points can exist.

It can be proven that the j-th component of the equilibrium payoff vector $(V_R(\sigma_R^+, \sigma_P^+, \sigma_I^+), V_P(\sigma_R^+, \sigma_P^+, \sigma_I^+), V_P(\sigma_R^+, \sigma_P^+, \sigma_I^+))$ is at least as large as the corresponding maximum payoff which is defined as $\max_{\sigma_j} \inf_{\sigma_i (i \varepsilon \{R,P,I\} \setminus \{j\})} V_j(\sigma_R, \sigma_P, \sigma_I)$.

The following solution concept makes sense only if some collusion is possible.

Definition

Let $\mathcal{U} \subseteq \mathbb{R}^3$ denote the range of the utility functions:

$$\mathcal{U} = (x_1, x_2, x_3) \varepsilon \mathbb{R}^3 \quad x_j = V_j(\sigma_R, \sigma_P, \sigma_I)$$

for one $(\sigma_R, \sigma_P, \sigma_I) G \Sigma_R x \Sigma_P x \Sigma_I \}$. The payoff vector $(u_R, u_P, u_I) \varepsilon \mathcal{U}$ is called *Pareto-optimal* if there is no $(v_R, v_P, v_I) \varepsilon \mathcal{U}$ such that

$$u_j \leq v_j \quad (j = R,P,I)$$

and $u_j < v$ for one j at least.

Discussion

Pareto-optimal payoff vectors are the undominated payoff vectors. Usually they exist in abundance. They are important in the case of collusion because then one can expect the players to use strategies yielding Pareto-optimal payoffs.

So far no comparison of utilities has been necessary. This is different for the following concept.

Definition

Let (u_R^+, u_P^+, u_I^+) denote the point of maximal possible payoffs called *bliss point*, i.e.

$$u_j^+ = \max(u_j \mid (u_R, u_P, u_I) \varepsilon \mathfrak{U}) \quad (j = R,P,I) \quad .$$

The payoff vector (u_R, u_P, u_I) is called *bliss-optimal* if

$$\sum_{j = R,P,I} (u_j^+ - u_j)^2 = \min(\Sigma(u_j^+ - v_j)^2 \mid (v_R, v_P, v_I) \varepsilon \mathfrak{U}) \quad .$$

Discussion

The bliss-optimal point depends on the norm. Here we have chosen the euclidean norm, but it is quite obvious that an l^p-norm with $p \neq 2$ may give other results. Furthermore, if the utilities are changed by linear positive transformation, the new bliss-optimal point is only in special cases related to the former by the same utility transformations.

Although R.D. Luce and H. Raiffa (1957) point out that the following concept is independent of positive affine transformations, this is no longer true for more general transformations.

Definition

Let (d_R, d_P, d_I) be a triple of payoffs the players obtain if they cannot reach an unanimous agreement or the choice of a payoff vector $u \varepsilon \mathfrak{U}$. Then the *Nash solution* is the point (u_R^+, u_P^+, u_I^+) at which the term $(U_R - d_R)\ (U_P - d_P)\ (U_I - d_I)$ is maximized subject to the requirement $(u_R, u_P, u_I) \varepsilon \mathfrak{U},\ u_j \geq d_j\ (j = R,P,I)$.

Discussion

d_j are called conflict payoffs. It is obvious that a Nash solution is Pareto-optimal. By definition as a product, the term $\prod_{j=R,P,I} (u_m - d_j)$ gives the same weight to each utility, hence the Nash solution is symmetrically dependent on the utilities. Sometimes d_j is assumed to be the maximum payoff of player j.

So far concepts without special assumptions about the announcement of strategies have been discussed. The following deals with a leadership concept yielding a different solution concept. It is assumed that the regulator has to announce his strategy first and then the producer. Optimal responses on part of the impactee and the producer can be regarded as solutions.

Definition

A *hierarchic solution* is a three-tuple (τ_R, τ_P, τ_I) of a strategy $\tau_R \varepsilon \Sigma_R$, and two maps

$$\tau_P: \Sigma_R \to \Sigma_P \quad ,$$

$$\tau_I: \Sigma_R \times \Sigma_P \to \Sigma_I \quad ,$$

such that

$$U_I(\sigma_r, \sigma_p, \tau_i(\sigma_R, \sigma_p)) = \max_{\sigma_I \varepsilon \Sigma_I} V_I(\sigma_R, \sigma_P, \sigma_I) \quad ;$$

$$V_P(\sigma_R, \tau_P(\sigma_R), \; \tau_I(\sigma_R, \tau_P(\sigma_R)) = \max_{\sigma_P \varepsilon \Sigma_P} V_P(\sigma_R, \sigma_P, \tau_I(\sigma_R, \sigma_P)) \quad ;$$

$$V_R(\tau_R, \tau_P(\tau_R), \tau_I(\tau_R, \tau_P(\tau_R)) = \max_{\sigma_R \varepsilon \Sigma_R} V_R(\sigma_R, \tau_P(\sigma_R), \tau_I(\sigma_R, \tau_P(\sigma_R)) \quad .$$

