A model of the effects of social interactions and risk experience on adaptation behaviours

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Abstract

We propose a micro economic model that aims to describe how individuals choose to adopt or not a protection measure against a risk by taking into account people's experience of the risk and the social interactions. It is derived from a dynamic aggregate model that explains the evolution of the adoption rate of a protection measure within a population [6]. Some behavioural implications of the micro economic model are presented. In particular, we show that the aggregate model can be explained by heterogeneous and sometimes unintuitive individual decision-making processes. Especially, our model implies that the expected loss has a positive effect on the utility of agents who were not previously protected and that the utility of adaptation of people who renew a protection behaviour increases with the price of the measure. We finally discuss the empirical testability of the model.

1 Introduction

The concept of risk is strongly intertwined with the evolution of Modern society. While disasters and harms were attributed to God's Will and considered unavoidable in the pre-industrial era, they have become risks since the rise of the industrial society. In other words, the eventuality of a loss is now often statistically describable and more or less predictable. Thus, events that could happen in the future can now often be taken into account for current decisions [1].

As a result, theoreticians have tried to understand how risks affect human behaviours since the eighteenth century. The consideration of the respective effects of risk probability and intensity lies at the core of most of these theoretical contributions [12], [11], [8]. On the other hand, psychological and economic experiments suggest that risks also affect behaviours differently depending on characteristics other than probability and intensity. For example, risk perception also depends on the controllability of the hazard. Indeed, people tend to perceive uncontrollable risks as more dangerous [7], [10].

Thus, it seems relevant to study the underlying mechanisms of decision under a specific risk to represent them more precisely. Here, we focus on a controllable risk against which an adaptation or protection measure[1] can be implemented in order to reduce the expected damage, such as a risk of flooding. More precisely, we explore how individuals decide to adapt to reduce an expected loss under a particular risk. We chose to explore individual

[1]In this article, we use "adaptation measure" and "protection measure" as synonyms.

adaptation because knowing better what triggers these behaviours could help to foster them and to design more efficient collective protection measures by taking individual actions into account [3].

Adaptation choice presents major features that must be taken into account in a formal representation.

Obviously, when deciding whether to adapt or not, people actually choose between a loss characterized by a particular probability, and conditioned by the occurrence of the risk, and the loss of a certain amount, which is the cost of adaptation. If the adaptation does not completely eliminate the risk, the choice to adapt also implies a risky loss that must be lower than the expected loss[2] without adaptation. This aspect is generally at the core of economic models of decision under risk according to which the agents compare the expected utility under the decision to adapt with the expected utility if they do not adapt. However, other characteristics of the choice must be considered to explore more in depth adaptation decisions.

First, adaptation behaviours can evolve with time. Indeed, since an adaptation is supposed to reduce the risk against which it is implemented, it can modify risk perception. In that case, feedback effects could be observed [2]. Thus, perception of the risk may depend on the adaptation status. Moreover, the reality of the risk may be more tangible for people who have experienced it recently. Hence, people's preferences regarding adaptation may change through time, depending on an exogenous factor, the experience of the risk, and on an intrinsic factor, the previous decision of adaptation or non-adaptation.

Moreover, the extent to which people are aware of the risk and of the adaptation measures that exist to reduce it can influence their propensity to adapt. By definition, a risk is an event that occurs with a probability lower than 1. In other words, people who are exposed to a specific risk do not experience it permanently and it is often difficult to directly observe what a risk implies in terms of potential damages. Thus, information about risks are generally acquired indirectly. In particular, social interactions can influence risk perception and adaptation [9].

To our knowledge, there exists only one mathematical model that explains adaptation decisions by taking into account not only the comparison of adaptation cost with expected loss, but also the dynamics of the behaviours and the diffusion of information through social interactions. This model was designed by Kunreuther et al [6]. It explains the adoption rate of an adaptation measure within a population. Thus, it is defined at the collective scale and does not specify the individual mechanisms of adaptation decisions. Hence, we propose in this article micro-economic foundations compatible with Kunreuther's model.

Our model suggests that the collective tendencies described by Kunreuther's model can emerge from heterogeneous individual decision-making processes. Moreover, some implications of our micro-economic model seem unintuitive but are compatible with the hypotheses at the collective level. In particular, our model implies that the utility of people who were not previously adapted increases with the expected loss and that agents who were already adapted benefit all the more from an adaptation decision as the cost of the implemented measure is high. Finally, this work could allow to test more easily the hypotheses proposed

[2]The expected loss is usually defined in economics as the product of the probability of the loss and its amount. However, in this paper, this notion refers to an undefined measure of the perceived threat that could be equal to the common economic definition of expected loss, but also to other types of measures.

by Kunreuther by confronting the micro-economic model with quantitative data, and thus contribute to a better understanding of adaptation mechanisms.

In the second section, we expose the method we followed to unravel micro-economic foundations from the aggregate model proposed by Kunreuther et al. Then, we present some implications of the micro-economic specifications. In the fourth section, we discuss the empirical applicability of these micro foundation before concluding.

