Catastrophic Risk Management and Economic Growth

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1. Introduction

The increasing vulnerability of the modern society is an alarming human-induced tendency. Losses from human-made and natural catastrophes are rapidly increasing. Within the last three decades the direct catastrophe damages only from natural disasters have increased nine-fold [5]. Catastrophes destroy communication systems, electricity supply and irrigation. They affect consumption, savings and investments. The direct economic costs are split approximately equally between developed and developing countries, but low-income countries are especially sensitive [4]. The main reason for the increasing catastrophe losses is the ignorance of risks leading to the clustering of people and capital in the risk prone areas as well as the creation of new risk prone areas. It is estimated [13] that within the next 50 years more than a third of the world population will live in seismically and volcanically active zones. By translating the historical data into current settings it was shown (Figure1) that insignificant hurricanes in the past may have devastating effects today.

This alarming human-induced tendency calls for new risk-based approaches to economic developments. The economy is a complex system, constantly facing shocks and changes, in particular with catastrophic consequences. Unfortunately, in traditional economic theory there is no special problem of catastrophic risks [3]. The modeling of the economic behavior under uncertainty is often based, in fact, on rather strong assumptions of certainty. It is assumed that all economic agents know all possible shocks (states of the world), i.e., they know when, how often, and what may happen to each of them. Therefore, they can easily organize "markets", where everyone insures everyone by pooling resources available in any state of the entire society, i.e., a catastrophe becomes small on a world-wide scale. In reality this pool does not exist, which calls for more realistic models with explicit representation of uncertainties and risks associated with decisions under uncertainties. The advanced computational approaches allow us today to deal with large-scale decision-making problems in the presence of multidimensional mutually dependent random variables.

