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ENVIRONMENTAL GAMES AND QUEUE MODELS

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Abstract: This paper considers a pollution and control game which uses a queuing framework. This framework allows an accounting of pollution events, environmental pollution quality and the application of controls to maintain a desirable quality of the environment. A number of examples are used to highlight the approach and demonstrates both its theoretical and practical usefulness.

Key words: Environment, Control, Quality, Queuing

Résumé : Cet article présente un jeu d'environnement et de contrôle de qualité de cet environnement par une agence de l'environnement qui utilise des modèles de file d'attente. Cette modélisation permet ainsi de développer une estimation et un calcul adaptés à des évènements aléatoire de pollution. Plusieurs exemples de jeux sont traités élaborant ainsi des éléments essentiels et pratiques dans la gestion des risques de pollution.

Mots-clés : Environnement, Contrôle de Qualité, Files d'attentes

1. Introduction

Conventional wisdom states that for a society to be sustainable it has to maintain the quality of its environment. Environmental quality, however, may mean different things in various circumstances and to several actors, each responding to its specific needs. ISO for example, defines quality as the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs (Tapiero, 1996, Kuhre, 1998). In contrast, environmental quality can have several attributes that have various meanings—potentially contradictory, to several, agreeing or disagreeing groups on the measurements applied to specify quality. There may also be objective—measured based and subjective attributes, expressing both tangible and intangible characteristics of environmental quality. For these reasons as well, environmental quality and its management involves complex issues which are often very difficult to resolve efficiently. Rather, models and analyses based on environmental models can at best provide satisfying solutions. These issues are assuming an accrued importance. For example, Le Monde (October 2, 2003, page 12), in a recent article reports that for the first time French Authorities have taken a sharp view of ships unloading mazout at sea and have established laws extending their control to 200 miles away from the

French coast. The ship Captain guilty of such an act was fined 600,000 Euros compared to symbolic payments in previous times. This polluting event was detected by an Helicopter pilot surveying regularly the sea for such violations. City mayors of adjoining beaches have also taken parts in the courts liberation raising the environmental issues associated to oil spills, their cleaning costs and their effects on the quality of the environment and beaches, an essential source of their livelihood.

The purpose of this paper is to suggest a queue based process for environmental quality assessment and management (Harris and Gross, 1985, Chaudhry and Templeton, 1983). We describe some environmental situations in terms of the elements that make up a queue and thereby use the many theoretical and empirical results available in queuing theory to provide explicit theoretical results applicable to specific environmental problems. A number of examples are treated providing a pedagogical background to using queue related models in ecological and environmental problems. Finally, the problems we consider are also framed in an environmental game framework, providing an approach to environmental policy formulation in a conflict based set up consisting of polluting firms and an environmental agency that seek the control environmental quality.. The modeling approach we present is consistent with the growing concern for environmental issues in Operations Research and Operations Management (for example, see Angel and Klassen, 1999, Bloemhof-Ruwaard et al., 1995 and Revelle, 2000).

2. An Environmental Queue Model and Gaming

The mathematical theory of queues has its origin in the study of telephony systems initiated by Erlang, a mathematician with the phone company in Copenhagen in 1917. Subsequently in the 50's numerous applications have been initiated in many fields spanning information technologies, industrial processes, pharmacology, population studies, biology etc. The mathematical theory of queues is thus an important subfield of discrete events stochastic processes (for example, see Harris and Gross, 1985).

Queue models consist essentially of three components:

(1) An input process expressing an arrival process to the queue. For example, such an input might be a polluting event occurring in a random manner at specific instants called epochs. The pollution process might be a function of a number of variables, due to multiple polluting firms and what not. Further, preventive efforts made by polluting firms might be applied to reduce the probabilities that such events occur. For example, investments in pollution abatement technologies might reduce the rate at which polluting events occur. In contrast, increased economic activity and production can increase the probability of such polluting events.

(2) The service queue process expresses the amount of time that an incoming arrival remains within the queue. For example, given a polluting event, it may take a certain amount of time for the polluting event to dissipate itself. This may be a natural time or the time needed to clean the polluting event once it has been detected. It may de deterministic, stochastic and a function of the efforts applied in cleaning the environment.

(3) The queue attributes and discipline. In a queue model, the discipline describes the behavior of incoming events who are "blocked", that is, joining a queue. In our case, "waiting queues" make little sense since pollution events, once they have occurred they "do not wait". This situation fortunately corresponds to a class of queuing models called infinite servers models where there is no waiting and each incoming event "is serviced".

A simple queue is represented graphically in Figure 1 below.