2 Unravelling micro-economics foundations from a collective scale model

2.1 The aggregate model

The discrete version of the aggregate model [6] rests on a single dynamic equation:

$$A_{t+1} = A_t + \alpha_{ct} A_t (1 - A_t) + \alpha_{ot}(1 - A_t) - \delta_{ct} A_t (1 - A_t) - \delta_{ot} A_t \ . \quad (1)$$

It explains the evolution of the fraction A_{t+1} of the population that protects himself by adopting a particular adaptation measure. In this expression:

- α_{ct} : is the fraction of contacts between adopters and non-adopters that induces non-adopters to protect themselves at date $t + 1$,
- α_{ot} : is the fraction of non-adopters who switch to adoption for reasons not related to contacts with adopters at date t,
- δ_{ct} : is the fraction of contacts between adopters and non-adopters that leads adopters to discontinue protecting themselves at date $t + 1$.
- δ_{ot} : is the fraction of adopters who discontinue protection for other reasons.

Those four coefficients implicitly depend on:

- π_t : the fraction of the population that has experienced a loss in the interval $[t-1, t]$. Parameters α_{ct} and α_{ot} increase with π_t whereas δ_{ct} et δ_{ot} decrease with π_t.
- L : the expected loss without protection. In case of protection, the expected loss is γL with $\gamma \in [0, 1[$. Adoption parameters (α_{ct} and α_{ot}) increase with L whereas the discontinuation parameters (δ_{ct} et δ_{ot}) decrease with L.
- p : the cost of protection. Adoption (respectively discontinuation) coefficients decrease (increase) with p.

We seek to model individual behaviours that would be consistent with this aggregate dynamic equation.

2.2 Fundamentals of the micro-economic model

Agents' preferences give a role to the context, depending on whether they have experienced a loss after a natural disaster, depending on the interactions with other people who have (or not) implemented adaptation measures and who have (or not) experienced a loss, and depending on whether they have previously adopted a protection measure (anchoring effect). This means that, at each date, agents can belong to four stylized categories:

1. category πP: agents who have experienced a loss (π) and have previously adopted a protection measure (P); there is a number (measure) $\pi_t A_t$ of such agents.
2. Category $\bar{\pi} P$: agents who have not experienced a loss ($\bar{\pi}$) and have previously adopted a protection measure (P); there is a measure $(1-\pi_t) A_t$ of such agents.
3. Category $\pi \bar{P}$: agents who have experienced a loss (π) and have not previously adopted a protection measure ($\bar{P}$); there is a measure $\pi_t (1 - A_t)$ of such agents.
4. Category $\bar{\pi}\bar{P}$: agents who have neither experienced a loss ($\bar{\pi}$) nor previously adopted a protection measure ($\bar{P}$); there is a measure $(1-\pi_t)(1-A_t)$ of such agents.

At each date t, each such category $j = \pi P, \bar{\pi} P, \pi \bar{P}, \bar{\pi}\bar{P}$ is a set with a continuum of agents, $S_t^j = \left[0, s_t^j\right]$ where the upper bound s_t^j evolves over time, more precisely:

$$S_t^{\pi P} = [0, \pi_t A_t] \ , \quad S_t^{\bar{\pi} P} = [0, (1-\pi_t) A_t] \ , \quad S_t^{\pi \bar{P}} = [0, \pi_t (1-A_t)] \ , \quad S_t^{\bar{\pi}\bar{P}} = [0, (1-\pi_t)(1-A_t)] \ .$$

Each agent i in category j can make only one decision P_{t+1}, to protect himself $P_{t+1} = 1$, or not $P_{t+1} = 0$, and is characterized by a parameter $\epsilon_{it}^j \in S_t^j$. This parameter reveals the way the agent chooses between the cost and benefits generated by a change in their adaptation status.

If the agent is not adapted at t, the factors which influence him to adopt an adaptation behaviour are the expected loss avoided (ΔL) thanks to the behaviour and the social interactions (A) whereas the factor which fosters the status quo is the adaptation cost (C). On the other hand, if the agent is adapted at t, the factors which incite him to discontinue his adaptation behaviour are the avoided cost (AC) generated by this decision and the social interactions and the factor which encourages him to pursue his behaviour is the cost of non adaptation, that is to say the additional expected loss ($L(1-\gamma)$). The agent's preferences are represented by utility functions:

- if $j = \pi\bar{P}$ or $j = \bar{\pi}\bar{P}$

$$U_i^j(P_{t+1}) = V^j(P_{t+1}; A_t, \pi_t, L(P_{t+1}), \Delta L(P_{t+1})) - \frac{\epsilon_{it}^j}{s_t^j} * C\left(P_{t+1}\right) \ ,$$

- if $j = \pi P$ or $j = \bar{\pi} P$

$$U_i^j(P_{t+1}) = V^j(P_{t+1}; A_t, \pi_t, L(P_{t+1}), C(P_{t+1}), AC(P_{t+1})) - \frac{\epsilon_{it}^j}{s_t^j} * (L(1-\gamma) - \Delta L\left(P_{t+1}\right)) \ ,$$

where $L(1) = \gamma L, L(0) = L,\ \Delta L(0) = 0, \Delta L(1) = L(1-\gamma),\ C\left(1\right) = p, C\left(0\right) = 0,\ AC(1) = 0, AC(0) = p$.

