International Institute for Applied Systems Analysis
Schlossplatz 1 • A-2361 Laxenburg • Austria
Telephone: (+43 2236) 807 342 • Fax: (+43 2236) 71313
E-mail: publications@iiasa.ac.at • Internet: www.iiasa.ac.at

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Analysis of applications of some ex-ante instruments for the transfer of catastrophic risks.

Piotr Nowak (pnowak@ibspan.waw.pl)

Approved by

Paul Freeman (freeman@iiasa.ac.at), Marek Makowski (marek@iiasa.ac.at)
Senior Research Scholars, Risk Modelling and Policy Project

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Abstract

The purpose of the work is to develop a prototype model that can be used to illustrate a model-based support for the analysis of decisions about ex-ante financial instruments for coping with consequences of natural catastrophes in developing countries. The prototype model is based on a model presented by P.K. Freeman and G.Ch.Pflug, but it has been adapted to the situation in Poland and modified to permit the analysis of various instruments for risk transfer. The proposed model considers a portfolio of assets (such as infrastructure, private property, etc.) that generates deterministic returns, but it is affected by damages caused by floods.
A stochastic model of damages caused by floods has been formulated in order to allow the comparison of risk transfer instruments (such as catastrophe bonds and insurance) for various layers of the portfolio values.

Acknowledgment

I would like to thank Professor Georg C. Pflug from Vienna University and IIASA's Risk Modeling and Policy Project for helpful hints and guidance during the Young Scientists Summer Program.

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Contents

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Piotr Nowak[*] *(pnowak@ibspan.waw.pl)*

1 Introduction

Natural disasters are a significant problem for developed and developing countries. Lately, they have occurred with an increasing frequency and severity. Floods, windstorms, earthquakes and other catastrophes have significantly damaged governmental and private property. In past ten years, three U.S. hurricanes, Andrew (1992), Hugo (1989) and Opal (1995), caused total direct damages of $40 billion. In the decade 1988 - 97, 65% of all flood losses occurred in Asia ([Munich Re. 1998a] and [Munich Re. 1998b]). Property damage from the Polish flood in 1997 amounted to about $3 billion.

Recently, substantial progress has been made in understanding the nature and consequences of natural hazard damages. Catastrophes are events of low probability and high impact. In developed countries, reconstruction following natural disasters is financed by risk transfer. Such a transfer can be made by purchasing policies by insurance companies or by issuing so-called "catastrophe bonds". These financial instruments are ex-ante risk financing instruments because they are arranged before a catastrophe takes place.

This article aims at discussing the advantages and disadvantages of ex-ante risk transfer instruments in Poland, either using catastrophe bonds and/or insurance. A model has been developed to analyze trade-offs between costs of risk transfer and the provided financial protection. The model also permits analysis of the costs and benefits of risk transfer for different layers of risk. This analysis is based on Monte - Carlo simulation.

The starting point for our considerations was the article *Infrastructure in Developing Countries : Risk and Protection* written by Paul K.Freeman and Georg Ch.Pflug [Freeman, Pflug 1999]. The model has been adapted to the Polish situation. The Freeman and Pflug model assumes damage is solely to government property and reconstruction is financed by government. Neither assumption applies to Poland. We consider the situation where different layers of risk may be transferred using different instruments. As the result of statistical analysis, sizes of damages are random variables with different probability distribution in each layer. The spatial correlations between the damaged assets were not considered.

[*]Systems Research Institute of the Polish Academy of Sciences, Newelska 6, 01-447 Warszawa, Poland.

The first section is devoted to a short discussion about catastrophe bonds, which are relatively new financial instruments. In the second section, a stochastic model of damages caused by floods has been formulated to allow the comparison of risk transfer instruments for various layers of the portfolio values. The implementation through Monte - Carlo methods is shown in the next two sections. The fifth section contains the conclusions.

2 Catastrophe Bonds

Catastrophe bonds are relatively new financial instruments. They are issued as means of risk transfer to private investors and are connected with a precisely described catastrophe event (the so-called triggering event).

The basic difference between them and other kinds of bonds is the fact that they are more risky for bondholders. It is so, because part of their principal values and sometimes whole "principals" are not repaid if event takes place that is acknowledged as triggering occur. For some cases of bonds the bondholders may also not receive interests. As we mentioned before, catastrophe events occur with low probability, but if they take place, losses of bondholders are relatively high. The amount of money obtained from investors and placed in an escrow account is then transferred to the insured by the escrow agent.

The first "cat bond" was a USD$50 million bond issues in 1990 (see [Zhang, Zakharia 1998]). The principal of the bond was payable to the issuing insurance company in the event of Richter scale 7 or greater earthquake in specified region of Japan. The best known bonds were the USAA (the fourth-largest U.S. home-owner insurer in 1996) "Act of God" bonds sold by Merrill Lynch & Co. The triggering event was a hurricane which cost USAA over $1 billion. The probability of the event was 1% and investors received interest based on one-month LIBOR (London Interbank Offering Rate) plus 3 points. In 1997 USAA issued almost $500 million in catastrophe bonds with a triggering event being a category three, four or five hurricane hitting one of twenty U.S. states or the District of Columbia and causing more than $1 billion of claims against USAA.

