Mathematical modeling and control of epidemics as decision support systems to steer effective public health policies

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Computational epidemiology has improved significantly through a multidisciplinary approach that combines high-quality data with techniques from statistical physics, nonlinear dynamics, and complex systems. These advancements have allowed policymakers to rely on models and simulations to understand and predict epidemiological trends. The COVID-19 pandemic has emphasized the need for realistic and actionable models to implement real-time intervention policies.

In the growing interest in designing interventions to manage epidemics, a promising multidisciplinary approach that combines epidemiology and control theory is being developed. The current body of literature on the subject is expanding but the scarcity of real-case studies using these techniques poses a significant obstacle to their practical application. Without more comprehensive and diverse examples of the approach, its true potential and limitations remain unclear.

In this thesis, we discuss the design of control strategies for containing epidemics using mathematical models, optimization techniques, scenario analysis, and control theory tools. We focus on different interventions type and aspects of the epidemic's spread by presenting four case studies and demonstrating how various methods can help to evaluate and design control action. We employ Pontryagin's maximum principle to control an infectious disease through individual behavioural changes. Two case studies focus on the design of optimal two-dose COVID-19 vaccination rollouts. The first study uses a nonlinear model predictive control to examine the ideal distribution of first and second doses based on vaccine first-dose protection and immunity duration. The second study uses convex second-order cone optimization techniques to study the impact of uncertainty on vaccine supplies. Finally, the synergy between meta-population models and activity-driven networks is leveraged to model, simulate, and predict the effect of social distancing and travel bans on the spread of the first wave of COVID-19.

Our findings, in addition to providing insight into optimal outbreak control, show the practical use of control approaches in real-world settings, providing a starting point for further research.