Agent i in category $\pi\bar{P}$ or $\bar{\pi}\bar{P}$ makes a protection decision if:

$$\begin{aligned} & V^j(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - \frac{\epsilon_{it}^j}{s_t^j} * p \geq V^j(0; A_t, \pi_t, L, 0) \\ & \Leftrightarrow \epsilon_{it}^j \leq s_t^j * \frac{V^j(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^j(0; A_t, \pi_t, L, 0)}{p} \end{aligned} \quad (2)$$

Agent i in category πP or $\bar{\pi} P$ makes a protection decision if:

$$V^j(1; A_t, \pi_t, \gamma L, p, 0) \geq V^j(0; A_t, \pi_t, L) - \frac{\epsilon_{it}^j}{s_t^j} * L(1-\gamma)$$

$$\Leftrightarrow \epsilon_{it}^j \geq s_t^j * \frac{V^j(0; A_t, \pi_t, L, 0, p) - V^j(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)} \quad (3)$$

2.3 Aggregation

Assume that, for each category j, ϵ_{it}^j is uniformly distributed in S_t^j. In other words the *probability density function, f,* for $\epsilon_{it}^j \in S_t^j$ is:

$$f(x) = \begin{cases} \frac{1}{s_t^j} & \text{for } x \in \left[0, s_t^j\right] \\ 0 & \text{otherwise,} \end{cases},$$

and the *cumulative distribution function* is:

$$\Pr\left(\epsilon_{it}^j \leq x\right) = \begin{cases} \int_0^x \frac{d\epsilon_{it}^j}{s_t^j} = \frac{x}{s_t^j} & \text{for } x \in \left[0, s_t^j\right[\\ 1 & \text{for } x \geq s_t^j. \end{cases},$$

From (2), in categories $j = \pi\bar{P}$ and $j = \bar{\pi}\bar{P}$ there is a mass:

$$\begin{aligned} m_t^j &= \Pr\left(\epsilon_{it}^j \leq s_t^j * \frac{V^j(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^j(0; A_t, \pi_t, L, 0)}{p}\right) \\ &= \frac{V^j(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^j(0; A_t, \pi_t, L, 0)}{p} \end{aligned}$$

of agents who protect themselves if $0 \leq s_t^j * \frac{V^j(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^j(0; A_t, \pi_t, L, 0)}{p} < s_t^j$. And there is a measure:

$$\begin{aligned} \overline{m}_t^j &= 1 - m_t^j \\ &= 1 - \frac{V^j(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^j(0; A_t, \pi_t, L, 0)}{p} \end{aligned}$$

of agents who do not protect themselves.

Similarly, from (3), in categories $j = \pi P$ and $j = \bar{\pi} P$, there is a mass:

$$\begin{aligned} m_t^j &= \Pr\left(\epsilon_{it}^j \geq s_t^j * \frac{V^j(0; A_t, \pi_t, L, 0, p) - V^j(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)}\right) \\ &= 1 - \frac{V^j(0; A_t, \pi_t, L, 0, p) - V^j(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)} \end{aligned}$$

of agents who pursue the adaptation behaviour if $0 \leq s_t^j * \frac{V^j(0; A_t, \pi_t, L, 0, p) - V^j(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)} < s_t^j$. And there is a measure:

$$\begin{aligned} \overline{m}_t^j &= 1 - m_t^j \\ &= \frac{V^j(0; A_t, \pi_t, L, 0, p) - V^j(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)} \end{aligned}$$

of agents who do not protect themselves.

The probability of adoption in the whole population accounts for:

1. the conditional probability of adoption among those who have experienced a loss and were not protected multiplied by the probability of an agent of belonging to this group: $Prob(P_{t+1} = 1|\pi\bar{P}) * Prob(\pi\bar{P}) = m_t^{\pi\bar{P}} * \pi_t * (1 - A_t) = m_t^{\pi\bar{P}} * s_t^{\pi\bar{P}}$,

2. the conditional probability of adoption among those who have not experienced a loss and were not protected multiplied by the probability of an agent of belonging to this group: $Prob(P_{t+1} = 1|\bar{\pi}\bar{P}) * Prob(\bar{\pi}\bar{P}) = m_t^{\bar{\pi}\bar{P}} * (1 - \pi_t) * (1 - A_t) = m_t^{\bar{\pi}\bar{P}} * s_t^{\bar{\pi}\bar{P}}$,

3. the conditional probability of adoption among those who have experienced a loss and who were protected multiplied by the probability of an agent of belonging to this group: $Prob(P_{t+1} = 1|\pi P) * Prob(\pi P) = m_t^{\pi P} * \pi_t * A_t = m_t^{\pi P} * s_t^{\pi P}$,

4. the conditional probability of adoption among those who have not experienced a loss and who were protected multiplied by the probability of an agent of belonging to this group: $Prob(P_{t+1} = 1|\bar{\pi}P) * Prob(\bar{\pi}P) = m_t^{\bar{\pi}P} * (1 - \pi_t) * A_t = m_t^{\bar{\pi}P} * s_t^{\bar{\pi}P}$,

The total mass of agents who adopt a protection for the next period is therefore:

$$\begin{aligned}
A_{t+1} &= Prob\left(P_{t+1} = 1\right) \\
&= Prob\left(P_{t+1} = 1|\pi\bar{P}\right) * Prob(\pi\bar{P}) + Prob\left(P_{t+1} = 1|\bar{\pi}\bar{P}\right) * Prob(\bar{\pi}\bar{P}) \\
&\quad + Prob\left(P_{t+1} = 1|\pi P\right) * Prob(\pi P) + Prob\left(P_{t+1} = 1|\bar{\pi}P\right) * Prob(\bar{\pi}P) \\
&= m_t^{\pi\bar{P}} * \pi_t * (1 - A_t) + m_t^{\bar{\pi}\bar{P}} * (1 - \pi_t) * (1 - A_t) \\
&\quad + m_t^{\pi P} * \pi_t * A_t + m_t^{\bar{\pi}P} * (1 - \pi_t) * A_t \ .
\end{aligned}$$