In the beginning the investors demand for cat-bonds was small, but has increased every year. The California Earthquake Authority was created to provide earthquake insurance (see [Stripple 1998]). It is a privately financed and publicly managed state agency. A $1 billion earthquake catastrophe bond issued by CEA in 1996 was the first governmental instrument of this type.

Why have catastrophe bonds developed? First, they may be cheaper than the traditional insurance or reinsurance. Second, since the face amount of the bonds is placed in an escrow account, there is no risk of delayed payoffs for the insured. Third, they can be accessible for countries with a significant catastrophe risk and limited domestic insurance markets (see [Freeman 1998]). Additionally, they are means of risk transfer for losses which are not otherwise insurable, since insurance companies do not insure a property or they limit insurance in some regions of high catastrophe risk. Finally, if the "cat bonds" are issued by government or local authorities, they reduce uncertainty to the public budget and of course, when the catastrophe occurs they cover potential losses.

Since catastrophe bonds are risky, they should give investors higher returns than "riskless bonds", such as treasury bonds. But this is not the only reason for purchasing them. They enable portfolio diversification, because they are not correlated with other financial instruments in the stock market. The market value of "cat bonds" is a very interesting and complicated theme. One of the methods of calculating it is the so called arbitrage pricing, i.e. calculation of the present market value under the assumption of no return without risk. Actually, financial mathematicians deal with this problem.

3 The Assumptions and Basic Formulations of the Model

3.1 Notations

$n > 0$ - number of layers of losses (for which different financial or insurance instruments may be applied).

i - index of a layer, $i = 1, 2, ..., n$.

l_{i-1} and l_i are lower and upper limit of i - th layer, $l_0 = 0$, $l_n = 1$.

γ_i - price coefficient for the best available risk transfer instrument in i - th layer.

$u = (u_1, u_2, ..., u_n)$ - vector index of binary variables describing risk transfer in each layer ($u_i = 1$ denotes transferring risk in i-th layer and $u_i = 0$ - not transferring risk); $u = \mathbf{0} = (0, 0, .., 0)$ denotes the case of no risk transfer.

$t = 0, 1, 2, ..., T$ - sequence of time period.

$J^u(t)$, $J_1^u(t)$ and $J_2^u(t)$ denote the values of fixed property, its authorities' part[1] and its private part respectively, at the beginning of year t, for a given strategy of risk transfer (defined by u).

$I^u(t)$, $I_1^u(t)$ and $I_2^u(t)$ - corresponding values at the end of year t.

$d \in (0, 1)$ - depreciation of property.

$r > 0$ - yearly private property growth constant.

$\theta \in [0, 1]$ - fraction of protected private property.

$p^u(t)$ - price of the risk transfer.

$\delta(t)$ - fraction of destroyed property in the year t.

$w(t)$ - fraction of net return invested in authorities' property in the year t.

$INV^u(t)$ - value of authorities investment.

[1]Further on by *an authority* we understand either central or local government that takes a responsibility for properties for which risk transfer instruments will be considered.

$v \in [0,1]$ - return constant.

$R^u(t)$ - the yearly authorities return from property.

$O^u(t)$ - outpayments to be made in year t.

$N^u(t)$ - yearly net return from the property.

$\mathcal{N}^u(t)$ - cumulated net return from the property.

In the next subsection we will use the following auxiliary variables:

$J_p^u(t) = J_1^u(t) + \theta J_2^u(t)$.

$I_p^u(t) = I_1^u(t) + \theta I_2^u(t)$.

We will also use the following notation for a given function f

$$f_+(x) = \begin{cases} f(x) & \text{if } f(x) > 0 \\ 0 & \text{if } f(x) \leq 0 \end{cases}.$$

3.2 Model Assumptions

- The value $I^u(t)$ is given by the formulae

  $$I^u(t) = I_1^u(t) + I_2^u(t), \quad I_1^u(0) = I_1, \ I_2^u(0) = I_2,$$

  where I_1 and I_2 are fixed values.

- The value of private part grows according to the following formula:

  $$J_2^u(t) = (1-d)\, I_2^u(t-1) + r(t)$$

  for a given sequence of increments: $\{r(t)\}_{t=1}^T$.

- The authorities protect their part $J_1^u(t)$ and take in responsibility a part $\theta J_2^u(t)$ of the private property. They transfer risk for this part or cover damages if the flood occurs (in the case $u = \mathbf{0}$ authorities cover the whole damaged part of $\theta J_2^u(t)$).