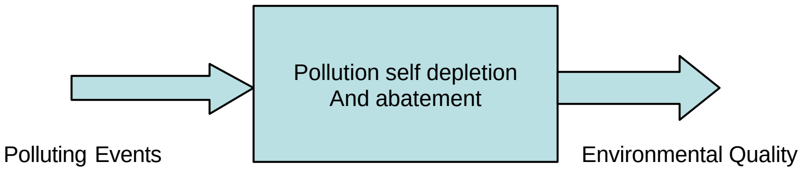

Figure 1: An Environmental Process Queue

Once a queue is defined, mathematical analysis is applied to determine its theoretical properties. These properties might include the number of events in a queue at a given time as well as the probability distribution of such events in steady state. For example, if arrivals are polluting events, and assuming that a polluting abatement technology is applied combined with controls and efforts to clean the environment, the probability distribution of effective polluting events over time and in steady state might provide a measurement of environmental quality. The time in the system of a specific event, the throughput rate at which polluting events are cleaned and their like are additional measurement that can be calculated theoretically.

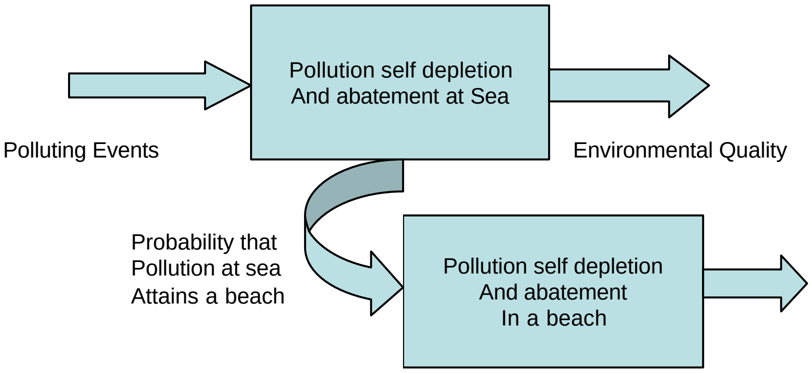

Figure 2: An Environmental Queue Network

A queuing system may consist as well of interacting queues that can be defined by a network of queue. For example, assume that a pollution occurring at sea defines one environmental queue. This pollution however can pollute as well a nearby beach thereby creating a network of two queues where pollution movement from one queue to the other occurs with known (or estimated) probability. Figure 2 above highlight such a network.

Similarly, we can construct series of queues, interacting queues, queues with feedback etc. to represent the dependent complexity of geographical environmental pollution.

In this paper we shall assume explicitly, that polluting events occur in a random manner but they may be cleaned, either naturally or through interventions by the polluting firms themselves or by authorities that regulate and control the polluting firms and thereby control the environment. The interaction of these events combining regulation and clean up of the environment produce a stochastic process of environmental quality (or rather unquality) which we quantify and assess in terms of a number of parameters. Our model, once constructed, provides a framework to investigate a number of factors that determine the effects of economic activity and environmental control on environmental quality. A number of simplifying assumptions are made initially in order to obtain analytical results. Subsequently some of these assumptions are released to render the process more realistic. For complex situations however, simulation can be used based on the queue framework which is deemed to model the environmental problem at hand.

The environmental problem we consider involves as well an environmental agency--"the regulator" and potentially "polluting firms", each with varied motivations and thereby leading to a game played between the agency and the firms (Nash, 1950, Reyniers and Tapiero, 1995a, 1995b, Tapiero, 1995, Tapiero, 2001). For our purposes and for simplification we assume that the firm uses a pollution technology determined by the quantity of products (or employment) it produces as well as by the preventive and pollution abatement technology it applies to its industrial and production processes. The firm motivation will be to maximize average profits once it takes into account both the payoff resulting from its economic activity and the costs associated to pollution (as well as the penalties incurred when the polluting firm is detected and penalized by the environmental agency). Pollution risks, measured by their consequences are, however, a function of the regulators controls. A polluting event which is not detected is costless to the firm but costly to "society" faced with cleaning the environment. A polluting event which is detected induces a cost borne by both the firm and "society". Environmental costs by the firm and the regulator involve penalties as well and can be assumed shared (or not). Thus, firms' policies consist in selecting an appropriate level of industrial activity (employment), investing in preventive measures as well, such as controlling ex-post polluting activities. The environmental agency however will seek to optimize the environmental quality by expending environmental control efforts which are subject to numerous constraints (such as budget, employment requirements and their like). This results in an environmental game which is used to draw some conclusions regarding the process of investment in pollution abatement technologies and the preventive efforts and controls to exercise by polluting firms while at the same time, determining the control effort that environmental regulators ought to apply.