The last line of the above expression can be rewritten:

$$\begin{aligned}
& A_{t+1} - A_t = \\
& s_t^{\pi\bar{P}} * \frac{V^{\pi\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^{\pi\bar{P}}(0; A_t, \pi_t, L, 0)}{p} + \\
& s_t^{\bar{\pi}\bar{P}} * \frac{V^{\bar{\pi}\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma)) - V^{\bar{\pi}\bar{P}}(0; A_t, \pi_t, L, 0)}{p} + \qquad (4) \\
& s_t^{\pi P} * \left(1 - \frac{V^{\pi P}(0; A_t, \pi_t, L, 0, p) - V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)}\right) + \\
& s_t^{\bar{\pi}P} * \left(1 - \frac{V^{\bar{\pi}P}(0; A_t, \pi_t, L, 0, p) - V^{\bar{\pi}P}(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)}\right) \\
& -A_t \qquad (5)
\end{aligned}$$

2.4 Specification of the micro-economic functions

It remains to clarify the relationship between this expression and that of Kunreuther et al:

$$\begin{aligned}
A_{t+1} - A_t &= \alpha_{ct} A_t (1 - A_t) + \alpha_{ot} (1 - A_t) \qquad (6) \\
&\quad -\delta_{ct} A_t (1 - A_t) - \delta_{ot} A_t \\
&= \left(\alpha_{ct} - \alpha_{ot}\right) A_t - \alpha_{ct} A_t A_t + \alpha_{ot} \qquad (7) \\
&\quad + \left(1 - \delta_{ct} - \delta_{ot}\right) A_t + \delta_{ct} A_t A_t - A_t. \qquad (8)
\end{aligned}$$

In Kunreuther et al, the expression:

$$\alpha_{ct}A_t(1-A_t)+\alpha_{ot}(1-A_t)=(\alpha_{ct}-\alpha_{ot})\,A_t\;\;-\alpha_{ct}A_tA_t+\alpha_{ot}$$

captures the behaviours of non-adopters who switch to adoption. Therefore it is supposed to correspond to categories $\pi\bar{P}$ and $\bar{\pi}\bar{P}$, *i.e.*:

$$\begin{aligned}
& (1-A_t)\pi_t * \frac{V^{\pi\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))-V^{\pi\bar{P}}(0;A_t,\pi_t,L,0)}{p}+\\
& (1-A_t)(1-\pi_t) * \frac{V^{\bar{\pi}\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))-V^{\bar{\pi}\bar{P}}(0;A_t,\pi_t,L,0)}{p}\\
= \;& (\alpha_{ct}-\alpha_{ot})\,A_t\;\;-\alpha_{ct}A_tA_t+\alpha_{ot},
\end{aligned}$$

A possible identification runs as follows. It decomposes the above identity into two blocks, one with positive terms and the other with negative terms:

$$\begin{aligned}
\pi_t * \frac{V^{\pi\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))}{p}+(1-\pi_t) * \frac{V^{\bar{\pi}\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))}{p} &= \frac{\alpha_{ot}+\alpha_{ct} * A_t}{(1-A_t)}\;,\\
\pi_t * \frac{V^{\pi\bar{P}}(0;A_t,\pi_t,L,0)}{p}+(1-\pi_t) * \frac{V^{\bar{\pi}\bar{P}}(0;A_t,\pi_t,L,0)}{p} &= \frac{\alpha_{ot} * A_t+\alpha_{ct} * A_t * A_t}{(1-A_t)}\;.
\end{aligned}$$

Regarding the first line, a possibility is:

$$V^{\pi\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))=\frac{\alpha_{ot} * p}{\pi_t(1-A_t)}\;,\;V^{\bar{\pi}\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))=\frac{\alpha_{ct} * p * A_t}{(1-\pi_t)(1-A_t)}\;.$$

And, for the second line:

$$V^{\pi\bar{P}}(0;A_t,\pi_t,L,0)=\frac{\alpha_{ot} * p * A_t}{\pi_t(1-A_t)}\;,\;V^{\bar{\pi}\bar{P}}(0;A_t,\pi_t,L,0)=\frac{\alpha_{ct} * p * (A_t)^2}{(1-\pi_t)(1-A_t)}\;.$$

Notice that:

$$V^{\pi\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))\geq V^{\pi\bar{P}}(0;A_t,\pi_t,L,0)\text{ and }V^{\bar{\pi}\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))\geq V^{\bar{\pi}\bar{P}}(0;A_t,\pi_t,L,0) \tag{9}$$

So that the conditions:

$$\begin{aligned}
s_t^{\pi\bar{P}} * \frac{V^{\pi\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))-V^{\pi\bar{P}}(0;A_t,\pi_t,L,0)}{p} &\geq 0\text{ and}\\
s_t^{\bar{\pi}\bar{P}} * \frac{V^{\bar{\pi}\bar{P}}(1;A_t,\pi_t,\gamma L,L(1-\gamma))-V^{\bar{\pi}\bar{P}}(0;A_t,\pi_t,L,0)}{p} &\geq 0
\end{aligned}$$

are respected.