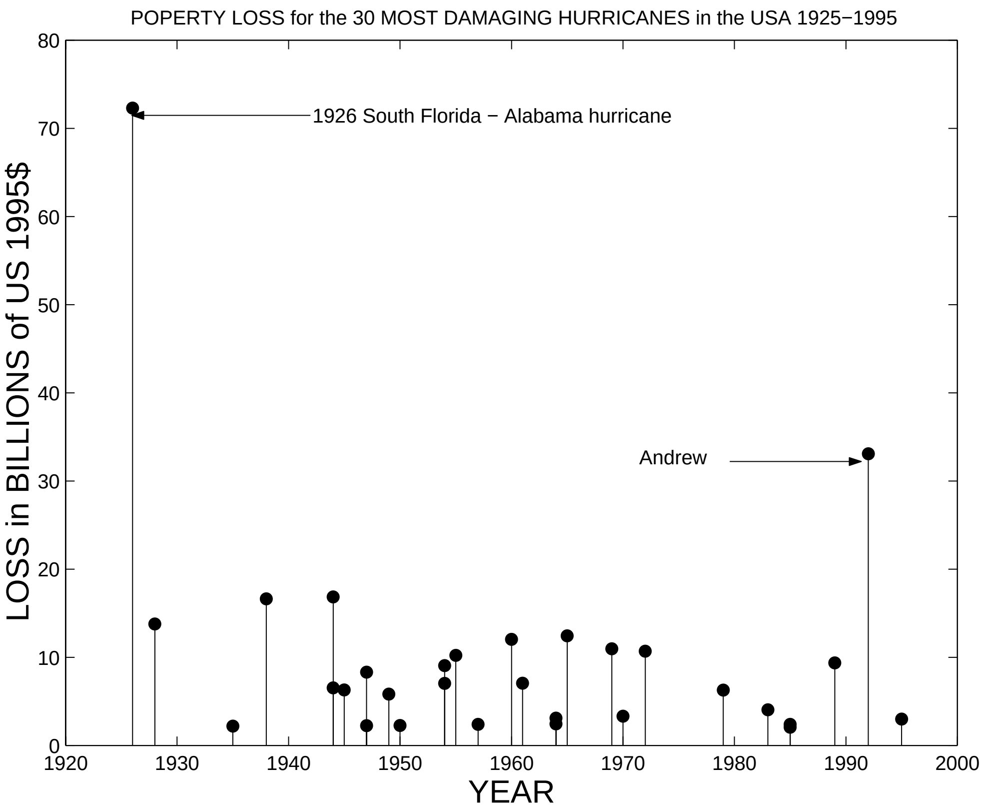

Figure 1. Losses resulting from the 30 costliest hurricanes as measured in property losses for storms reaching the US coast during the period 1925–1995. The losses are normalized to 1995 US dollars taking into account inflation, wealth, and population (Pielka and Landsea, 1998). Inflation is accounted for using the implicit price deflator published in the Economic Reports of the President. Wealth or total property value is measured using an economic statistic kept by the US Bureau of Economic Analysis called “Fixed Reproducible Tangible Wealth,” and includes goods, equipment and structures owned by private individuals, business, and governments. Population is dealt with by using US Census data for 168 coastal counties from Texas to Maine. Using the Pielka-Landsea normalization, the greatest loss (US$ 72.3 billion) was associated with the southeastern Florida-Alabama hurricane of 1926. The second costliest hurricane was Andrew (US$ 33.1 billion) in 1992, while the 30th costliest (US$ 2.06 billion) was Elena, which struck Mississippi, Alabama and northwestern Florida in 1985.

This paper analyzes some methodological challenges involved in catastrophic risk management. In a sense, it summarizes and extends the discussions of papers [1-2], [6-8]. Section 2 outlines the main features of catastrophic risk management: endogenous risks, highly mutually dependent losses, the lack of information, the need for long-tem perspectives and geographically explicit models, the involvement of various agents such as individuals, governments, insurers and investors. Section 3 discusses the main features of GIS-based catastrophe modeling and the need for an integrated risk management based on the contributions of individual risks. Sections 4, 5 sketch out an appropriate decision-making model, which is a multiagent (multicriteria), spatial and dynamic stochastic optimization model. This model emphasizes the cooperation of various agents in dealing with catastrophes, direct and indirect (negative and positive) effects, and the coexistence of anticipative long-term ex-ante policies with adaptive short-term ex-post policies. Sections 6 and 7 discusses in more detail the long-term economic effects of shocks. It points out that shocks which persist in time implicitly modify even sustained exponential economic growth towards stagnation. A proper injection of capital may be necessary only at certain stages of the growth. Section 8 concludes.

2. The Role of Models

There is a number of methodological challenges involved in catastrophic risks management.

2.1. Complex interdependencies. Catastrophes produce severe consequences, characterized by mutually dependent in space and time losses. The multivariate distribution of these losses is in general analytically intractable. It depends on the clustering of values in the region and the patterns of catastrophes. Besides, it may dramatically depend on policy variables. For example, a dam fundamentally modifies the flood conditions downstream and along the site. This creates favorite conditions for insurance and new land-use transformations. On the other hand, a failure of the dam may lead to rare but more devastating losses in the protected area. Such interdependencies of decisions and risks restrict the straightforward "one-by-one" evaluations of feasible options. The so-called "if-then" analysis runs quickly into an extremely high number of alternatives. Thus, with only 10 feasible decisions, say 10%, 20%, …, 100% of the insurance coverage for a particular site, and 10 possible heights of the dam, the number of possible "if-then" combinations is 10^{10}. At one second per evaluation, more than 90 years are required to carry out the computations. The main idea in dealing with this problem is to avoid exact evaluations of all possible alternatives and concentrate attention on the most promising directions. From a formal point of view this is equivalent to the design of special search techniques (in the space of decision variables), making use of random simulations of catastrophes. This is a task of stochastic optimization [10]. Certain of these search procedures can also be viewed as adaptive scenario analysis, or adaptive Monte Carlo optimization. They generate feedback to policy variables after each simulation and automatically drive them towards desirable combinations without going into exhausting "it-then" analyses.