- The authorities invest an amount $INV^u(t)$. This amount is given by a sequence $\{w(t)\}_{t=1}^T$ of fractions of the previous net return from the authorities property $N^u(t-1)$ (calculated according to the formula (1), pg.5), if it was positive.

  $$INV^u(t) = w(t)\, N_+^u(t-1).$$

- The dependence of $J_1^k(t)$, and $J_p^k(t)$ from the values of the corresponding properties in the end of the previous year is given by formulas:

  $$J_1^u(t) = (1-d)\, I_1^u(t-1) + INV^u(t),$$
  $$J_p^u(t) = (1-d)\, I_p^u(t-1) + INV^u(t) + \theta r.$$

- The losses in the i - th layer are defined by a random variable X_i. Distributions of X_i may be different for different i. Layer of losses in each year changes according to the Markov chain described in the next subsection. A random event connected with the i-th. layer destroys the property in lower layers and the fraction $\delta(t) - l_{i-1}$ of property in this layer.

- The price $p^u(t)$ of the risk transfer is calculated by the formula

$$p^u(t) = J_p^u(t) \sum_{i=1}^{n} u_i \gamma_i (l_i - l_{i-1}).$$

- In the end of year t we have the following equations for the values of authorities and private property:

$$I_1^u(t) = J_1^u(t) \{1 - \delta(t) + \sum_{i=1}^{n} u_i [\min(l_i, \delta(t)) - \min(l_{i-1}, \delta(t))]\},$$

$$I_2^u(t) = J_2^u(t) [1 - \delta(t) + \theta \delta(t)].$$

- The yearly authorities' return $R^u(t)$ from property $I_1^u(t)$ is calculated according to the formula

$$R^u(t) = v I_1^u(t).$$

- The outpayments to be made in year t are

$$O^u(t) = INV^u(t) + p^u(t) +$$

$$+\theta J_2^u(t) \sum_{i=1}^{n} (1 - u_i) [\min(l_i, \delta(t)) - \min(l_{i-1}, \delta(t))].$$

- The net return from the authorities' property is

$$N^u(t) = R^u(t) - O^u(t). \qquad (1)$$

- Cumulated net return from authorities property is calculated by using of formula: $\mathcal{N}^u(t) = \sum_{s=1}^{t} N^u(s)$. This is a measure of wealth of the country because $\Delta GDP(s)$ is an increasing function of $N^u(s)$.

3.3 The Occurrence of the Flood

The occurrence of the flood is described by the homogenous Markov chain $\xi(t)$ with the discrete time $t = 0, 1, 2, ...$ satisfying the following properties:

1. The space of its states is the set $\{1, 2, ..., n\}$.

2. There are $p_1, p_2, ..., p_n$ belonging to the interval $[0, 1]$ being the initial distributions, i.e.

$$P(\xi(0) = i) = p_i, \quad i = 1, 2, ..., n.$$

3. There is a parameter ρ belonging to the interval $[0,1]$ such that the transition matrix is of the form:

$$(1-\rho)\begin{pmatrix} p_1 & p_2 & \dots & p_n \\ p_1 & p_2 & \dots & p_n \\ \dots & \dots & \dots & \dots \\ p_1 & p_2 & \dots & p_n \end{pmatrix} + \rho \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

   $\xi(t)$ takes the value i when flood damages in the year t occur in the layer i. The parameters $p_i = P(\xi = i)$ are ergodic probabilities of the occurrence of the flood with damages in the i-th. layer and ρ is the correlation between the random variables $\xi(t)$ and $\xi(t+1)$.

The probability distribution of the relative size of damages depends on the state and the random variable describing it is denoted by $X_i(t)$. In this case $\delta(t) = X_i(t)$, $t = 1, 2, \dots$

3.4 Price Coefficients for the Risk Transfer Instruments

For each layer considered in the model the available instruments of risk transfer are evaluated "off line" (i.e. a separate study for each instrument has to be done) and the corresponding prices are determined. For each layer the instrument with the cheapest price coefficient (denoted by γ_l) is selected and used for the approach described in this paper.[2] In the model we will estimate coefficients γ_l from above by the values of corresponding insurance coefficients.

It is generally known (see [Freeman, Pflug 1999]) that if the random variable X describes percentage values of losses of a given property then its insurance price is given by the formula:

$$\gamma = (1+\beta) EX,$$

where EX is the expected value of X and β is a risk premium.

Applying this formula we will name the right - hand side quantity by the price coefficient for the best available risk transfer instrument.

4 Monte - Carlo Simulations

4.1 Assumptions and Parameters Settings

To illustrate the model by using the Monte - Carlo simulations we set its parameters. The number of states $n = 4$. The meaning of them is:

- the first - flood with an occurrence more frequent than 20 years ($p_1 = 0.95$);

- the second - flood with an occurrence between 20 and 50 years ($p_2 = 0.03$);

[2] Pricing of financial instruments is a complex issue and therefore it is far beyond the scope of this paper. The related problems are discussed for example in [Maksymiuk, Gatarek 1999].

- the third - flood with an occurrence between 50 and 100 years ($p_3 = 0.01$);
- the fourth - flood with an occurrence rarer than 100 years ($p_4 = 0.01$).