In an environmental game framework, both the firm and the environmental regulator-managers must become aware of the mutual relationships and inter-dependencies of investments in pollution (production) abatement technologies, in the control effort they exercise on the processes under their control and the control regulators might exercise. For example, demanding a zero-pollution technology might lead to excessive costs and thereby to a firm demise, resulting in a loss of jobs, tax income and their like that are needed to a collective and population survival. Over-protection of fish or animals and facing a starving a population at the same time may not be realistic. By the same token, an oil tanker with a propensity to pollute that does not take effective preventive measures ought to be penalized if a polluting event takes place. The same rationale can be applied as well to oil tankers that produce pollution at sea when they believe they may not be caught (see also Reyniers and Tapiero, 1995a, 1995b and Tapiero 1995). The problems that both the firm and the regulator are faced with are then two-fold: (1) Given a polluting technology and a shared penalty cost for polluting event, what are the control effort to exercise by the firm and what control and preventive efforts to exercise by the firm and (2) What are the effects of the technology choice and penalty-cost sharing parameters on the firm and society's payoffs.

3. The Pollution Process and Environmental Quality

For simplicity and expository purposes, we shall assume first that pollution events by a firm (and generally a number of M potentially polluting firms) are known to occur as a Poisson process. This implies that: (1) Polluting events are independent of one another; (2) The probability that any one time a polluting event occurs is known and proportional to the interval of time considered; (3) Polluting events occur one at a time. This assumptions as sufficient to justify our use of the Poisson counting process, determining the probability distribution of the number of polluting events within a given time period.

Explicitly, say that an individual firm, *j*, is engaged in an economic-industrial activity a_j which generates a return denoted by $p(a_j)$. This activity affects the probability that a pollution event occurs in a small time interval however and assumed given by $q_j\left(a_j(1-u_j)\right)dt$ where u_j represents the preventive actions taken by the firm. Note that $0 \le u_j \le 1$ and let the cost of prevention be given by a function $C_{pr,j}\left(a_j u_j\right)$ with $C_{pr,j}\left(a_j\right) = \infty$, $C'_{prj}(\ ) > 0$. Further, we also assume that $q_j' > 0, q_j'' < 0$, with $q_j(0) = 0$ (i.e. a firm that fully environmentally control its economic output, will not pollute at all) and the maximum probability of pollution is evidently $q_j\left(a_j\right)dt$.

Assuming that firms' polluting events are statistically independent, the number of pollution events has also a Poisson distribution as with mean pollution rate given by:

$$(1)\quad l = \sum_{j=1}^{M} q_j\left(a_j(1-u_j)\right)$$

Further, due to the Poisson assumption, given that a polluting event has occurred, the probability that it is due to a specific firm *j* is given by:

$$(2)\quad q_j = \frac{q_j\left(a_j(1-u_j)\right)}{\sum_{j=1}^{M} q_j\left(a_j(1-u_j)\right)}$$

Each polluting event by firm *j* produces a random damage expressed in terms of both time and money. "Time" is measured by the amount of time needed for polluting events to be cleaned naturally. For example, some organic pollution may be self deteriorating and thereby eventually self-dissipated. Alternatively, when a pollution event is detected by a regulator, special actions might be taken to help "Mother Nature" in negating the consequences of such an event. Let the time for a pollution by firm *j* to be cleaned be given by a random variable $\tilde{T}_j$ with *B(.)* its cumulative density functions. This density function is of course a function of the firms and the agency efforts applied in cleaning the environment. We let $\left(v_j, a_j\right)$ be these respective variables.. If we let $b_j(.)$ be the probability distribution of $\tilde{T}_j$ and $b_j^*(.)$ be its generating function, then since polluting firms are independent, the probability distribution that a polluting time event—any event, has a generating function given by:

$$(3)\quad b^*(s) = \prod_{j=1}^{M} b_j^*(s) \text{ with distribution function } b(.)$$

This model is therefore equivalent to an infinite servers queue process with a Poisson "arrival rate" given by equation (1) and "service time" given by the arbitrary distribution function $b(.)$. In other words, the environmental quality process can be considered as an M/G/ ∞ queue with parameters $\left(l, b(.)\right)$ which we can analyze by the standard techniques in queuing theory (for example, see Harris and Gross, 1985). In this model, the number of active polluting events at any one time and the time needed to clean them can therefore be used as a measure of environmental quality. In this framework, environmental quality is determined by the firm economic activity, the firms' preventive and control measures and of course the controls exercised by the environmental agency. In this context, a number of properties can be determined directly. A first proposition provides the probability that a polluting event has not been cleaned by time t. Proof of this proposition is a standard result in queuing theory (Harris and Gross, 1985).