Regarding the behaviour of the adopters who stop protection, we must have:

$$\begin{aligned}
& A_t\pi_t\left(1-\frac{V^{\pi P}(0;A_t,\pi_t,L,0,p)-V^{\pi P}(1;A_t,\pi_t,\gamma L,p,0)}{L(1-\gamma)}\right)+\\
& A_t(1-\pi_t)\left(1-\frac{V^{\bar{\pi}P}(0;A_t,\pi_t,L,0,p)-V^{\bar{\pi}P}(1;A_t,\pi_t,\gamma L,p,0)}{L(1-\gamma)}\right)\\
= \;& (1-\delta_{ct}-\delta_{ot})\,A_t+\delta_{ct} * A_t * A_t
\end{aligned}$$

Identification of positive terms yields:

$$\pi_t \frac{V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)} + (1-\pi_t)\frac{V^{\bar{\pi} P}(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma)} = 1 + \delta_{ct} * A_t - \frac{1}{L(1-\gamma)}$$

which is consistent, for instance, with:

$$\begin{aligned} V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0) &= \frac{1}{2} * \left(\frac{L(1-\gamma)}{\pi_t} * (1 + \delta_{ct} * A_t) - \frac{1}{\pi_t} \right) , \\ V^{\bar{\pi} P}(1; A_t, \pi_t, \gamma L, p, 0) &= \frac{1}{2} * \left(\frac{L(1-\gamma)}{1-\pi_t} * (1 + \delta_{ct} * A_t) - \frac{1}{1-\pi_t} \right) , \end{aligned}$$

Identification of negative terms yields:

$$\pi_t \frac{V^{\pi P}(0; A_t, \pi_t, L, 0, p)}{L(1-\gamma)} + (1-\pi_t)\frac{V^{\bar{\pi} P}(0; A_t, \pi_t, L, 0, p)}{L(1-\gamma)} = \delta_{ct} + \delta_{ot}$$

which is consistent, for instance, with:

$$V^{\pi P}(0; A_t, \pi_t, L, 0, p) = \frac{1}{2} * \frac{L(1-\gamma)}{\pi_t} (\delta_{ct} + \delta_{ot}) \ , \ V^{\bar{\pi} P}(0; A_t, \pi_t, L, 0, p) = \frac{1}{2} * \frac{L(1-\gamma)}{1-\pi_t} (\delta_{ct} + \delta_{ot}) \ .$$

To summarize, it is possible to generate Kunreuther's aggregate dynamic equation out of microeconomic decisions when, for instance, utility functions are:

$$\begin{aligned} U_i^{\pi \bar{P}}(P_{t+1}) &= V^{\pi \bar{P}}(P_{t+1}; A_t, \pi_t, L(P_{t+1}), \Delta L(P_{t+1})) - \frac{\epsilon_{it}^{\pi \bar{P}}}{s_t^{\pi \bar{P}}} * C(P_{t+1}) \\ &= \begin{cases} \frac{\alpha_{ot} * p}{\pi_t(1-A_t)} - \frac{\epsilon_{it}^{\pi \bar{P}}}{s_t^{\pi \bar{P}}} * p & \text{if } P_{t+1} = 1 \\ \frac{\alpha_{ot} * p * A_t}{\pi_t(1-A_t)} & \text{if } P_{t+1} = 0 \end{cases} \end{aligned}$$

$$\begin{aligned} U_i^{\bar{\pi} \bar{P}}(P_{t+1}) &= V^{\bar{\pi} \bar{P}}(P_{t+1}; A_t, \pi_t, L(P_{t+1}), \Delta L(P_{t+1})) - \frac{\epsilon_{it}^{\bar{\pi} \bar{P}}}{s_t^{\bar{\pi} \bar{P}}} * C(P_{t+1}) \\ &= \begin{cases} \frac{\alpha_{ct} * p * A_t}{(1-\pi_t)(1-A_t)} - \frac{\epsilon_{it}^{\bar{\pi} \bar{P}}}{s_t^{\bar{\pi} \bar{P}}} * p & \text{if } P_{t+1} = 1 \\ \frac{\alpha_{ct} * p * (A_t)^2}{(1-\pi_t)(1-A_t)} & \text{if } P_{t+1} = 0 \end{cases} \end{aligned}$$

$$\begin{aligned} U_i^{\pi P}(P_{t+1}) &= V^{\pi P}(P_{t+1}; A_t, \pi_t, L(P_{t+1}), C(P_{t+1}), AC(P_{t+1})) - \frac{\epsilon_{it}^{\pi P}}{s_t^{\pi P}} * (L(1-\gamma) - \Delta L(P_{t+1})) \\ &= \begin{cases} \frac{1}{2} * \left(\frac{L(1-\gamma)}{\pi_t} * (1 + \delta_{ct} * A_t) - \frac{1}{\pi_t} \right) & \text{if } P_{t+1} = 1 \\ \frac{1}{2} * \frac{L(1-\gamma)}{\pi_t} * (\delta_{ct} + \delta_{ot}) - \frac{\epsilon_{it}^{\pi P}}{s_t^{\pi P}} * L(1-\gamma) & \text{if } P_{t+1} = 0 \end{cases} \end{aligned}$$

