ScuDo
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35° Cycle

Modeling and controlling social and networked systems with applications to epidemics

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Research context and motivation

- **Modern epidemiology** has advanced thanks to the integration of epidemiological models with **complex networks** and the availability of **data about human interactions** and movements. These elements have allowed epidemiology to place social interactions and personal behaviour at the centre of disease dynamics.
- **Mathematical and computational models** are the building blocks. They are used to study the non-trivial and emerging behaviour of epidemics, to make forecasts, and are the key to assessing the effect of different of intervention policies.
- The COVID-19 pandemic has accelerated the need for realistic epidemiological models for **informing policy for controlling epidemics.**

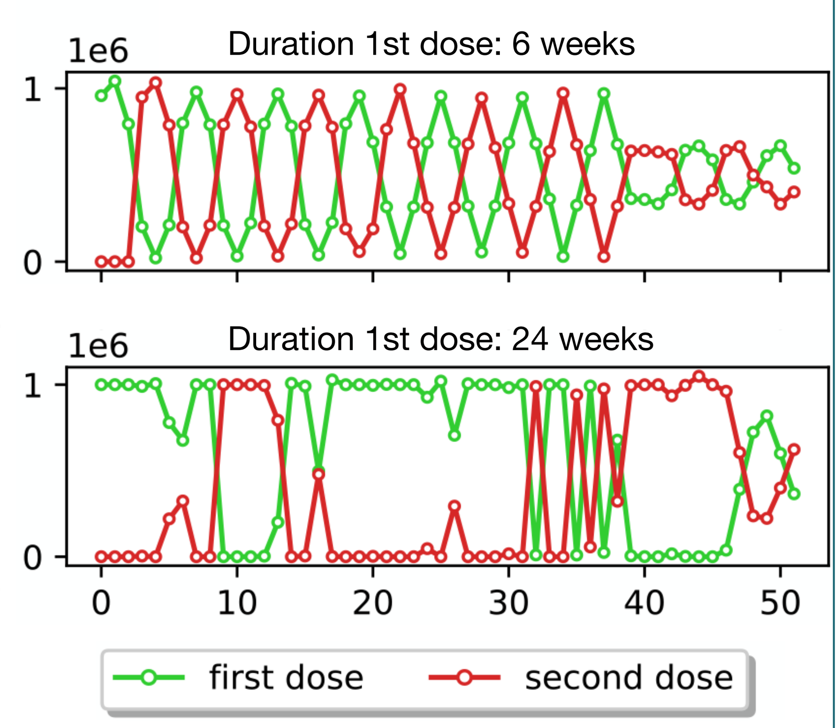
Addressed research questions/problems

- Only recently we are **combining epidemiology with the control theory**, which provides mathematical and practical tools for steering the dynamic of natural and engineered systems.
- We address the research questions regarding the **design of optimal intervention policies** to contain epidemics, analysing different scenarios:
  1. Vaccination rollouts where COVID-19 poses the issue of a **two shots vaccination**.
  2. Non-pharmaceutical interventions focusing on **travel bans** and **stay-home** policies.
  3. Interventions that encourage individuals to adopt **self-protective behaviours**.
- In addressing these research questions, first, we create mathematical models featuring the key elements of each scenario; secondly, we study the intervention policies, making an effort to combine control theory techniques with the models developed.

