EPIDEMIC CONTROL THROUGH INCENTIVES, LOCKDOWN, AND TESTING

The government's perspective

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OUTLINE

INTRODUCTION

Impact of the epidemic. Cost for the society:

- cost of care related to the disease;
- indirect costs related to the saturation of the hospital system;
- but also a cost for the individual, not necessarily monetary, linked to the infection (QALY/DALY).

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Lockdown and social distancing. While waiting for:

- an effective treatment against the disease induced by the virus;
- a vaccination campaign...

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Impact of social distancing. These restrictions have a cost for individuals: social and economic, but also in terms of (mental) health (no in-person conferences at La Grande Motte).

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- **Societal Optimum.** Recent literature focuses on the search for a societal optimum – Viewpoint of a global planner. Bonnans and Gianatti [2] (2020), Charpentier et al. [3] (2020), Djidjou-Demasse et al. [4] (2020)...

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- Without guidelines? **Individual point of view**, with R. Elie and G. Turinici.

- Modeling individual choices towards the epidemic spread, and look for a Nash – Mean-field equilibrium among the population.

Epidemic control via social distancing: political or individual choice?

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- Without guidelines? **Individual point of view**, with R. Elie and G. Turinici.
- Modeling individual choices towards the epidemic spread, and look for a Nash – Mean-field equilibrium among the population.

- Cost of anarchy: Nash equilibrium different from societal optimum...

How can we make the interests of the population converge towards the interests of the society?

- **Governmental point of view and incentives**, with T. Mastrolia, D. Possamaï and X. Warin.

Noteworthy papers (in continuous-time): Holmström and Milgrom [5] (1987), Sannikov [6] (2008).

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The Agent (he) accepts or not the contract proposed by the Principal.

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Asymmetry of information.

Moral Hazard: the Agent's behaviour is not observable by the Principal.

Output process: Stochastic process X with dynamic, for $t \in [0, T]$:

$$dX_t = \alpha_t dt + \sigma_t dW_t.$$

Effort: given a contract ξ, the Agent controls X through the drift α, in order to maximise the following criteria:

$$\mathbb{E}^{\mathbb{P}^\alpha}\left[U_A(\xi) - \int_0^T c(\alpha_t) dt\right].$$

Moral Hazard: the Principal only observes X in continuous-time.

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- The optimal form of contracts for the Agent satisfies (see [5, 6]):

$$U_A(\xi) = Y_0 - \int_0^T \mathcal{H}(Z_s)ds + \int_0^T Z_s dX_s, \tag{1}$$

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where

(i) $Y_0 \in \mathbb{R}$ is chosen by the principal to ensure participation of the agent;
(ii) Z is chosen by the Principal to encourage effort from the agent;
(iii) $\mathcal{H}$ is the Agent's Hamiltonian.

THE MODEL: SIR AND PRINCIPAL-AGENT

- SIR compartment model: during the epidemic, individuals go from “Susceptible” to “Infected” and then “Recovered”.

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- Dynamic of a stochastic SIR model:

$$\begin{cases} dS_t = -\beta_t \sqrt{\alpha_t} S_t I_t dt + \sigma \alpha_t S_t I_t dW_t, \\ dI_t = (\beta_t \sqrt{\alpha_t} S_t - \gamma) I_t dt - \sigma \alpha_t S_t I_t dW_t, \\ dR_t = \gamma I_t dt, \end{cases} \quad \text{for } t \in [0, T].$$

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Initial distribution (S_0, I_0, R_0) at time $t = 0$ known, s.t. $S_0 + I_0 + R_0 = 1$.

- $S_t + I_t + R_t = 1$ for all $t \geq 0$.

- 3 main parameters to describe the dynamics of the epidemic: γ, β and α.

$$
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dR_t = \gamma I_tdt,
\end{cases}
$$

- Recovery rate γ. Exogenous, constant, assumed known, and given by

$$
\gamma := \frac{1}{\text{duration of the contagious period}}.
$$

- In absence of an effective treatment against the disease induced by the virus, no possibility to control γ.

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PARAMETERS OF THE EPIDEMIC: TRANSMISSION RATE

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  (i) intrinsic characteristics of the disease;
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- The population can make a costly effort to reduce their interactions and thus decrease the effective transmission rate of the virus.

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- We assume that β takes values in $[0, \beta_0]$, where β_0 is the "initial" transmission rate, when the population makes no social distancing effort.
- Limiting case: if individuals are fully isolated, then $\beta = 0$ and the virus does not spread.

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- “Uncertainty rate” α. By increasing testing among the population, the government can:

(i) to reduce the uncertainty related to the spread of the epidemic, i.e. $\sigma\alpha_t$;

(ii) to isolate those who test positive and thus reduce the effective spread rate, i.e. $\beta_t\sqrt{\alpha_t}$.

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- We assume that α takes values in $[0, 1]$:
  - $\alpha = 1$ means no testing policy;
  - limiting case: if all individuals are tested regularly, the spread of the epidemic is precisely known (without randomness), and isolation of positive individuals stop the propagation, i.e. $\alpha \to 0$.

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- The government – the principal – observes $(\mathrm{S}, \mathrm{I}, \mathrm{R})$ (not β) and implements two policies:

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(ii) a tax policy χ to encourage the population to lockdown.

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- **Stackelberg equilibrium.**

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  (i) Given a pair (α, χ) fixed by the government, solve the population's optimisation problem to find the optimal transmission rate $\beta^\star(\alpha, \chi)$.