2.2. Rare events. The principal problem with the management of rare catastrophic risks is the lack of historical data on losses at any particular location, although rich data may exist on an aggregate regional level. Historical data are relevant to old policies and may have very limited value for new policies. Models have to play a key role for generating data and designing new policies.

Catastrophes may be of quite different nature from episode to episode, exhibiting a wide spectrum of impacts on public health, the environment and the economy. Each of these episodes seems to be improbable and may be simply ignored in the so-called "practical approaches" or "scenario thinking". This may lead to rather frequent "improbable" catastrophes: although each of N scenarios (episodes) has a negligible probability p, the probability of one of them increases exponentially in N as $1-(1-p)^N = 1-\exp\{N\ln(1-p)\}$. In other words, the integrated analysis of all possible, although rare, scenarios is essential.

2.3. Long-term perspectives. The proper assessment and management of rare risks requires also long-term perspectives. The occurrence of a catastrophe within a small interval Δt is often evaluated by a negligible probability $\lambda\Delta t$, but the probability of a catastrophe in an interval $[0,T]$ increases as $1-(1-\lambda\Delta t)^{T/\Delta t} \approx 1-e^{-\lambda T}$. Purely adaptive "learning-by-doing" or "learning-by-catastrophe" approaches may be extremely expensive. The year-by-year adjustments of economic developments with the so-called anualization of catastrophes may be very misleading. In this case a 50-years catastrophe of an airplane is reduced, in fact, to the sum of annual crashes of its parts, say, wheals in the first year, a wing in the second, and so on.

2.4. Spatial aspects. Catastrophes have different spatial patterns and quite differently affect locations. The location of properties or structures with regard to the center of an earthquake is an extremely important piece of information. Together with the regional geology and the soil conditions the location influences the degree of shaking, and, hence, damage incurred at the location. The deforestation at a particular location modifies the flood conditions only downstream and affects the insurance claims only from specific locations. In other words, management of complex interdependencies among catastrophic risks, losses and decisions is possible only within a geographically explicit framework.

2.5. Assessment vs. robust solutions. Uncertainty is associated with every facet of catastrophe risk assessment. The exact evaluation of all complex interdependencies is impossible and thus risk assessment will yield poor estimates. In this situation the most important task seems to be the design of robust management strategies. Although the assessment is not exact, the preference structure among different decisions may be rather stable to errors. This is similar to the situation with two parcels: to find out their weights is a much more difficult task than to determine the heavier parcel. This simple observation, in fact, is the basic idea of the stochastic optimization approaches proposed in [1-2], [6-8]: the evaluation of the optimal decisions is achieved without exact evaluation of all possible alternatives.

2.6. Multiagent aspects. The high consequences of catastrophes call for the cooperation of various agents such as governments, insurers, investors, and individuals. This often leads to multi-objective stochastic optimization problems and game-theoretical models with stochastic uncertainties.

For all these reasons models become essential for catastrophic risks management. The occurrence of various episodes (scenarios) and dependent losses in the region can be simulated on a computer in the same way as the episode may happen in reality [14]. The stochastic optimization techniques can utilize these information for designing robust management strategies.

3. Catastrophe Modeling and Integrated Management

The lack of historical data on catastrophic losses and the absence of analytical forms of the joint distribution create a rapidly increasing demand for catastrophe modeling [14]. GIS-based computer catastrophe modeling attempts to simulate samples (scenarios) of mutually dependent catastrophe losses on the levels of a household, a city, and a region from various natural hazards, e.g., floods, droughts, earthquakes, hurricanes. These models are used as a tool for planning, emergency systems, lifeline analyses, and estimation of losses. All models have the same structure and are comprised, roughly speaking, of three modules. Thus, in the case of earthquakes, the catastrophe model includes the seismic hazard module, the vulnerability module, and the financial module. The seismic hazard module simulates actual earthquake shaking. It uses or simulates locations and magnitudes of earthquakes. This module often comprises other physical phenomena associated with an earthquake including subsequent fires, landslides. The movement of the seismic waves through the soil is modeled by attenuation equations. Seismic effects at a site depend on earthquake magnitude, distance from the source, and site characteristics, such as regional geology and soil types. The vulnerability module relates seismic shaking to structural and property damage. It determines the extent of damages to buildings and content at a site. The financial module assigns a cost to these damages and calculates the maximum potential and/or expected losses for either individual sites or regions. It calculate losses to structural damage, damage to property and content, and often business interruption. This includes data on building locations, building type and building contents. The estimates are presented either in percentage of the total value or as a monetary value.