$$\begin{aligned} U_i^{\bar{\pi} P}(P_{t+1}) &= V^{\bar{\pi} P}(P_{t+1}; A_t, \pi_t, L(P_{t+1}), C(P_{t+1}), AC(P_{t+1})) - \frac{\epsilon_{it}^{\bar{\pi} P}}{s_t^{\bar{\pi} P}} * (L(1-\gamma) - \Delta L(P_{t+1})) \\ &= \begin{cases} \frac{1}{2} * \left(\frac{L(1-\gamma)}{1-\pi_t} * (1 + \delta_{ct} * A_t) - \frac{1}{1-\pi_t} \right) & \text{if } P_{t+1} = 1 \\ \frac{1}{2} * \frac{L(1-\gamma)}{1-\pi_t} * (\delta_{ct} + \delta_{ot}) - \frac{\epsilon_{it}^{\bar{\pi} P}}{s_t^{\bar{\pi} P}} * L(1-\gamma) & \text{if } P_{t+1} = 0 \end{cases} \end{aligned}$$

2.5 Verification of the hypotheses on the coefficients

The other way around, it is possible to elicit some microfoundations for Kunreuther's coefficients:

$$\begin{aligned}
\alpha_{ct} &= V^{\bar{\pi}\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma)) * \frac{(1-\pi_t)(1-A_t)}{p * A_t} = V^{\bar{\pi}\bar{P}}(0; A_t, \pi_t, L, 0) * \frac{(1-\pi_t)(1-A_t)}{p * (A_t)^2} \ , \\
\alpha_{ot} &= V^{\pi\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma)) * \frac{\pi_t(1-A_t)}{p} = V^{\pi\bar{P}}(0; A_t, \pi_t, L, 0) * \frac{\pi_t(1-A_t)}{p * A_t} \ , \\
\delta_{ct} &= \frac{V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0) * 2\pi_t + 1}{L(1-\gamma) * A_t} - \frac{1}{A_t} = \frac{V^{\bar{\pi}P}(1; A_t, \pi_t, \gamma L, p, 0) * 2(1-\pi_t) + 1}{L(1-\gamma) * A_t} - \frac{1}{A_t}, \\
\delta_{ot} &= \frac{V^{\pi P}(0; A_t, \pi_t, L, 0, p) * 2\pi_t}{L(1-\gamma)} - \delta_{ct} = \frac{V^{\bar{\pi}P}(0; A_t, \pi_t, L, 0, p) * 2(1-\pi_t)}{L(1-\gamma)} - \delta_{ct}.
\end{aligned}$$

Therefore, the assumptions made on coefficients in Kunreuther implie the following structure at our micro level:

$$\frac{\partial \alpha_{ct}}{\partial L} > 0 \implies \frac{\partial V^{\bar{\pi}\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma))}{\partial L} > 0 \text{ and } \frac{\partial V^{\bar{\pi}\bar{P}}(0; A_t, \pi_t, L, 0)}{\partial L} > 0 \ , \quad (10)$$

According to this assumption, $V^{\bar{\pi}\bar{P}}$ increases with L.

$$\frac{\partial \alpha_{ct}}{\partial p} < 0 \text{ is necessarily true within our micro economic model.} \quad (11)$$

$$\begin{aligned}
\frac{\partial \alpha_{ct}}{\partial \pi_t} &> 0 \iff \\
\frac{\partial V^{\bar{\pi}\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma))}{\partial \pi_t} * \frac{(1-\pi_t)(1-A_t)}{p * A_t} &- V^{\bar{\pi}\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma)) \frac{(1-A_t)}{p * A_t} > 0 \text{ and} \\
\frac{\partial V^{\bar{\pi}\bar{P}}(0; A_t, \pi_t, L, 0)}{\partial \pi_t} * \frac{(1-\pi_t)(1-A_t)}{p * (A_t)^2} &- V^{\bar{\pi}\bar{P}}(0; A_t, \pi_t, L, 0) * \frac{(1-A_t)}{p * (A_t)^2} > 0 \ , \quad (12)
\end{aligned}$$

These conditions are possible given our micro foundations.

$$\frac{\partial \alpha_{ot}}{\partial L} > 0 \implies \frac{\partial V^{\pi\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma))}{\partial L} > 0 \text{ and } \frac{\partial V^{\pi\bar{P}}(0; A_t, \pi_t, L, 0)}{\partial L} > 0 \ , \quad (13)$$

According to this assumption, $V^{\pi\bar{P}}$ increases with L.

$$\frac{\partial \alpha_{ot}}{\partial p} < 0 \text{ is necessarily true within our micro economic level,} \quad (14)$$

$$\begin{aligned}
\frac{\partial \alpha_{ot}}{\partial \pi_t} &> 0 \iff \\
\frac{\partial V^{\pi\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma))}{\partial \pi_t} * \frac{\pi_t(1-A_t)}{p} &+ V^{\pi\bar{P}}(1; A_t, \pi_t, \gamma L, L(1-\gamma)) * \frac{(1-A_t)}{p} > 0 \text{ and} \\
\frac{\partial V^{\pi\bar{P}}(0; A_t, \pi_t, L, 0)}{\partial \pi_t} * \frac{\pi_t(1-A_t)}{p * A_t} &+ V^{\pi\bar{P}}(0; A_t, \pi_t, L, 0) * \frac{(1-A_t)}{p * A_t} > 0 \ , \quad (15)
\end{aligned}$$