  (ii) Given the optimal response of the population to any couple (χ, α), solve the government's problem to find the optimal couple $(\chi^\star, \alpha^\star)$.

RESOLUTION

- Given a testing policy α and a tax policy χ, the population's optimal control problem is:

$$V_0^A(\alpha, \chi) := \sup_{\beta \in \mathcal{B}} \mathbb{E}\left[\int_0^T u(t, \beta_t, I_t)dt + U(-\chi) \right], \tag{2}$$

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where $u : [0, T] \times [0, \beta_0] \times \mathbb{R}_+ \longrightarrow \mathbb{R}$ and $U : \mathbb{R} \longrightarrow \mathbb{R}$ are given by:

$$u(t, b, i) := -\frac{1}{2}\left(i^3 + (\beta_0 - b)^2\right) \text{ and } U(x) := \frac{1 - e^{-4x}}{4} + \frac{1}{2}x.$$

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- Interpretations:

(i) the utility is zero when there is no epidemic, i.e. $I = 0$;

(ii) the population is scared by a large number of infected – term i^3 in u;

(iii) an increase in the tax lowers the utility – U increasing function;

(iv) a decrease in the level of interaction (below β_0) lowers the utility – u increasing w.r.t. $b \leq \beta_0$.

- HJB technics and BSDEs theory...

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Main theoretical result. Given an admissible contract (α, χ), there exist a unique Y_0 and Z such that:

$$U(-\chi) = Y_0 - \int_0^T \Big(\gamma Z_t I_t + u(t, \beta_t^\star, I_t) - \beta_t^\star \sqrt{\alpha_t} S_t I_t Z_t \Big) dt - \int_0^T Z_t dI_t, \quad (3)$$

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Optimal effort. For all $t \in [0, T]$, $\beta_t^\star := b^\star(t, S_t, I_t, Z_t, \alpha_t)$ is the maximiser of:

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- Under some assumptions for existence and smoothness of the inverse of the function U, (3) gives a representation for the tax χ.

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  - the optimal form for the tax χ satisfies (3), i.e., the government only has to choose Z and Y_0;
  - the optimal effort of the population is given by $\beta^\star_t := b^\star(t, S_t, I_t, Z_t, \alpha_t)$ for all $t \in [0, T]$, and thus the epidemic spreads with the transmission rate $\beta^\star \sqrt{\alpha}$.
- It remains to solve the government problem to find the optimal Y_0, Z and α.

- The government chooses the parameter Y_0 and Z in the tax χ, as well as α to maximise her utility:

$$V_0^P := \sup_{Y_0, Z, \alpha} \mathbb{E}\left[\chi - \int_0^T \big(c(I_t) + k(\alpha_t)\big)dt\right], \tag{4}$$

where $k(a) := \kappa_g(a^{-\eta_g} - 1)$, and $c(i) := c_g(i + i^2)$.

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- Interpretations:

(i) the utility is zero when there is no epidemic, i.e. $I_0 = 0$;

(ii) an increase in the tax increase the utility;

(iii) the principal pay a linear cost per infected individual, plus a quadratic cost to represent saturation of health care facilities;

(iv) testing is costly – k increases when α decreases.

- In contrast to usual PA problems, the government implements a mandatory tax: the population cannot refuse it.
- Nevertheless, the government is "benevolent": she will choose Y_0 in order to ensure a sufficient level $\underline{v}$ of utility for the agent.
- In particular, $\underline{v}$ is defined by the agent's utility in the event of an uncontrolled epidemic, i.e., $\beta = \beta_0$, $\alpha = 1$, and $\chi = 0$.

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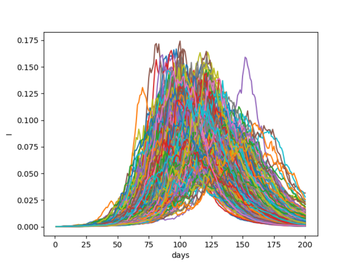
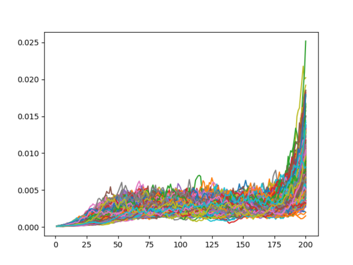
Results.

- Theoretically: PDE obtained through HJB technics.
- Numerically: semi–Lagrangian schemes, with truncated higher–order interpolators, as proposed by Warin [7] (2016).

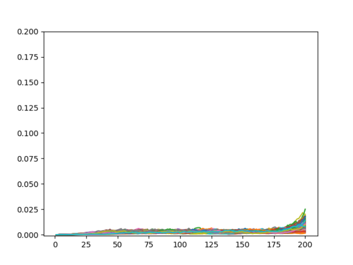
SOME NUMERICAL RESULTS: PROPORTION OF INFECTED INDIVIDUALS



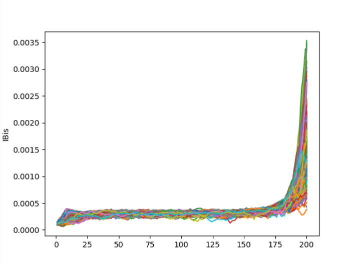
Without governmental intervention



With incentives but without testing



With incentives and testing



Without moral hazard (first–best)

LIMITS AND EXTENSIONS

On the epidemic modelling.

- Uncertainty about the parameters, especially when the epidemic is of a new kind.
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- Individual's costs are hard to measure and calibrate.

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Extensions.

- Model by Aurell et al. [1] (2020) that combines MFG in the population and incentives.
- What about vaccination?

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