Thus histograms of aggregate losses for a single location, a particular catastrophe zone, a country or worldwide can be derived from catastrophe modeling. But catastrophe modeling has only marginal benefits [14] when it is used in a traditional manner for obtaining estimates of aggregate losses. First of all, it is a decision-making tool, but the decision variables are not explicitly incorporated in the existing catastrophe models. The explicit introduction of decisions opens up a possibility for integrated catastrophic risks management based on the contribution of individual risks to aggregate losses. Following [14], we can admit that the currently existing form of catastrophe modeling can only be a necessary subset of more extensive models used to optimize portfolios of catastrophic risks in an integrated manner.

4. The Stochastic Optimization Model

Stochastic optimization provides a framework for incorporating decisions into the catastrophe models. These decisions can control the contribution of individual risks to the catastrophe losses. The approach adopted in [1-2], [6-8] is based on subdividing the study region into cells (locations) $j = 1,2,...,m$. These cells may correspond to a collection of households at a certain site, a zone with a similar land use structure, an administrative district or a segment of a gas pipe-line. The choice of cells provides a desirable representation of different components of losses. A catastrophe is simulated by a catastrophe model. It affects at random different cells and produces mutually dependent losses L_j^t, which can be modified by various decision variables. Some of the decisions reduce losses, say a dyke, whereas others spread them among cells, e.g., insurance contracts, catastrophe securities, credits and aid. If $x = (x_1, x_2, ..., x_n)$ is the vector of decision variables, then losses L_j^t are transformed into $L_j^t(x)$. Thus, if x_1, x_2 correspond to the insurance decisions at cell j, then $L_j^t(x)$ have the form

$$L_j^t(x) = L_j^t - \min\{x_1, \max[x_2, L_j^t]\} + \pi_j^t(x_1, x_2).$$

Here losses $\min\{x_1, \max[x_2, L_j^t]\}$ are retained by the insurance, and $\pi_j^t(x_1, x_2)$ is a premium function.

In general cases vector x comprises decision variables of different "agents", since the management of catastrophic risks requires the cooperation of various agents. For more discussion on these issues see [2]. In particular, the partial compensation of catastrophe losses by the government enforces the individual decisions on loss reductions and, hence, increases the insurability of risks. The compensation by the government may also help the insurance to avoid insolvency. At the same time, the operation of the insurance combined with individual and governmental risk reduction measures can reduce loans and debts of the government and stabilize the economy. In a rather general form the economic growth of each cell is modeled by the following equation (see, for example, [8]). If y_j^0 is the initial wealth of the cell j, then its wealth at time $t+1$ is

$$y_j^{t+1} = y_j^t + I_j^t(x) - O_j^t - L_j^t(x),\ t = 0,1,\ldots,$$

where $I_j^t(x)$ represents the income induced by decisions x, say, benefits from the new land-use transformations in the cells protected by the dyke of certain height and O_j^t stands for outcomes such as costs, debts, taxes, etc. Thus vector x affects losses and the growth path of wealth y_j^t. The main reason for increasing the vulnerability as discussed in Section 1, is that losses $L_j^t(x)$ are generated not only by the occurrence of the earthquakes, floods, and droughts, but also by inappropriate concentration of wealth y_j^t among the locations. If I_j^t includes returns from investments of different cells, then the growth of y_j^t can be endogenized with respect to catastrophic risks by introducing appropriate decisions.