These conditions are possible given our micro foundations.

$$\frac{\partial \delta_{ct}}{\partial p} > 0 \Longrightarrow \frac{\partial V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0)}{\partial p} > 0 \text{ and } \frac{\partial V^{\bar{\pi} P}(1; A_t, \pi_t, \gamma L, p, 0)}{\partial p} > 0 \quad (16)$$

According to this assumption, the utility generated by the protection decision must increase with its cost for the agents who were previously adapted and who have experienced a loss.

$$\begin{aligned} \frac{\partial \delta_{ct}}{\partial L} &< 0 \\ \Longleftrightarrow \frac{2\pi_t}{L(1-\gamma) * A_t} &- (1-\gamma)A_t * \frac{V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0) * 2\pi_t + 1}{(L(1-\gamma)A_t)^2} < 0 \\ \text{and } \frac{2(1-\pi_t)}{L(1-\gamma) * A_t} &- (1-\gamma)A_t * \frac{V^{\bar{\pi} P}(1; A_t, \pi_t, \gamma L, p, 0) * 2(1-\pi_t) + 1}{(L(1-\gamma)A_t)^2} < 0 \quad (17) \end{aligned}$$

These conditions are possible given our micro foundations.

$$\begin{aligned} \frac{\partial \delta_{ct}}{\partial \pi_t} &< 0 \\ \Longleftrightarrow \frac{2\pi_t}{L(1-\gamma) * A_t} * \frac{\partial V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0)}{\partial \pi_t} &+ \frac{2 * V^{\pi P}(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma) * A_t} < 0 \\ \text{and } \frac{2(1-\pi_t)}{L(1-\gamma) * A_t} * \frac{\partial V^{\bar{\pi} P}(1; A_t, \pi_t, \gamma, p, 0)}{\partial \pi_t} &- \frac{2 * V^{\bar{\pi} P}(1; A_t, \pi_t, \gamma L, p, 0)}{L(1-\gamma) * A_t} < 0 \quad (18) \end{aligned}$$

These conditions are possible given our micro foundations.

$$\begin{aligned} \frac{\partial \delta_{ot}}{\partial p} &> 0 \\ \Longleftrightarrow \frac{2\pi_t}{L(1-\gamma)} * \frac{\partial V^{\pi P}(0, A_t, \pi_t, L, 0, p)}{\partial p} &- \frac{\partial \delta_{ct}}{\partial p} > 0 \text{ and} \\ \frac{2(1-\pi_t)}{L(1-\gamma)} * \frac{\partial V^{\bar{\pi} P}(0, A_t, \pi_t, L, 0, p)}{\partial p} &- \frac{\partial \delta_{ct}}{\partial p} > 0 \quad (19) \end{aligned}$$

These conditions are possible given our micro foundations.

$$\begin{aligned} \frac{\partial \delta_{ot}}{\partial L} &< 0 \\ \Longleftrightarrow \frac{2\pi_t}{L(1-\gamma)} * \frac{\partial V^{\pi P}(0; A_t, \pi_t, L, 0)}{\partial L} &- (1-\gamma) * \frac{V^{\pi P}(0; A_t, \pi_t, L, 0) * 2\pi_t}{(L(1-\gamma))^2} < 0 \text{ and} \\ \frac{2(1-\pi_t)}{L(1-\gamma)} * \frac{\partial V^{\bar{\pi} P}(0; A_t, \pi_t, L, 0)}{\partial L} &- (1-\gamma) * \frac{V^{\bar{\pi} P}(0; A_t, \pi_t, L, 0) * 2(1-\pi_t)}{(L(1-\gamma))^2} < 0 \quad (20) \end{aligned}$$

These conditions are possible given our micro foundations.

$$
\begin{aligned}
\frac{\partial \delta_{ot}}{\partial \pi_t} &> 0 \\
\iff \frac{2\pi_t}{L(1-\gamma)} * \frac{\partial V^{\pi P}(0; A_t, \pi_t, L, 0, p)}{\partial \pi_t} &+ \frac{2}{L(1-\gamma)} * V^{\pi P}(0; A_t, \pi_t, L, 0, p) - \frac{\partial \delta_{ct}}{\partial \pi_t} > 0 \text{ and} \\
\frac{2(1-\pi_t)}{L(1-\gamma)} * \frac{\partial V^{\bar{\pi} P}(0; A_t, \pi_t, L, 0, p)}{\partial \pi_t} &- \frac{2}{L(1-\gamma)} * V^{\bar{\pi} P}(0; A_t, \pi_t, L, 0, p) - \frac{\partial \delta_{ct}}{\partial \pi_t} > 0 \quad (21)
\end{aligned}
$$

These conditions are possible given our micro foundations.

3 Discussion

Economics can be defined as "a science of thinking in terms of models joined to the art of choosing models which are relevant to the contemporary world" [5]. Thus, we must specify the contexts which could be compatible with our model and the behaviours that we should observe in these contexts if the model properly describes the individual adaptation mechanisms.

3.1 Situations compatible with the micro economic model

First, since our model aims to explain individual adaptation behaviours within a specific population, the community considered must be exposed to a risk against which it is individually possible to implement mitigation measures. This excludes risks that are individually non-controllable, such as nuclear risks for example.

