

Titre en français : Développement des outils issue la théorie des jeux et control afin de combattre la pandémie de Covid-19.

Titre en anglais: Developing an arsenal of Game theory and Control tools in the fight against Covid-19.

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Context of the PhD

In the fight against the Covid-19 pandemics, three approaches have been considered: (a) Herd Immunity (Herd Immunity occurs when enough people have been infected and then recover, making them immune to being re-infected and infecting others in their community [Who20, CCDC20, John00, Fine93], (b) mitigation, which focuses on slowing but not necessarily stopping epidemic spread reducing peak healthcare demand while protecting those most at risk of severe disease from infection, and (c) suppression, which aims to reverse epidemic growth, reducing case numbers to low levels and maintaining that situation indefinitely. The third approach was successfully used by China [Kupf20]. The challenges in that approach is to combat and prevent future outbreaks of the epidemic as when the epidemics die, the vast majority of the population have not developed herd immunity. Indeed, almost all countries have opted to combat the Covid-19 by imposing unprecedented restrictions on social and professional activities for entire populations. They follow the harsh Chinese methods, which seems at this moment more efficient to kill the virus but without developing any immunity into the population. From several studies, the mortality of the virus will not land evenly across age groups. The main observation of all these studies is the mortality rate increases significantly when the age approaches 60 years. It approaches 25 percent among older populations (70 and up) since the immune system becomes weaker with age and older individuals are more likely to have underlying health concerns. It's very clear that this virus has greater mortality and morbidity in vulnerable populations, who have a higher risk of becoming severely ill from infection diseases.

The outbreak of the Covid-19 pandemics has found a divided world, unprepared for the battle against the virus. In many countries the public health infrastructure has been overwhelmed, and basic equipment - masks, test kits, ventilators and beds in hospitals are lacking. In lack of pharmaceutical measures, epidemiological modeling and prediction allow adapting and assessing the efficiency of non-pharmaceutical measures such as closing schools, bars, restaurants, and social distancing. Each country had its own priorities in selecting between keeping the economy turning and protecting human lives. This is pushing the limits of traditional

public health interventions and research, and requires the development of novel methodologies and approaches to be able to tackle this new complex scenario.

Models for virus propagation have been thoroughly studied since the seminal work of Kermack and McKendrick [Ker27, McK11]. In the last 20 years, new lines of research appeared in computational epidemiology and have unveiled the crucial role of social and professional activities for entire populations in the propagation of epidemics [Pastor15]. As a consequence, in order to manage countermeasures against viruses, significant effort has been devoted to understanding how viruses spread in a population, and how to efficiently design countermeasures able to mitigate such threats [Gro16, Vilc20].

Objectives of the PhD

In this thesis, we aim to develop analytical models for decision makers within public health administration which would allow us to best choose and adapt the health care policies both in preventing the epidemic, in fighting against it, and in moving out of the epidemics. Both game theoretical tools as well as optimal control theory will be used. We shall identify free rider's behavior and suggest incentives for cooperation. We shall assess the impact of the herd immunity on the propagation of Covid-19 by considering different isolation policies to different risk groups. This allows vulnerable populations to be indirectly protected by the rest of the population.

Another aspect of the thesis is vaccinations. While the development of vaccinations are not in the scope of the thesis, estimation of their potential availability or non-availability within some time may influence non-pharmaceutical measures. The goal is to understand the intertwined mechanisms connecting the actual impacts on vaccination policy, the mutation of virus, the immunity of population against the virus and the current public health infrastructure. We aim to provide tools, rooted in complex system and game theory, to both detect and react to these new complex scenarios.

The thesis will include collection of (possibly unreliable) data and use statistical methods for estimation of the pandemics' dynamics in time and space. We are planning to collaborate with other groups during this study to facilitate the collection of this data and potential adoption of results within and outside our group. In particular, we will work closely with several groups : INSERM- CNRS (DR. Nabila Jabrane-Ferrat), Fudan University, Shanghai (Prof. Yuedong Xu) and Federal University of Rio de Janeiro (Prof. Daniel Sadoc Menasche). We aim to combine our knowledge about human behaviour, epidemics, big data and mathematical modelling into building a global system predictive model that can modify how health authorities approach Covid-19 pandemics and future unknown viruses.

Methodology

A key aspect on Covid-19 crisis, is lack of cooperation between governments (or between states) and a lack of common strategy to protect the population against the virus. Hesitation and the failure to tackle the problem collectively will increase the losses – in terms of lives and economy. In such a scenario, game theory is a useful tool to model the competition between the main actors (Countries, Health care insurance, pharmaceutical companies, etc) and characterize the lack of cooperation and its impact on the spread of the virus. In this context, it is important to lay foundations for the application of Cooperative Game theory to study how coordination between agents could change the outcome (Equilibrium) of the game. An important aspect is the process through which groups of actors consolidate into an emergent “agent” in the coalition formation, addressing the following questions: Under which conditions actors will try to coordinate their common resources? What are the conditions that need to be met for the actor to communicate and engage into such bargaining processes? Would the outcome of such an agreement be beneficial for all populations?

In order to describe the coupling of spreading processes of the virus we will devise new mathematical models rooted in optimal control, algorithmic and general game theory. Research on immunization policies including herd immunity, will provide input into novel mathematical models of strategic interaction. In these models we also aim to capture the effect of social and professional activities for entire populations in the propagation of epidemics. We shall study in particular the capacity of the public health infrastructure. In fact, actions of policy makers within public health administrations, will trigger actions impacting the *spread* of Infections and *viruses* and consequent reactions of individuals. In this context the solution concept is that of Stackelberg equilibrium for fighting against Covid 19: for a given budget those will determine the global success or the failure of policies.

Differential equations will be used to formulate and study the mean field limits of the pandemics, extending those describing standard epidemics SIR models. We shall use singular perturbed differential equation models to study different time scales in the propagation of the viruses due to control of the mobility of people and of crowding control. We shall study optimal and equilibrium policies by using the Pontryagin maximum principle and Hamilton-Jacoby-Bellman equations.

Work program of the PhD

- 6 months: Collecting data and annotating them by adding related events in the pandemics, such as confinement decisions, restrictions on gathering etc. Estimating the pandemics dynamics out of this noisy and unreliable data.
- 6 month constructing mathematical models and trying to determine its parameters so as to match best the observed history and predict future evolution.
- 1 year Formulate game models to study the free riding phenomenon, study the utility function of different countries, study the advantage of free riding versus cooperation and propose incentives and threats so as to create cooperation

- 1 year Solve the differential equations, obtain the structure of optimal and of equilibrium policies

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