With every state we linked the risk premiums: 1.0, 0.21, 0.15, 0.09
and limits of relative sizes of losses:

$l_0 = 0$, $l_1 = 0.1$, $l_2 = 0.3$, $l_3 = 0.5$, $l_4 = 1$.

The random variables describing the relative (i.e. percentage) size of damages if a flooding event in a given state would occur, have the following distributions:

$$X_1 \sim (l_1 - l_0)\,\beta_1(1, 99),$$

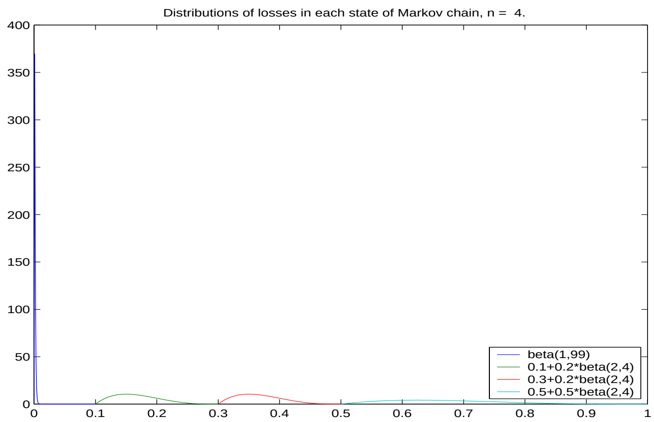
$$X_2 \sim l_1 + (l_2 - l_1)\,\beta_2(2, 4),$$

$$X_3 \sim l_2 + (l_3 - l_2)\,\beta_3(2, 4)$$

and

$$X_4 \sim l_3 + (l_4 - l_3)\,\beta_4(2, 4),$$

where $\beta_1, \beta_2, \beta_3$ and β_4 are independent, $\beta(1, 99)$ and $\beta(2, 4)$ distributed random variables, respectively. Fig. 1. depicts probability density functions of variables X_1, X_2, X_3 and X_4.



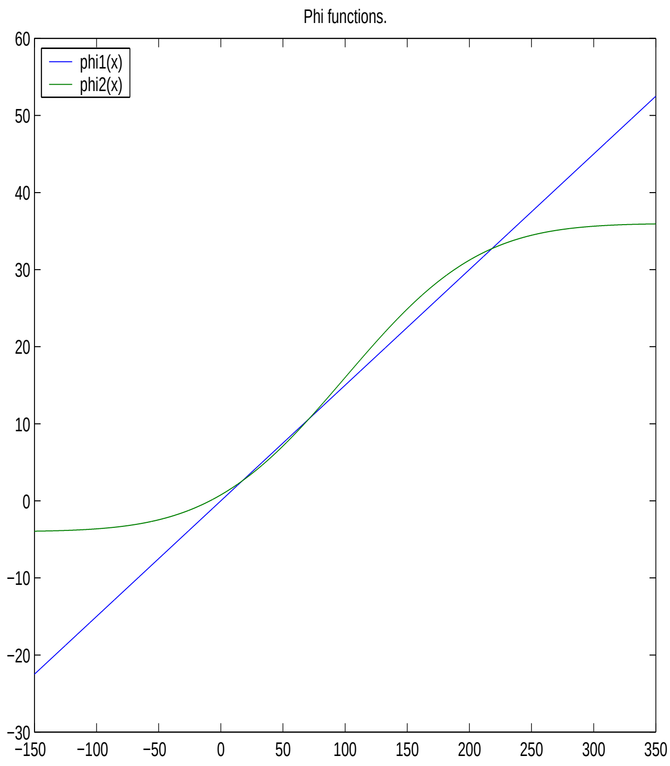
1. Densities of flood losses.[3]

[3]Due to the technical limitations figures in the printed version of this paper are grayscaled. However, the electronic versions of this paper (available from `http://www.iiasa.ac.at/docs/Admin/PUB/Catalog/`) contain color figures that are much easier to interpret.

Parameters setting for X_1 corresponds to the situation of very frequent floods with not significant losses. It may be replaced by $\delta_{\{1\}}$ distribution which corresponds to no losses case in the first state of Markov chain. The rest of the parameters settings is presented in the following table:

d	0.033
r, θ, w	0.1
ρ	0.05
v	0.15
$I_1,\ I_2$	100.0
$\varphi_1(x)$	$v * x$
$\varphi_2(x)$	$R = 20 * erf(\frac{x-90}{50})) + 12$

where φ_1 and φ_2 are two cases of phi function having the the following graphs:

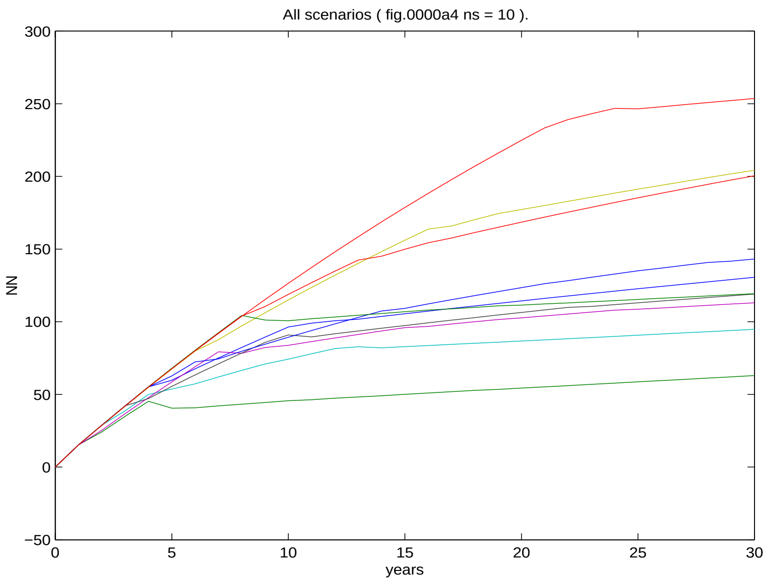


2. Phi functions.

Choice of the phi function depends on region considered in the model.

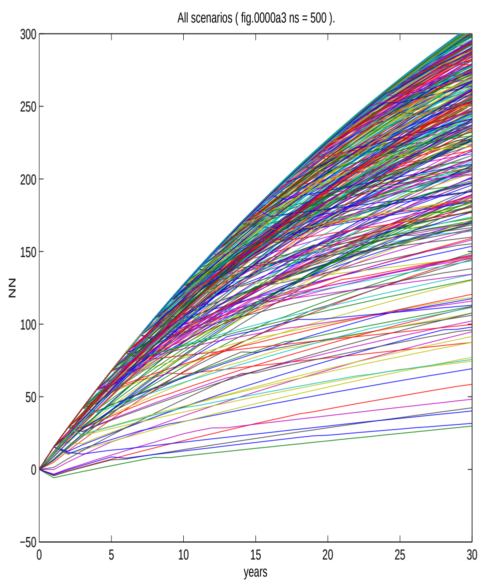
4.2 Simulations Results

Figure 3 depicts 10 scenarios obtained from the Monte Carlo simulations made with the parameters from previous subsection. Each bend of a scenario denotes flooding event with big losses. Observing the behavior of scenarios it is easy to notice that if a sever catastrophe occurs at the beginning, it is very difficult to obtain substantial cumulated net return at the end of the time period.

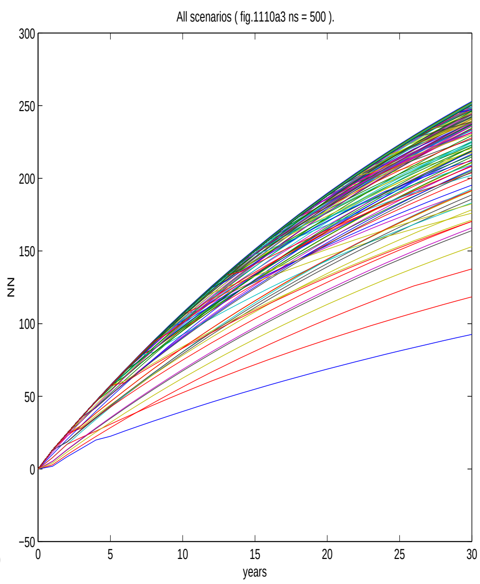


3. Illustration of ten scenarios. NN denotes cumulated net return $\mathcal{N}$.

The next two figures shows 500 scenarios in two cases: no risk transfer and the risk transfer in three first layers of losses.



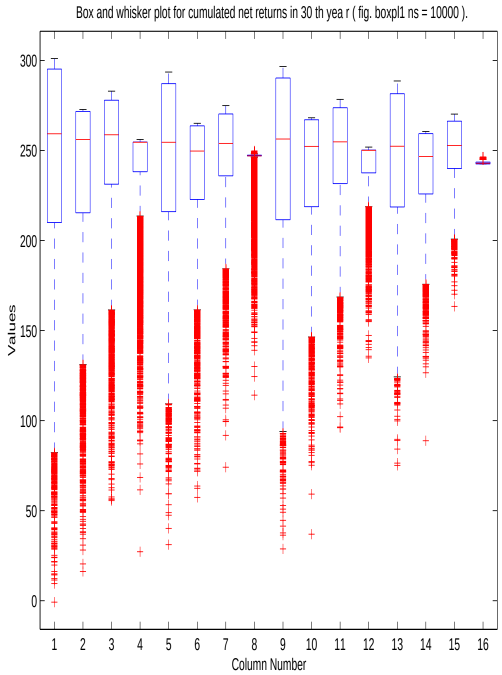
4. No risk transfer.