> *Proposition 1:*
> *The probability that a polluting event in* $\left(0, t\right]$, *Q(t), is cleaned before or at time t is given by:*
>
> $$(4)\quad Q(t) = \frac{1}{t}\int_0^t B(z)\,dz,\; B(z) = \int_0^z b(x)\,dx = P\left(t \le z\right)$$
>
> *While 1-Q(t) is the probability that a polluting event has not been cleaned by time t.*

Further, due to the Poisson property, if there are exactly $N(t) > 0$ polluting events in $(0,t]$, the probability that there are exactly $0 \le k \le N(t)$ polluting events still un-cleaned is given by the binomial distribution :

$$(5)\quad P\left(K(t) = k\right) = \binom{N(t)}{k}\left(1 - Q(t)\right)^{k}\left(Q(t)\right)^{N(t)-k}, 0 \le k \le N(t)$$

However, since the number of polluting events is given by the Poisson distribution, we have as well the following result:

Proposition 2:

The probability distribution of the number of still un-cleaned polluting events is:

$$(6)\, P\left(K(t) = k\right) = e^{-l\,\Phi(t)}\,\frac{\left(l\,\Phi(t)\right)^{k}}{k!}, k = 0,1,2,3,...; \Phi(t) = \int_{0}^{t}\left[1 - B(z)\right]dz$$

Where l *is given by equation (1),* $l = \sum_{j=1}^{M} q_j\left(a_j(1 - u_j)\right),$ *and* $0 \le u_j \le 1$. *B(.) is the time to clean up of a polluting event (any event and by any firm) density function with first two moments given by:*

The probability distribution given by proposition 2 is a non-homogenous Poisson process with parameter $l\,\Phi(t)$ which equals as well the mean number of polluting events that have not yet been cleaned, providing again an assessment of environmental quality. At the limit, in steady state, the number of un-cleaned pollution events is therefore given by

$$(7)\quad E(S) = \int_{0}^{\infty}\left[1 - B(z)\right]dz$$

and the number of polluting events is a Poisson distribution given by:

$$(8)\quad P\left(K = k\right) = e^{-l\,E(S)}\,\frac{\left(l\,E(S)\right)^{k}}{k!}, k = 0,1,2,3,...$$

and determined as a function of the economic activity of the firm, environmental controls and preventive measures. An example to this effect will highlight these relationships.

Example:

Say that pollution events occur at the Poisson rate and let the time a pollution event is active be exponential. We set by *P(n,t),* the probability that at time t there are n active pollution events. In this case, it is simple to show that the pollution counting process has a Poisson distribution with mean λ/μ :

$$P_n = \frac{e^{l/m}\left(l/m\right)^{n}}{n!},\ E(n) = \left(l/m\right) = \frac{qa(1-u)}{m}\ n = 0,1,2,\ldots$$

The evolution over time can be calculated as well by noting that:

$$\frac{dE\left(n(t)\right)}{dt} = -mE\left(n(t)\right) + l\,;\; n(0) = n_0$$

Interestingly, the pollution counting process remains the same even if the polluting time of any pollution event has any other distribution. For example, if there are M firms each with its own polluting time $\left(t_j\right)$, then the probability distribution of a polluting event is:

$$\tilde{t} = \begin{cases} \tilde{t}_1 & w.p \quad q_1 \\ . & \\ . & \\ t_M & w.p \quad q_M \end{cases}$$

Or,

$$\tilde{t} = \sum_{j=1}^{M} \tilde{t}_j q_j,\; q_j = \frac{q_j\left(a_j(1-u_j)\right)}{\left[\sum_{j=1}^{M} q_j\left(a_j(1-u_j)\right)\right]}$$

Assuming that firms pollute independently, we have as well:

$$E\left(\tilde{t}\right) = \sum E(\tilde{t}_j)q_j,\; \text{var}\left(\tilde{t}\right) = \sum q_j^2\, \text{var}\left(\tilde{t}_j\right)$$

An approximation might be the Weibull distribution given by (see also Heo, Salas and Kim, 2001, for estimation of this distribution using environmental data)::

$$b(\tilde{t}) = \frac{d}{u}\left(\frac{\tilde{t}}{u}\right)^{d-1} e^{-\left(\frac{\tilde{t}}{u}\right)^{d}},\; B(\tilde{t}) = 1-e^{-\left(\frac{\tilde{t}}{u}\right)^{d}},\; \tilde{t} \ge 0$$

where the mean and the variance are:

$$E(\tilde{t}) = u\Gamma(1+1/d) = \sum E(\tilde{t}_j)q_j,\; \text{var}(\tilde{t}) = u^2\left[\Gamma(1+2/d) - \Gamma^2(1+1/d)\right]$$

and therefore using the first two moments fit, we can calculate the parameters $\left(u, d\right)$ and calculate:

$$E(S) = \int_0^\infty \left[1-B(z)\right]dz = \int_0^\infty e^{-\left(\frac{z}{u}\right)^{d}} dz$$