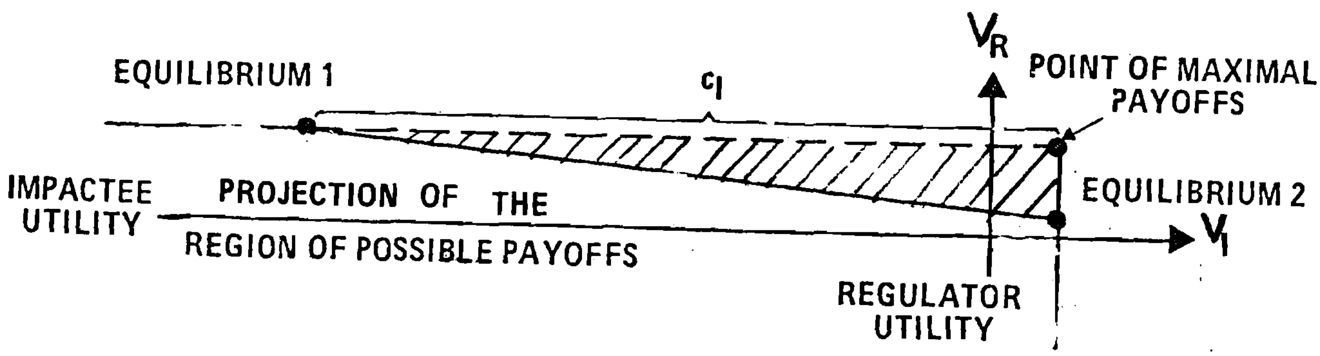
Discussion

The definition of hierarchic solution indicates that such a solution is the solution of a dynamic programming problem over function spaces. Hence, besides the rather restrictive requirements sufficient for the existence of a solution (K. Hinderer, 1970), the calculation of a solution can be carried out only for special models. However, the hierarchic solution is especially convincing if the corresponding payoffs are Pareto-optimal since then collusion cannot increase the payoff of all players. Furthermore, it is an equilibrium point, as can easily be seen. In the case of a one-stage game, the hierarchic solution coincides with the solution concept used in D. v. Winterfeldt, (1978, 1) under the conditions specified there.

CONCLUDING COMMENTS

Whether it is worth it or not to develop a game-theoretic framework in any sense (e.g. normative or descriptive) for the conflict situation among the interest groups involved in a pollution problem, can only be decided on the basis of case studies. Actually, there is only the study on carbon dioxide where all the solution concepts have been applied, and the noise study where due to a lack of time only the hierarchic solution was applied.

If in the case of carbon dioxide the impactee is more cautious than the regulator, a region of possible payoffs is that in the following Figure 2, assuming that the producer acts rationally.



Equilibrium 1: $\left(c_2 \frac{C_R - C}{\beta},\ c_5 \frac{C_R - C}{\beta} + c_I\right)$

Equilibrium 2: $\left(c_2 \frac{C_I - C}{\beta},\ c_5 \frac{C_I - C}{\beta}\right)$

Figure 2. Payoff Diagram
for Regulator and Impactee ($C_R > C_I$)

The Pareto-optimal points Equilibrium 1 and Equilibrium 2 actually stem from equilibrium points. It is obvious that Equilibrium 2 is an approximation of the bliss-optimal point and the Nash solution. The hierarchic solution concept, however, yields Equilibrium 1 as payoff vector. From the formulas given below Figure 2, one can see the parameters that determine the solution. The analysis has yielded strategies of the impactee that can be taken as an assessment of a response function. This oversimplified model already confirms the dominating importance of the parameters C_R and C_I.

The noise study once more demonstrates that the framework is broad enough for a variety of cases. While in some cases extensions might be appropriate, it seems that there exist basic features of the pollution problem, the structuring of which would specialize the framework in greater detail, thus rendering it much more powerful. One such feature is the monitoring aspect or surveillance whether the producer operates within the standard. Since there is an analysis of this problem in D. v. Winterfeldt, 1978, 1, and since both authors have knowledge of the inspection problem (R. Avenhaus, 1977), (R. Avenhaus, E. Höpfinger, 1970), (E. Höpfinger, 1975), this problem has been postponed especially since the approach of M. Maschler, 1966, where the inspector announces his inspection strategy, can apparently be carried over without too many difficulties. One other aspect not fully treated is the way of modification of subjective probabilities if new data are available. For an introduction, we refer to M.H. DeGrout (1970), and T.S. Ferguson (1967).

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