Evolutionary game theory and human behavior in modeling an epidemic

カビー, ケー, エム, アーリファル

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氏　名 : KABIR K M ARIFUL

Name

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論 文 内 容 の 要 旨

Thesis Summary

Modeling evolutionary game theory, coupled with epidemiology, has become an attractive framework for painting human behavior, becoming increasingly important in biological and social systems. The conception of evolutionary game theory (EGT) on disease transmission presents a reasonable and convincing perspective on long-term competition between various species or peoples in nature. EGT has seen incredible achievements in the last few decades and exhibits reliable performance in modeling the evolution of the human decision-making process and ethos. However, EGT to human behavior is still relatively new and has many challenges. Many queries about human behavior, disease incident, vaccination conduct, protecting measure, and economic burden to social scientists and researchers have yet to be explored. This thesis sets out to contribute to modeling epidemics and evolutionary game theory on social context by addressing a large pool of models, ranging from simple epidemic disease dynamics to behavioral dynamics and vaccination game models, so that we may:

- provide the deterministic theoretical framework with which we can describe disease pattern and control policy;
- model a biological question to a mathematical model;
- focus on mean-field epidemic dynamics on well-mixed and heterogeneous networks;
- generalize the repeated and non-repeated vaccination game model under the EGT;
- recognize the interplay between cost-effectiveness of vaccination;
- establish the social efficiency deficit (SED) indicator for dual-dilemma and triple-dilemma aspects to quantify the existence of social dilemma;
- discuss experimental field survey analysis, statistical techniques for fitting models, and studies the data.

The first chapter in Part 1 of this thesis background study about the epidemic model, game theory, vaccination game theory, behavioral model, and historical contextual is carried out.

In Part 2, the thesis starts with introducing a cyclic evolutionary game dynamic on three strategy games. Chapter 2 brings the non-linear dynamics of the symmetric rock-paper-scissors game by considering demographic and environmental noises.

Part 3 gives an account of the deterministic epidemic modeling framework to discuss the effect of the appropriate choice of a control intervention. An epidemic SIR-UA (susceptible-infected-recovered-unaware-aware) model for the information spreading called "awareness" combined with the susceptible-infected-recovered model are discussed in chapter 3. Along with the model, chapter 4 discusses a two-layer SIR-UA epidemic model on heterogeneous social networks, in which a virtual network represents the connections of information spreading, and a physical structure denotes disease spreading. Chapter 5 focuses on metapopulation migration and SIS-UA models and their analysis on four graphs: star, cycle, wheel, and complete. Chapter 6 builds a two-body exportation and importation SEIQJR (susceptible-exposed-infected-

quarantine-isolation-recovered) epidemic model for COVID 19 by considering three countries: China, Italy, and the Republic of Korea.

In Part 4, we formulate and analyze various vaccination game models globally, considering the repeated season model. Chapter 7 introduces a vaccination game model combined with information spreading and SIR/V (susceptible-infected-recovered/ vaccinated) epidemic model. Chapter 8 extends approaches of chapter 6 to heterogeneous networks and introduces the degree distribution model. Chapter 9 describes a metapopulation migration model combined with the vaccination game, information spreading, and SIR/V (susceptible-infected-recovered/ vaccinated) epidemic model for four graphs: star, cycle, wheel, and complete. Finally, chapter 10 discusses SIR/V-UA epidemic vaccination game model with information buzz by familiarizing information costs and adverse information effects.

Part 5 introduces the spontaneous behavioral epidemic dynamics under evolutionary game theory, considering the local timescale's single-season model. Chapter 11 focuses on a simple SIR/V vaccination game model by presenting the concept of social learning dynamics. To investigate a multi-serotype disease alongside antibody-dependent enhancement (ADE) consequence in a situation with pre-emptive voluntary vaccination, chapter 12 introduces two kinds of vaccination; primary and secondary vaccines. Our framework dovetails mathematical epidemiological model, incorporating susceptible–vaccinated–infected–recovered-susceptible (SVIRS) epidemic model, with evolutionary dynamics to reproduce the human decision-making process. Chapter 13 dedicates to a vaccination epidemic game model for an artificial immunity, naturally obtained immunity by disease, and waning immunity. Chapter 14 explains the dynamical behavior process of economic shutdown and shield immunity of the COVID 19 pandemic. Finally, Chapter 15 applies the cyclic game models to account for the coexistence between disease and vaccination in the behavioral model, considering two scenarios: cyclic mean-field and cyclic behavioral models for how vaccine reduces disease spreading.

Part 6 explores the novel idea of the dual-dilemma game aspect in an epidemic vaccination game model combined with antiviral treatment. Chapter 16 dedicates to embedding an antiviral treatment option into a vaccination-dilemma epidemic game model. We deliberate a mathematical SITR/V epidemic model consisting of treatment in one season (local timescale) followed by the evolutionary process to consider both vaccination and treatment costs in the global timescale. In chapter 17, we introduce the social efficiency deficit (SED) indicator to quantify the co-existence of dual-dilemma situation in the evolutionary vaccination game aspect combined with the treatment game. The model presents a dual-social dilemma situation (two evolutionary games). The treatment behavior changes on a local timescale, and the vaccination uptake later involves a global time scale.

Chapter 18 in Part 7 studies the co-evolutionary dynamics of advanced and late provisions for assessing the triple-dilemma game aspect. The model explores late-vaccination and self-protection measures on a local timescale on the framework of three strategies evolutionary game. Later, the pre-vaccination game model is considered on the global timescale. We also devote a social efficiency deficit (SED) to quantify the triple-dilemma situation in the co-evolutionary game aspect.

Chapter 19 in Part 8 implements the cost-effectiveness analysis to estimate people's preferences and willingness to pay (WTP) for future dengue vaccine in Bangladesh. Our findings also observed some relationship between effectiveness and cost for the vaccine, comparable to the vaccination game models' results.

In the last part (Part 9), each chapter's results are summarized, and future recommendation is outlined.

We include some mathematical formulations, analysis, mathematical tools, and statistical analysis in the appendix.