The pollution counting process is again Poisson with mean $l\,E(S)$ which we can write explicitly by:

$$l\,E(S) = \left[\sum_{j=1}^{M} q_j\left(a_j(1-u_j)\right)\right]\int_0^\infty e^{-\left(\frac{z}{u}\right)^{d}} dz$$

Where the parameters (u, d) are determined the mean and variance of the pollution time calculated above. By the same token,

$$Q(t) = \frac{1}{t}\int_0^t B(z)dz = 1 - \frac{1}{t}\int_0^t e^{-\left(\frac{z}{u}\right)^d} dz, t \geq 0$$

which can be written in term of incomplete gamma integrals. Over time, the mean number of pollution events can thus be written by as an evolution over time given explicitly by:

$$\frac{dE\left(n\left(t\right)\right)}{dt} = -\frac{1}{E(S)}E\left(n\left(t\right)\right) + \left[\sum_{j=1}^{M} q_j\left(a_j(1-u_j)\right)\right];\ n\left(0\right) = n_0$$

This equation can oc course be calculated numerically.

4. The Firm and Environmental Agency Management Policies

We consider next the management problems of both a controlling environmental agency and the firms. For simplicity however we consider only a representative individual firm and its environmental game with the environmental agency. Further, we shall also define long run average objectives calculated by average cycle costs justified by application of a renewal theorem. Explicitly, we shall defined a cycle time as the time between two detection events when the environmental agency detects a polluting event by the firm, in which case the polluting firm will be penalized. In this case, the firm long run average profit is given by:

$$\text{Average Profits} = \frac{\text{E(Profits Less Costs)}}{\text{E(Cycle Time)}}$$

The Cycle Time

Assume that en environmental agency applies a control effort which consists in effecting a control with probability q while the probability that the firm generates a polluting even at this time is $l = qa(1-u)$. As a result, the probability that a polluting event is detected is defined in the following proposition. This proposition specifies as well the number of undetected polluting events within a cycle which is mostly borne by society in a poorer environmental quality..

Proposition 3:

Let a detection (renewal) cycle be defined by the inter-event of two controls applied and detecting pollution events. Let environmental controls be applied by the environmental agency with a probability q *and let* $l = qa(1-u)$ *be the firm pollution rate. Then, the joint probability distribution that such a cycle is of length K with i undetected polluting events within such a cycle is given by:*

$$(9)\quad F(i,K) = \binom{K-1}{i-1} l\,q\left[(1-q)\,l\,\right]^{i-1}\left[1-l\,\right]^{K-1};\ i = 1,2,\ldots,K-1; K = 1,2,\ldots$$

The marginal distributions are given by:

$$(10)\quad g(K) = lq\left[(1-l\,)\left(1+(1-q\,)\,l\,\right)\right]^{K-1}$$

$$(11)\quad h(i)=ql\left((1-q)l\right)^{i-1}\sum_{j=0}^{\infty}\binom{j+i-1}{i-1}(1-l)^{j}$$

With means

$$(12)\qquad E(K)=\frac{q\left[(1-l)\left(1+(1-q)l\right)\right]}{l\left(1-(1-q)(1-l)\right)^{2}}$$

$$(13)\qquad E(i)=\frac{1-q}{q}+1-l(1-q)$$

As a result, the probability of detecting a polluting event is:

$$(14)\qquad a=\frac{1}{E(K)}=\frac{l}{(1-l)}\frac{\left[q+(1-q)l\right]^{2}}{q\left[1+(1-q)l\right]}$$

While the firm propensity to pollute has a cumulative density function given by:

$$(15)\qquad P\left(\frac{i}{K}\le x\right)=\sum_{K=\left[\frac{1}{x}\right]}^{\infty}(lq)(1-l)^{K-1}\sum_{i=1}^{[xK]}\binom{K-1}{i-1}z^{i-1};\quad z=\frac{l(1-q)}{1-l}$$

Proof: See Appendix

Proposition 3 has a number of implications that are worth mentioning. First, the average number polluting events that are not detected is defined by the renewal theorem by:

$$(16)\qquad \bar{i}=\frac{E(i)}{E(K)}=\frac{l\left(1-(1-q)(1-l)\right)^{2}\left\{\left[1-l(1-q)\right]+\frac{1-q}{q}\right\}}{q\left[(1-l)\left(1+(1-q)l\right)\right]}$$

where E(K) is the cycle time (see also Figure 3) below.