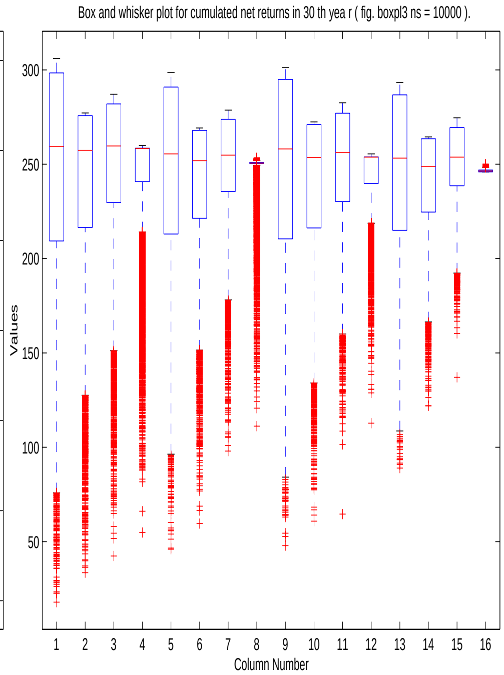
5. Risk transfer in first three layers.

We see that much more scenarios is focused in the upper part of figure in the second case.

A good characteristic of obtained results are the so-called boxplots with whiskers which depict typical variability intervals for medians of net returns in the year 30 for functions φ_1 and φ_2 generating return from property:



6. Box&Whiskers Plots (for $\varphi_1(I)$).



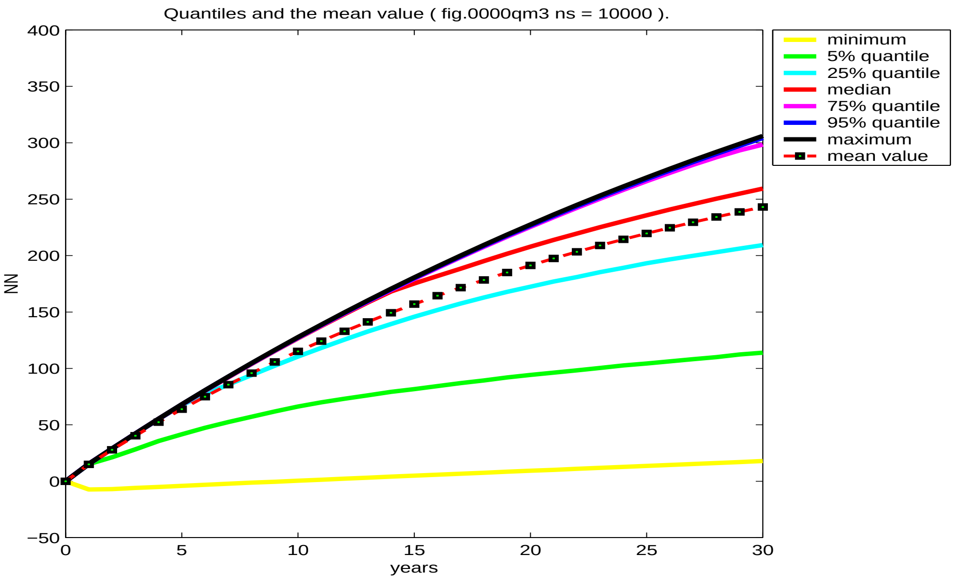
7. Box&Whiskers Plots (for $\varphi_2(I)$).

The upper side of rectangle is value of upper (third) quartile, the lower one of lower (first) quartile and the red segment inside rectangle denotes the median. Whiskers are essential maximum and minimum. Red pluses are the values below or above minimum or maximum, respectively, which differ very much from median. The meaning of Column Numbers is described by the following table:

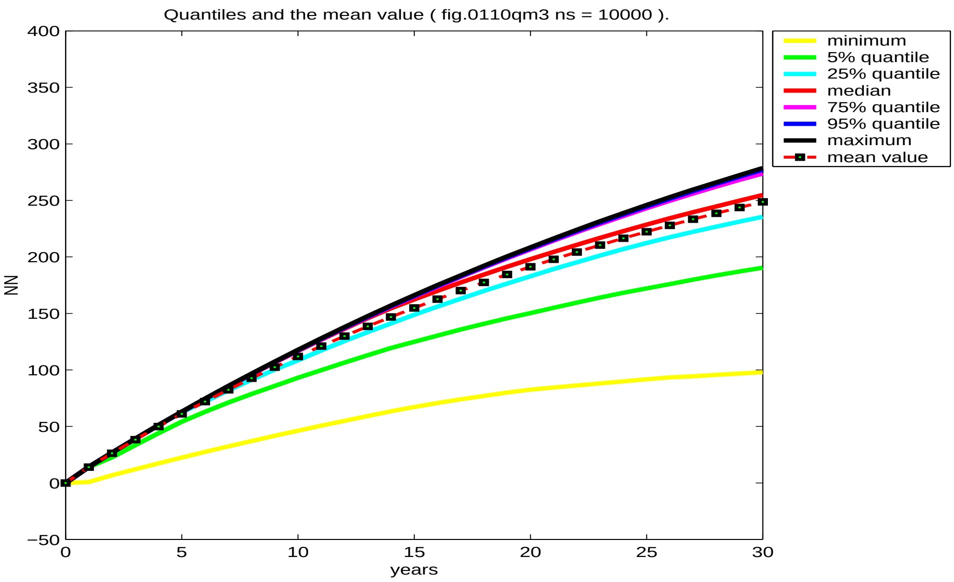
Column Number	Value of u	Column Number	Value of u
1	$(0,0,0,0)$	9	$(0,0,0,1)$
2	$(1,0,0,0)$	10	$(1,0,0,1)$
3	$(0,1,0,0)$	11	$(0,1,0,1)$
4	$(1,1,0,0)$	12	$(1,1,0,1)$
5	$(0,0,1,0)$	13	$(0,0,1,1)$
6	$(1,0,1,0)$	14	$(1,0,1,1)$
7	$(0,1,1,0)$	15	$(0,1,1,1)$
8	$(1,1,1,0)$	16	$(1,1,1,1)$