5. The Coexistence of Ex-ante and Ex-post Decisions

The model outlined in Section 4 includes long-term ex-ante (anticipative) and short-term ex-post (adaptive) decisions. The need for the coexistence of such decisions is especially evident in extreme situations. For example, we can not drive a car just by looking backward, i.e., the synergy of the forward looking and the backward looking behavior are key factors for survival.

An ex-ante decision corresponds to risk-averse behavior and an ex-post decision models risk-prone behavior. The coexistence of these two types of behavior can be viewed as a rather flexible decision-making framework when we commit ourselves ex-ante only to a part of possible decisions and, at the same time, keep other options open until more information becomes available and can be effectively utilized by appropriate ex-post decisions. This type of models, the so-called two-stage stochastic optimization models, produces strong risk aversion even for linear utility functions. Consider a simple situation. Let us assume that there are two options to deal with catastrophe: to protect values against losses before the occurrence of a catastrophe or to borrow after its occurrence. We assume that the decision maker has a risk-neutral, linear disutility function $f(x,y)=cx+dy$, where c is the marginal cost for protection x, and $d(L)$ is the marginal cost for borrowing y in the case of losses L. The decision making process has two stages. First of all, decision x is chosen before the observation of L. Decision y is chosen after the occurrence of the catastrophe, i.e., the observation of L. Therefore we have (because of the linear disutility) $y=\max\{0,L-x\}$. Thus, the decision x minimizes, in fact, the function $F(x)=cx+Ed(L)\max\{0,L-x\}=cx+\int_x^{\bar{L}}d(l)(l-x)\varphi(l)dl$. Assume that the probability distribution of L, $L\le\bar{L}$, has a continuous density function φ. Then $F(x)$ is a strictly concave continuously differentiable function and, as it is easy to verify,

$$F'(x)=c-\int_x^{\bar{L}}d(l)\varphi(l)dl\,.$$

The function $F'(x)$ is monotonically increasing for $x\to\bar{L}$. Therefore, if $c<Ed$, then there is a positive value $x=x^*$, $x^*\ne\bar{L}$, such that $F'(x^*)=0$. Here $x^*=\bar{L}$ is excluded because $c>0$. Hence, the minimization of the linear expected disutility function does not lead to the dominance of the preferable on average ex-ante decision ($c<Eg$): both types of decisions coexist.

6. Indirect Effects

Besides visible direct damages, catastrophes have long-term indirect effects. The cost of a damaged bridge may be incomparable to the cost of interrupted activities. A large catastrophic loss may absorb domestic savings and force government into debt. The low-income countries lack the budgetary resources that would enable them to undertake the necessary growth adjustments. In Section 4 the growth of the economy was represented by the growth of each cell. Investments are channeled through terms I_j^t, whereas returns are affected through L_j^t. The trade-off between these forces defines the growth path of the cell j, its possible stagnation and the contribution to the wealth of the region. Let us consider this issue by using a stylized model of the sustained economic growth. This model illustrates the importance of stochastic versus deterministic approaches to the economic growth.

7. Economic Growth under Shocks: Stochastic vs. Deterministic Model

Let us assume that the wealth (output) of the economy is defined by two factors: "capital" and "labor", and constant returns to scale. Then the output can be characterized in terms of capital to labor ratio k, and output to labor ratio y, $y = f(k)$, where $f(k)$ is the production function. Assume that output is subdivided into consumption and savings, and savings are equal to investments. If investments are simply a fraction s, $0 < s < 1$, of the output, and productivity of capital $f(k)/k$ is constant θ, then this leads to the very influential in growth planning Harrod-Domar model [11], [12] with an exponential growth rate defined by the linear function

$$\ln y = y_0 + (s\theta - \gamma - \delta)t, \ t > 0, \quad (1)$$

where γ is an exponential population growth rate, and δ is the capital depreciation rate. Shocks occur at some random time moments $T_1, T_2, \ldots$ and transform the linear function (1) into a highly nonlinear jumping random function (Figure 2)