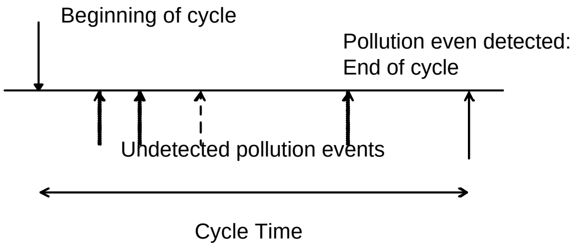

Figure 3: Detection Cycle

Thus, if the expected cost of an undetected polluting event equals C_i, the average cost of non-detected pollution events is $\bar{i}C_i$. If there are M firms, the total average cleaning cost is equal $\sum_{j=1}^{M}\bar{i}_j C_{i,j}$. At the same time, the expected amount of time that pollution events are active is given by:

$$(17)\quad \bar{i}_{Time}=\frac{E(i)\Lambda(K)}{E(K)}$$

which can be used as a measure of environmental quality. These elements can be used next to calculate both the firm and the agency's long run average objectives.

The Firm Long Run Average Profit

Within a cycle the firm profot is assumed given by:

(18) $C_F = \left[Kp\left(a\right) - KC_{pr}\left(au\right)\right](1-k) - C_3 - C_1 iv$

where $p\left(a\right)$ is the firm period profit due its economic activity $a \geq 0$, $C_{pr}\left(au\right)$ defines a period prevention cost of environmental pollution. When $u = 1,\ C\left(a\right) = \infty$ while $u = 0,\ C_{pr}\left(0\right) = 0$. As a result, the firm prevention cost is denoted by $0 \leq u < 1$. The firm tax rate is assumed given by k while the penalty cost sustained by the firm if it is detected in a polluting act is C_3. Finally, if a polluting event occurs and is undetected, the firm may choose to attend to it. In this case, the cleaning cost over the cycle is $C_1 iv,\ 0 \leq 0 \leq K$ while v is the probability that it does so. For simplicity, we shall assume that $v = 0$ however and the undetected pollution events are borne only by society.

As a result, the firm long run average profit is given by:

(19) $\underset{a,u}{Max}\ A_F = \dfrac{E\left(C_F\right)}{E\left(K\right)} = \left[p\left(a\right) - C_{pr}\left(au\right)\right](1-k) - \dfrac{C_3}{E(K)}$

With:

(20) $E(K) = \dfrac{q(1-l)\left(1+(1-q)\,l\right)}{l\left(1-(1-q)(1-l)\right)^2},\ E(i) = \dfrac{1-q}{q} + 1 - l(1-q)$

and $\partial p(a)/\partial a > 0, \partial^2 p(a)/\partial a^2 \leq 0,\ \partial C_{pr}\left(x\right)/\partial x > 0,\ \partial^2 C_{pr}(x)/\partial x^2 > 0$ and of course the pollution rate $l = qa(1-u)$. In this expression, note that the firm is oblivious to undetected polluting events. Further, the firm policy variables are determined by its economic activity and its investment in pollution preventive efforts only. These policy variables will be necessarily a function of the agency's propensity to implement environmental controls however. An analysis of the firm objective leads to the following proposition:

Proposition 4.

1. For a given environmental control policy, and assuming interior solutions, the firm's marginal revenue equals the marginal cost of environmental prevention,

(21) $\dfrac{\partial p\left(a\right)}{\partial a} = \dfrac{\partial C_{pr}\left(x\right)}{\partial x};\ x = au$

2. Let $a = 1/E(K)$ be the probability of detecting a polluting event and consider the marginal effect of a change in pollution rate occurrences and

the probability of detection. This marginal effect is then proportional to the cost of prevention and given by:

(22) $$\frac{\partial a}{\partial l}=\frac{(1-k)}{qC_3}C_{pr}(x)$$

Proof:

Optimization of the average cost with respect to a yields,

(23) $$\left[\frac{\partial p(a)}{\partial a}-u\frac{\partial C_{pr}(x)}{\partial x}\right](1-k)-C_3\frac{\partial a}{\partial a}=0 \text{ where } \frac{\partial a}{\partial a}=\frac{\partial a}{\partial l}q(1-u)$$

Similarly, optimization with respect to u, the preventive effort of the firm yields result 2. of the proposition:

(24) $$\frac{\partial A_f}{\partial u}=0 \text{, leading to: } qC_3\frac{\partial a}{\partial l}=\frac{\partial C_{pr}(x)}{\partial x}(1-k)$$

Combining these two equations we obtain the first result of the proposition.