The smaller dispersion the better results. The best situation is in the case of full risk transfer (16), good in the case of risk transfer in three layers (8, 12 and 14), the worst in the case of no transfer of risk (1). The second observation is that risk transfer in the first layer diminishes dispersion. However the payments for the risk transfer decreases cumulated net returns. To the end of this subsection we will

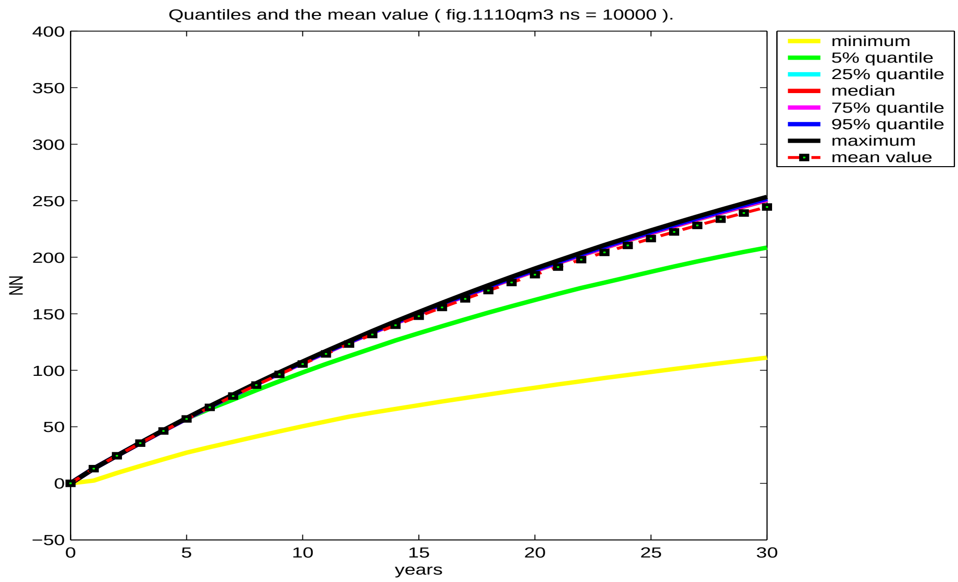
analyze results only for $\varphi = \varphi_2$ because there is not a big difference between them and results obtained for $\varphi = \varphi_1$. (It is easy to notice this fact for two previous figures).
The next four figures shows quantile curves for cumulated net return from property in the whole time period.



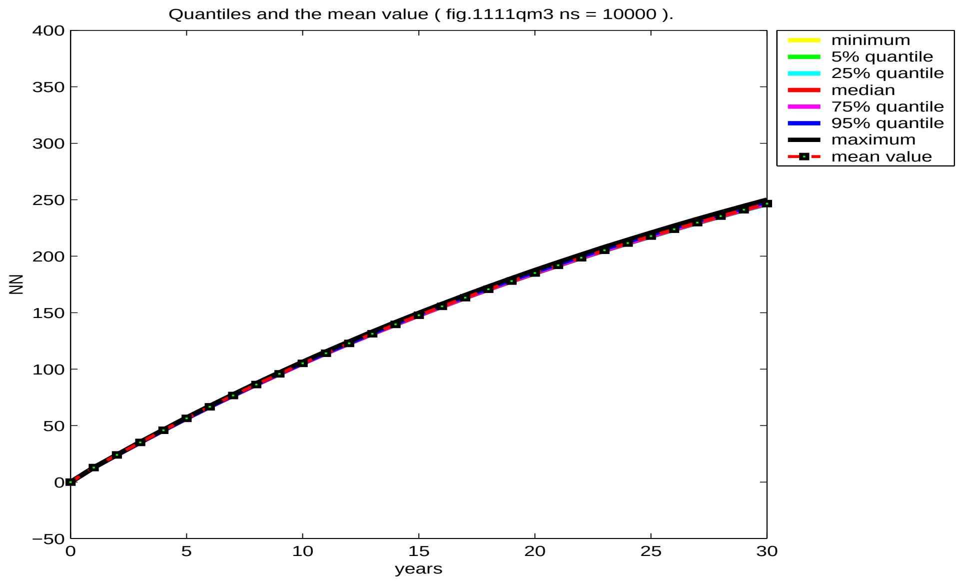
8. Quantiles for $u = (0, 0, 0, 0)$.