$$\ln y(t) = y_0 + (s\theta - y - \delta)t - L_1 - L_2 - ... - L_{N(t)} \qquad (2)$$

where $N(t)$ is the (random) number of shocks in the interval $[0,t]$. For the purpose of illustration only let us ignore that shocks $L_1, L_2,...$ depend on the state of the economy. In our economy it is $y(t)$. Let us also assume that random sizes of shocks $L_1, L_2,...$ are independent, identically distributed with a mathematical expectation μ; they are also independent of the intershock times $T_{k+1} - T_k$, and the intershock times have a stationary distribution with mathematical expectation λ. Then the expected exponential growth is still characterized by the linear in t function (Figure 2)

$$E \ln y(t) = y_0 + (s\theta - \gamma - \delta - \lambda\mu)t\,. \qquad (3)$$

From the strong law of large numbers it follows that $\ln y(t)/t$ approaches $s\theta - \gamma - \delta - \lambda\mu$ for large enough t and for each random path $y(t)$. In other words the sustained exponential growth "takes off" only after a long random time T specific for each path: $\ln y(t) \approx y_0 + (s\theta - \gamma - \delta - \lambda\mu)t$, for $t > T$. On the way to sustained growth for $t < T$ the economy may stagnate as Figure 2 shows. The ignorance of risk is equivalent to the substitution of the complex jumping process $\ln y(t)$ by deterministic linear function (3). This function still shows the exponential growth, although with a greater depreciation rate $\delta + \lambda\mu$, but it ignores possible stagnation of the economy in the interval $[0,T]$. The uncertainty analysis, which is usually recommended after such substitutions, can not reveal the possibility of the stagnation either, since in our case it is equivalent to the turning around of the same linear function (3). The stabilization of growth with the above mentioned shocks is similar to the problem discussed in [6-8]. A challenging situation arises when shocks are endogenously defined by dynamic and spatial patterns of the growth. In general case shocks $L_1, L_2,...$ and other parameters are affected by the growth $y(t)$. The saving rate s may critically depend on the overall level y and its distribution in the economy. Obviously, at low income levels, saving rates are small. In this case a shock may further reduce them even to negative values (borrowing). The growth path in such cases may exhibit thresholds and traps. In other words, starting from the same initial conditions, the economy may end up (without appropriate assistance) at different traps (locally stable equilibriums) and stagnate within these traps thereafter [9].

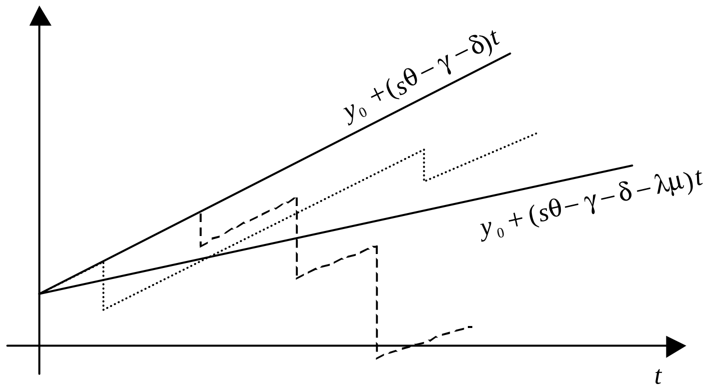

Figure 2. Expected and real growth rates

8. Concluding Remarks

The model outlined in Section 4 can be used for risk management with the so-called rolling horizon. The model includes a time horizon τ, which may be a random variable, say the time of the first catastrophe from the given initial state at $t = 0$. This generates a sequence of decisions for $t = 0,1,...$. After implementing decisions at $t = 0$, new information becomes available. At $t = 1$ the model is updated, a new sequence of decisions for $t = 1,2,...$ with a new time horizon is obtained, decisions for $t = 1$ are implemented, and so on. Several data-intensive numerical experiments with the type of models outlined in this paper are discussed in [1-2], [6-7]. In these experiments data on earthquakes from Russia and Italy are used.

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