Moreover, the micro foundations propose that individual behaviours at $t+1$ are influenced by A_t, which is the proportion of adapted people within the considered population, and by π_t, which is the proportion of the population that has been impacted by the risk at time t. This implies that every agent is more or less able to picture himself in a situation where he is exposed to the same risk as those who are adapted and those who have already experienced the risk. Thus, the risk considered must be rather homogeneous among the population. In other words, L must not vary greatly from one agent to another. As a result, the model can not be used to understand adaptation behaviours to very specific risks, such as health risks increased by rare genetic conditions, or highly localized risks. Instead, our model is more compatible with diffuse risks, such as risks of flooding.

Furthermore, because individual adaptation decisions are influenced by A_t and π_t in our model, all adapted members of the population are supposed to have the same impact on an agent's decision and all people who have experienced the risk at t influence the agent's decision in the same way. Thus, the considered population should consist of people who are influenced more by collective tendencies than individual and specific behaviours. This suggests that there must not be big divides among the population.

Then, since people can abandon the adaptation behaviour explained by the model, this latter must be reversible.

Finally, our model is designed to study individual decisions regarding reversible adaptation behaviours aimed to mitigate a diffuse risk. This risk must be rather homogeneous among a population with a good social cohesion.

3.2 Behavioural implications of Kunreuther's hypotheses on the individual level

In the type of situations presented above, the tendencies in terms of individual behaviours deduced from the hypotheses on the aggregate model in section 2.5 should be observed if our model describes the adaptation mechanisms properly. In particular, the results of (10), (13), and (16) can be directly translated into behaviours which must be observed to validate our model.

In (10) and (13), we found that the benefits of adaptation and non adaptation at time $t+1$ increase with the expected loss for agents who were not adapted at time t. An interpretation of this result could be that, both for adaptation and non adaptation, people are all the more satisfied as they avoid a greater cost: if they adopt an adaptation behaviour, they avoid an all the more important additional expected loss if the expected loss without adaptation is greater (the adaptation efficiency being stable), and if they choose to stay unprotected against the risk, they avoid an all the more important adaptation cost as the expected loss is greater. This latter assumption relies on the hypothesis that the adaptation cost increases with the importance of the risk (the adaptation efficiency being stable).

Then, from (16), we deduced that agents that were adapted at time $t+1$ benefit all the more from adaptation as the adaptation cost is important. This could be explained by the fact that the price could be considered by the agents as an indicator of the adaptation efficiency. Hence, if the satisfaction provided by the adaptation increases with its efficiency, it could also increase with its cost.

Finally, our micro economic model reveals that the collective behaviour described by Kunreuther et al. [6] can emerge from heterogeneous individual behaviours. Some of them are even contradictory with the collective tendencies, such as those of people non adapted at t who have all the greater benefits as the expected loss is higher and those of agents adapted at t whose benefits from adaptation increase with its price.

The behavioural assumptions directly deduced from our model seem unintuitive and to differ from common observations. Indeed, the expected loss has generally a negative impact on people's satisfaction since it is positively correlated with the feeling of fear and the adaptation cost is negatively correlated with the propensity to implement an adaptation measure [4], [2]. However, these tendencies are observed without distinguishing between groups of people with different previous adaptation status and risk experience, whereas in the micro foundations presented in this work the utility functions differ according to these two characteristics. Moreover, our model does not allow to conclude regarding the importance of the positive effects of expected loss and adaptation cost on the satisfaction of people who adopt an adaptation measure compared to their effects on the utility of agents who prefer to be non adapted against the risk. For example, if the impact of expected loss on the benefits of adaptation is greater than its effect on the utility of non adaptation, the adaptation rate within the group of people who were not adapted at t will increase with the expected loss, as hypothesized by Kunreuther and as observed in many empirical surveys [2]. Similarly, if the adaptation cost has a greater positive effect on the utility of non adaptation than on the utility of adaptation, the adaptation rate will decrease with the cost.

For these reasons, we can not directly compare the implications of our model with results from existing empirical studies on adaptation to risks in order to assess its realism. Thus, it would be interesting to design an empirical survey in order to collect data with which the model could be confronted. Such a survey could also indicate the effect of A_t on the utility functions whereas our model does not provide this information in the version described in this article.

4 Conclusion

The micro foundations we propose for Kunreuther's aggregate model reveal that the evolution of the adaptation rate within a population can be explained by unintuitive individual behaviours. Especially, the utility of people who were not previously adapted can increase with the expected loss and the utility of adaptation for agents who were previously adapted can increase with the adaptation cost.

However, even if these implications are mathematically consistent, they rely on several assumptions. First, given the factors' definition, our model can only explain the adoption of reversible adaptation behaviours within a population with a good social cohesion and whose members are all more or less exposed to the same diffuse risk. Then, we assumed that an agent's adaptation decision results from the comparison of the utility provided by the adaptation with the utility provided by the non adaptation. We also relied on two main hypotheses regarding the utility functions. First, we specified that the utility of an agent depends on the way he compromises on the costs and benefits of a change in his adaptation status. Then, we hypothesized that the parameter which describes this way of compromising is uniformly distributed within each group ($\bar{\pi}\bar{P}$, $\pi\bar{P}$, $\bar{\pi}P$, πP). This assumption suggests that there is no tendency within each group regarding the preferences of the agents as for the compromise between the costs and the benefits.

Thus, we must confront our model to empirical data in order to assess the realism of its hypotheses and implications. Depending on the results, we may have to modify the micro economic model.

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