9. Quantiles for $u = (0, 1, 1, 0)$.



10. Quantiles for $u = (1, 1, 1, 0)$.



11. Quantiles for $u = (1, 1, 1, 1)$.

Let us pay attention at the fact that the border line of 5% lower quantile goes up when the number of layers with transferred risk growths.

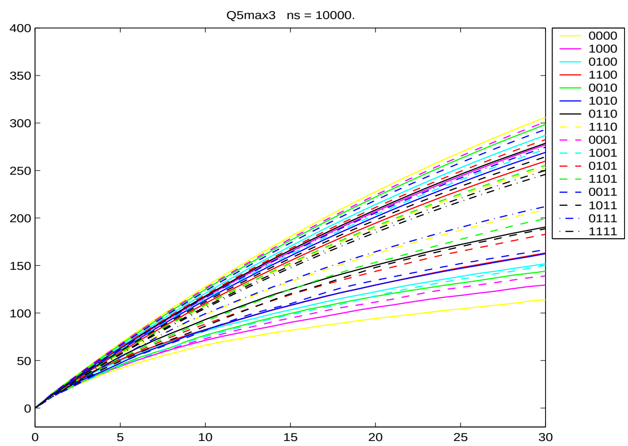
Observations made to this time are confirmed by analysis of standard deviations apearing in the following table:

Column Number	σ	Column Number	σ
1	61.50	9	53.32
2	48.56	10	40.67
3	42.54	11	32.20
4	32.16	12	18.78
5	49.96	13	42.25
6	35.79	14	26.32
7	29.03	15	19.94
8	16.27	16	0.74

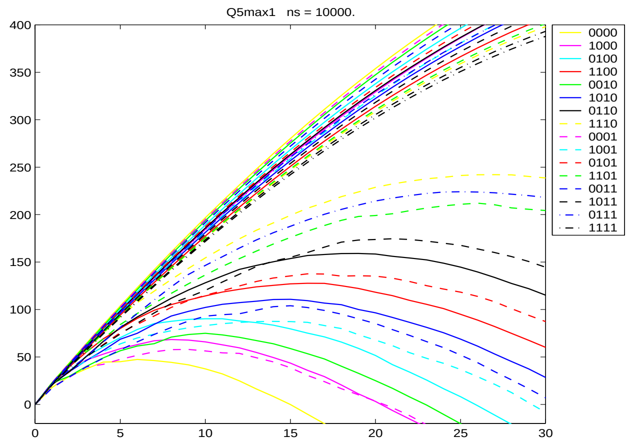
5 Discussion of Results

As the results of the considerations one can formulate the following conclusions:

- Risk transfer across more layers causes smaller dispersion of results. The greatest dispersion is linked to the situation of no risk transfer. The almost zeros dispersion takes place in the situation of full risk transfer in all layers (it is zero for $\theta = 0$).
- Layers with the greatest probability of occurrence have especially important role in this dispersion reduction.
- The risk transfer payments cause small decrease of maximum, mean value, median and upper quantiles in the situation of risk transfer.
- Right parameters setting of the φ function (which may be different for different regions) is also very important for this model. As an illustration we will show Fig.12. (for $\varphi(x) = \varphi_2(x)$) and Fig.13. (for $\varphi(x) = \varphi_3(x) = 40 \cdot erf(\frac{x-40}{100})$) describing results of Monte - Carlo simulations for each u in the form of pairs: lower 5% quantile and maximum curves.



12. 5%quantile - max, $\varphi = \varphi_2$.



13. 5%quantile - max, $\varphi = \varphi_3$.

- It is highly likely that for some regions and corresponding to them parameters, risk transfer in the first layer may be not profitable.

5.1 The Influence of the Application of Financial Instruments on GDP

It is also possible to consider the influence of the ex-ante instruments upon GDP. The main difference of such a model from the previous one may be formulated as follows.
The dependence between GDP and the value of infrastructure is given by an increasing function $\psi : \mathbb{R}_+ \to \mathbb{R}_+$. We have the equalities:

$$GDP^k(t) = \psi\left(I^k(t)\right),$$
$$GDP^k(0) = G_0.$$

The main trouble with the application of this model is the fact that economists have no good mathematical models which describe the dependence between the change of infrastructure value caused by a catastrophe and the corresponding decrease of GDP. Currently, IIASA has a research project in partnership with The World Bank focusing on these issues. However, the description of this new research is beyond the scope of this paper.

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