Novel contributions

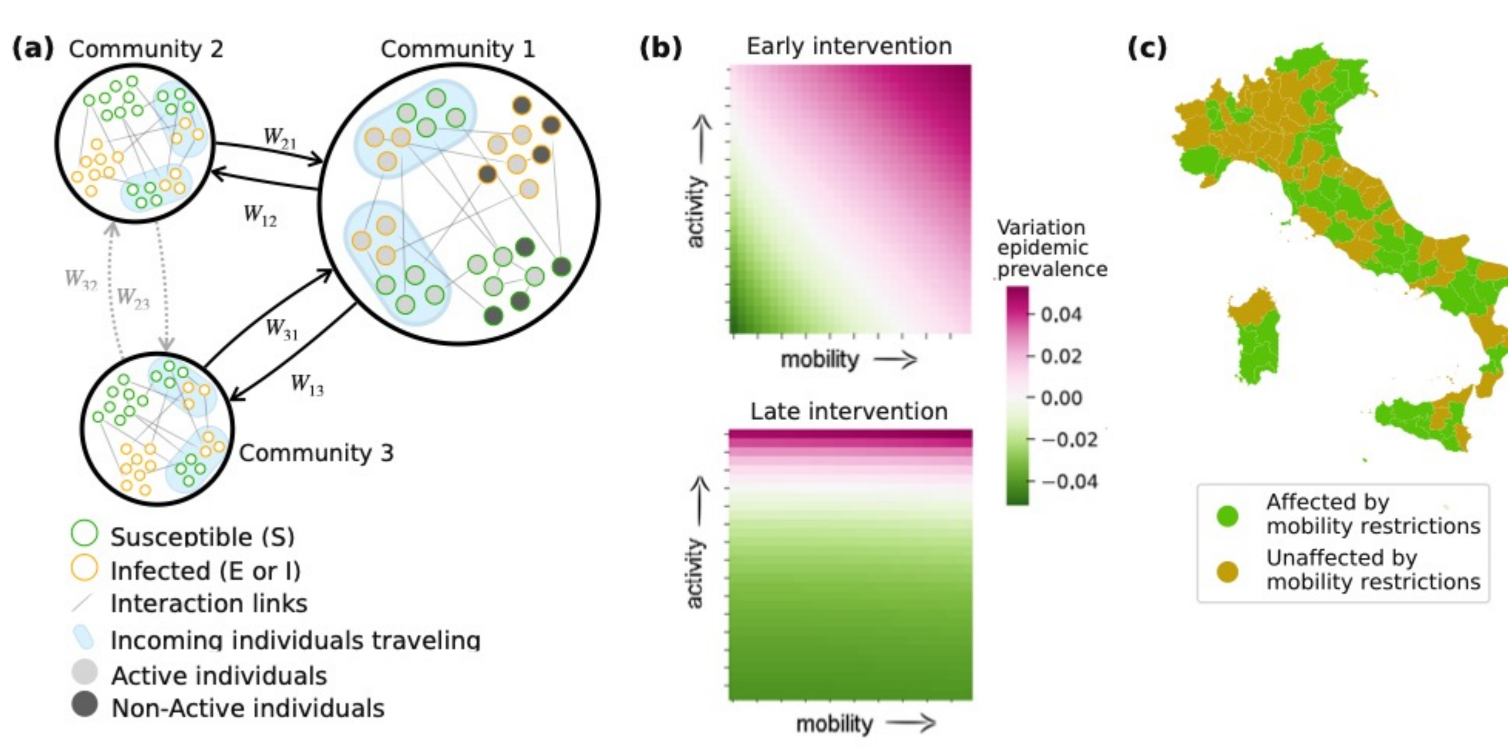
Optimization of vaccination campaigns

- A model that combines epidemic waves with a two-shots vaccination campaign.
- By formulating and solving an optimization problem, we found that the optimal campaign is **nontrivial**, and the **first doses can be prioritized** for vaccines with good efficacy and duration of the first dose (AstraZeneca).
- We consider **uncertainty in vaccine supply**. We evaluate the negative effect the uncertainty and the benefit of re-evaluating the optimal strategy.



Model and predict the effect of social distancing and travel restrictions

- A model that combines the **geographic spread of the epidemics** with a realistic time-varying **description of social contacts**.
- We fit the model to the first Italian wave of COVID-19. Using scenario analysis, we geography assess the impact of the reduction of social activity and travel restrictions.



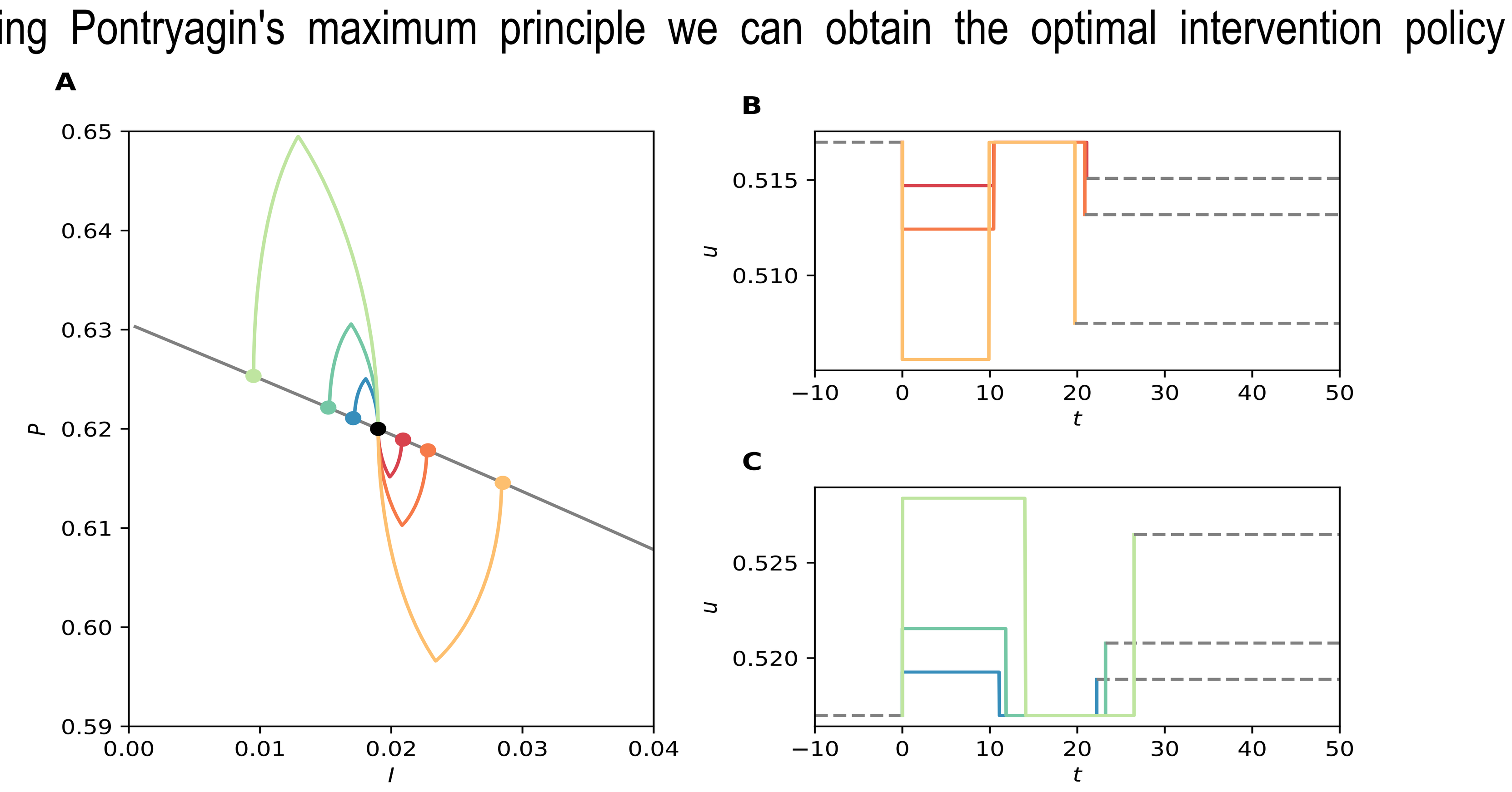
Optimal control of epidemics with behavioural response