Q.E.D.

The implications of these results are revealing. The larger the pollution arrival rate the larger the probability of detection. The larger this term, the larger u--the pollution prevention effort. Similarly, the larger the penalty cost and the larger the tax rate the greater the effort u. In addition, if the firm is oblivious to environmental cost, then $C_{pr}(0)=0$ and therefore, $\frac{\partial p(a)}{\partial a}=0$. As a result, investing in pollution abatement is likely to reduce the level of economic activity of the firm. The reduction in this economic activity is a function of the marginal profits and marginal costs of prevention. Using implicit differentiation, we have:

(25) $$\frac{da}{du}=-\frac{\partial\Phi(a,u)/\partial u}{\partial\Phi(a,u)/\partial a}=\frac{a\partial^2 C_{pr}(x)/\partial x^2}{\dfrac{\partial^2 p(a)}{\partial a^2}-u\dfrac{\partial^2 C_{pr}(x)}{\partial x^2}}<0$$

Note $\frac{\partial^2 p(a)}{\partial a^2}\le 0, \frac{da}{du}<0$ .However, if $\frac{\partial^2 p(a)}{\partial a^2}>0, \frac{da}{du}<0$ if $\frac{\partial^2 p(a)}{\partial a^2}\le u\frac{\partial^2 C_{pr}(x)}{\partial x^2}$. If this is not the case, then we have $\frac{da}{du}>0$ implying that pollution preventive efforts can increase the level of economic activity.

The Environmental Agency Problem

The environmental agency long run average objective will be assumed given by an environmental quality objective while at the same time recognizing the constraints (budgets and otherwise) it is subjected to. As a result, we shall assume for simplicity that the agency's policy problem consists in selecting a control strategy which minimizes the long run average environmental non-quality subject to a set of constraints stated below:

Environmental Non-Quality: the expected average amount of time that pollution events are active within an inspection cycle

$$(26)\quad \operatorname*{Min}_{0\le q\le 1} \bar{i}_{Time} = \frac{E(i)E\left(\Lambda(K)\right)}{E(K)},\; E\left(\Lambda(K)\right) = qa(1-u)E\left(\int_0^K [1-B(z)]dz\right)$$

Subject to the Constraint Cost:

$$(27)\quad qC_q \le B_A + aC_3,\; a \ge a_{\min}$$

and

$$(28)\quad \frac{1}{a} = E(K) = \frac{q(1-l)\left(1+(1-q)l\right)}{l\left(1-(1-q)(1-l)\right)^2},\; E(i) = \frac{1-q}{q} + 1 - l(1-q)$$

Note here that the penalty to the firm C_3 is a revenue to the agency which is added to its budget B_A while qC_q is the average environmental control costs borne by the agency. Further, note that undetected polluting events are not attended to either by the firm or the environmental agency (although our analysis can be easily extended to deal with such an issue). In addition, while the environmental agency expends funds to control potentially polluting firms and clean when necessary the environment, it also collects money from the government allotted budgets and penalties collected from firms. At the same time however, it has contradictory objectives, seeking a greater economic activity (given by a constraint for least economic activity $a_{\min}$), augmenting the tax base to finance governments' budgets and at the same time it seeks to augment the quality of the environment. These results in environmental games the firm and the agency are involved in. Assuming interior solutions only, the solution of the agency's problem simultaneously with the firm optimization conditions provides a pure Nash equilibrium. However, assuming that the agency is a leader in a Stackleberg game (Stackleberg, 1934) with the firm, the optimal solution of such a game is an optimization problem which is defined by the following:

$$(29)\quad \operatorname{Min} \bar{i}_{Time} = \frac{E(i)E\left(\Lambda(K)\right)}{E(K)},\; E\left(\Lambda(K)\right) = qa(1-u)E\left(\int_0^K [1-B(z)]dz\right)$$

Subject to the Constraints

$$(30)\, qC_q \le B_A + aC_3;\; a \ge a_{\min};\; \text{and}\; \frac{\partial p(a)}{\partial a} = \frac{\partial C_{pr}(x)}{\partial x};\; \frac{\partial a}{\partial l} = \frac{(1-k)}{qC_3} C_{pr}(x),\; x = au$$

This is of course a nonlinear optimization problem which can be dealt with by the usual Kuhn-Tucker conditions. Finally, a generalization to the environmental control of M firms is straightforward and is left here for further study and application.