- We create dynamic system that couples an **epidemic spreading with the individual decision to adopt self protective behaviour**.
- We study the properties of the resulting non-linear planar dynamical system. We obtain the conditions that characterize system's equilibriums stability.

- $x = (I(t), P(t))$: fraction of the population infected and adopting safe behaviour
- $\beta(P)$: the force of infection depends on the adoption of safe-behaviour
- $\alpha(I)$: individual temptation in risky behaviour, it depends in the disease prevalence
- $u(t)$: control as an incentive in adopting safe behaviour

Dynamics	Cost	Optimization Problem
$\begin{cases} \dot{I} = \beta(P)(1-I)I - I \\ \dot{P} = \varepsilon\alpha(I)P(1-P) \end{cases}$	$J_h = hI^2 + (1-h)u^2$	$\min_{u(t)} \int_{t_0}^{T} J_h(x(t))dt + \phi(x_T)$ s.t. $\dot{x}(t) = \dots$, $x(t_0) = x_0$, $u_l \geq u(t) \geq u_u$

- Using Pontryagin's maximum principle we can obtain the optimal intervention policy



Adopted methodologies

We adopt paradigms from complex networks, game theory and epidemiology.
- **Population dynamical model**, ODEs to describe epidemics at the population level
- **Activity-driven & metapopulation network**, to capture the complex human interaction.
- **Population game,** to model the individual decision to adopt certain strategies.

To derive optimal strategies, we adopt methodologies from control theory:
- **Non-linear model predictive control** (MPC)
- **Pontryagin's maximum principle**
- Convex **second-order cone optimization**

Side project

- Classification of network components based on their dynamics, in complex network where **multiple dynamics coexist**

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Future work

- Future research will focus on **increasing model complexity** while maintaining mathematically tractable models suitable for a control theory approach. Indeed, the challenge will be employing control theory approaches in more complex models, where, for example, epidemics spread over a **complex network of social interactions**.

Submitted and published works

- Parino, F., Zino, L., Porfiri, M., & Rizzo, A. (2021). **Modelling and predicting the effect of social distancing and travel restrictions on COVID-19 spreading**. Journal of the Royal Society Interface, 18(175), 20200875.
- Parino, F., Zino, L., Calafiore, G. C., & Rizzo, A. (2021). **A model predictive control approach to optimally devise a two-dose vaccination rollout: A case study on COVID-19 in Italy**. International Journal of Robust and Nonlinear Control.
- Calafiore, G. C., Parino, F., Zino, L., & Rizzo, A. (2022). **Dynamic planning of a two-dose vaccination campaign with uncertain supplies**. European journal of operational research.
- Parino, F., Zino & Rizzo, A. (2022). **Optimal control in epidemics with behavioral response**. In submission to SIAM, Journal on Control and Optimization (SICON).

List of attended classes

- 01TRARV - Big data processing and programming (8/6/2021, 26.67)
- 01SCVIU - Data analytics for science and society (15/7/2020, 25.00)
- 01QTEIU - Data mining concepts and algorithms (1/2/2021, 33.33)
- 01QSAIU - Heuristics and metaheuristics for problem solving (10/7/2020, 26.67)
- 01RGBRV - Optimization methods for engineering problems (7/6/2022, 50.00)
- 01TSBRV - Scienza dei dati applicata alle reti complesse (12/11/2021, 26.67)

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