5. Extensions and Discussion

This introduction to queue models of environmental games and environmental quality control have provided an approach which can be used extensively in both the modeling such of such problems as well as in providing a statistical based approach for predicting and estimating environmental pollution effects. The combination of such models, testing their validity, parameters estimation and optimization (or simulation) can then be used as an environmental management tool. This paper has considered explicitly simple models and examples to demonstrate the possibility of obtaining results. Extensions and generalizations are of course possible, some of which are straightforward. For example, pollution events—once they occurred can have different magnitudes. In this case, Bulk queues with infinite servers might be used in predicting and estimating the effects of pollution events. In other cases, arrivals might not occur at discrete epochs but occur continuously in time. This might be the case of lakes pollutions. In such cases, diffusion approximation to infinite server queues might be used in modeling continuous pollution processes. Dependent pollution events as stated in the introduction of this paper can also be construed as networks of queues, representing the causal (albeit probabilistic) relationship between pollution events. A similar approach might be used to model pollution and development of interacting species. In this context, a broad number of feedback phenomena, multiple pollution sources etc. might be used.

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Appendix: Proof of Proposition 3

The proof we shall follows has the distinct advantage of being both general and adaptable to other approaches and control-detection cycles. The joint distribution *F(i,K)* satisfies a system of recursive equations together with a stopping boundary when the cycle is ended and a pollution event is detected.. Namely, we have:

$$
\begin{aligned}
&F(0,j)=(1-l)F(0,j-1),\ j=0,1,2,3,...K-1\\
\text{(A1)}\quad &F(i,j)=(1-l)F(i,j-1)+l(1-q)F(i-1,j-1),\ i=1,2,..j;\ j=0,1,2,3,...K-1\\
&F(i,K)=lqF(i-1,K-1)
\end{aligned}
$$

A solution by induction yields the solution stated in the proposition. The first expression calculates the probability that in j periods no pollution occurs leading to $(1-l)^j$. The second equation calculates the probability that i polluting events when j periods have passed prior to the detection of a polluting event. Finally, the third equation is a stopping condition since both a polluting event occurred and it is detected. Using the joint distribution we also find the following marginal distributions:

$$
\begin{aligned}
&g(K)=\sum_{i=1}^{K-1}F(i,k)=\sum_{i=1}^{K-1}\binom{K-1}{i-1}lq\left[(1-q)l\right]^{i-1}[1-l]^{K-1}=\\
\text{(A2)}\qquad &=lq[1-l]^{K-1}\sum_{j=0}^{K-1}\binom{K-1}{j}\left[(1-q)l\right]^{j}=lq[1-l]^{K-1}\left[(1-q)l+1\right]^{K-1}=\\
&=lq\left[(1-l)(1+(1-q)l)\right]^{K-1}=lqn^{K-1}
\end{aligned}
$$

where $n=\left[(1-l)(1+(1-q)l)\right]$ which conforms the proposition result. The mean is in this case given by:

$$
\text{(A3)}\quad E(K)=lq\sum_{K=1}^{\infty}Kn^{K-1}=lqn\frac{d}{dn}\sum_{j=1}^{\infty}n^{j}=lqn\frac{d}{dn}\left[\frac{1}{1-n}\right]=\frac{lqn}{(1-n)^{2}}
$$

And therefore,

$$
\text{(A4)}\quad E(K)=\frac{q\left[(1-l)(1+(1-q)l)\right]}{l\left(1-(1-q)(1-l)\right)^{2}}
$$

As a result, the probability of detection is:

$$
\text{(A5)}\quad a=\frac{1}{E(K)}=\frac{l}{(1-l)}\frac{\left[q+(1-q)l\right]^{2}}{q\left[1+(1-q)l\right]}
$$

It is obvious that we have a renewal cycle since each cycle where the pollution event is detected for the first time are independent.

By the same token, the marginal distribution *h(i)* is:

$$h(i)=\sum_{K=1}^{\infty}F(i,k)=\sum_{K=1}^{\infty}\binom{K-1}{i-1}ql\left((1-q)l\right)^{i-1}(1-l)^{K-i}= \tag{A6}$$
$$=ql\left((1-q)l\right)^{i-1}\sum_{j=0}^{\infty}\binom{j+i-1}{i-1}(1-l)^{j}$$

Of course, the means and other moments can be computed using these distributions. For example, the expected value of i for a given K, the number of defectives equals one plus a random variable given by the binomial distribution with parameters $\left(K,J\right)$ where J has a mixture distribution with parameter $1-q$ and therefore its mean is $l(1-q)E(K-1)$. Thus,

$$E(i)=1+l(1-q)\left(1/lq-1\right)=\left[1-l(1-q)\right]+\frac{1-q}{q} \tag{A7}$$

If $q=0$ and the agency performs no environmental controls, then the number of polluting events is infinite while for full control, $q=1$, we have $E(i)=1$ as expected.

Q.E.D.

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