Progress Report

BAMS3216 Project

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Title: Studies of Human Behavioural Patterns During the COVID-19 Pandemic Using Evolutionary Game Theory – Prisoner's Dilemma	

1. Introduction

Herd immunity is the ultimate goal to control the spread of an infectious disease. (Abdullah, 2021) With the outraging spread of Coronavirus-19, the Malaysian government has taken many precautions in hopes to contain the spread of the virus. However, all efforts seemed to have gone in vain as it is difficult to ensure the cooperation of the entire population. It is known that many new standard operating procedures have been introduced in Malaysia, with efforts to contain the spreading virus, such as having to keep a 1-meter distance with other individuals, limited business hours, forbidden crossover between states and districts, prohibition of dining in restaurants, etc. However, the new norm has deprived many of social interactions and has limited the freedom of individuals, at the same time ceasing businesses to operate, causing some to find it difficult to comply. It is inevitable that some may not comply with the standard operation procedures, which makes the virus even harder to be contained.

Though vaccines take time to be developed, the ongoing rapid evolution of the virus makes the development of vaccines difficult as new strains of the virus are constantly evolving. Dr Noor Hisham Abdullah, the Director-General of Health Malaysia and Senior Consultant in Breast, Endocrine & General Surgery has also mentioned that the threshold to achieve herd immunity for Covid-19 is still being studied, unlike polio and measles which require 80% and 95% of a population to receive vaccination respectively. (Abdullah, 2021) However, the only way to keep the population protected from the virus is by providing the available vaccine to the resilient group in order to minimize the threat of the vulnerable group who are not able to receive vaccines being exposed to the virus.

With that said, the Malaysian government bears the heavy burden to make a quick-witted decision to control the spread of the virus efficiently and effectively. By that, through identifying the human behaviours in the pandemic whilst coming up with a deliberately planned vaccination strategy to reach the population as fast as possible and ensure the vast majority of the population chooses to receive vaccines concomitantly.

This is said because consumers may feel sceptical and unease in receiving the vaccine as receiving the vaccine poses risks of side effects such as fever, chills, body ache, etc to the receiver. Moreover, some believe that due to the urgent needs of the covid vaccine, some pharmaceutical makers may have compromised stages of the development cycle of a vaccine, (i.e., the phase 3 clinical trial which is also known as large-scale testing and researching different development stages simultaneously) due to the time constraints. (Shah, 2020)Thus, not all potential risks and side effects can be evaluated on time as the reactions towards the vaccine vary on different individuals. (WHO Team, 2020)

With that said, it is rather a difficult task to ensure the whole population will accept and receive the coronavirus vaccine though it is a subsidized expense incurred by the Malaysian Government. According to an interview conducted by (Roberts, 2020), mathematical biologist, Chris Bauch said that some people may play a ‘wait-and-see’ game in the face of uncertainties and concerns towards the vaccine. (Bhattacharyya & T. Bauch, 2011) Thus, individuals who opt out of the vaccine gets benefited effectively as the transmission of the virus greatly reduces as others receive the vaccine, generating a collective threat while opted-out individuals reap the fruit equally. This reinforces that the pandemic can be explained by a type of game in game theory – The Prisoner’s Dilemma. (Bauch & Earn, 2004)

Game theory is a game that aids the strategizing of a decision-making problem among rational or irrational decision-makers by the use of a mathematical model. The Game theory is founded by John von Neumann, a mathematician, and Oskar Morgenstern, an economist back in the 1940s, they have pioneered and broken the grounds of a completely new mathematical and economic theory that revolutionized a whole new field of economics and social sciences altogether. (Neumann & Morgenstern, 1944)

Game theory is most commonly used to break down and simulate a real-world situation to analyse and strategize a solution that yields the best payoff with the use of a mathematical model. There are several types of games in game theory that can be used based on the various natures of the problem such as Cooperative and Non-Cooperative Games, Constant Sum, Zero Sum, and Non-Zero-Sum Games, Symmetric and Asymmetric Games, etc. One of the most used games in game theory is the Prisoner's Dilemma Game.

Game theory is also utilized in the analysis of a mathematical model used to strategize decision making when two or more individuals make decisions that will affect the welfare of the related parties as a whole which is also known as the payoff of the game. (Myerson, 2013) The most famous game in game theory is known as The Prisoner's Dilemma Game. The Prisoner's Dilemma is a cooperative and non-Cooperative game that was unfolded in the 1950s by employees at the Rand Corporation, an American research and development non-profit global policy institution, Merrill Flood and Melvin Dresher, and was then ratified and named by a Princeton mathematician, Albert William Tucker. The Prisoner's Dilemma was named after the prison's sentence rewards. However, The Prisoner's Dilemma game is now more widely used to investigate other situations such as vaccinations strategies. The Prisoner's Dilemma game is a game that involves two players with strategies known as "corporate" and "defect". (Turocy & Stengel, 2003)

1.1 Objective:

Since vaccination strategies are considered as governmental investment decisions, social costs are to be incurred to ensure Malaysian populations are protected from the virus without having to incur unnecessary expenses on top of the struggles of the crippling economy due to the pandemic lockdown. Hence, an appropriate strategy is to be taken. With that said, this study aims to determine if the pandemic – COVID-19 is a Prisoner's Dilemma game. This makes it possible with the simulation of the real-life situation by analysing the human behavioural pattern in a well-mixed population.

Based on past findings, it is likely that conventional models do not take into consideration the cooperation of the populations in the vaccination strategies. One of the objectives of this study is to analyse the human behavioural patterns and the role of payoff incentives in vaccination strategies from the past using evolutionary game theory to better tackle the vaccination problems that are faced due to the pandemic. This is because people have different views and make different decisions be it for themselves or the interests of the group. Thus, this study is done to realise the impact various behaviours of individuals brings in a dilemma in a vaccine strategy. Moreover, this research is conducted to identify the dominant strategies in the dilemma by recognizing the important factors influencing the vaccination decision an individual makes.

The expected outcome of this study is to prove that the pandemic - COVID-19 can be explained by the Prisoner's Dilemma game and with that, the payoff incentives of the vaccination strategy in a well-mixed population whilst taking into consideration the human behavioural patterns in a well-mixed population. A simulation model on vaccination is to be built to make predictions of the player's choice of vaccination.

1.2 Project scope:

This study intends to further expand the knowledge put out by previous researches regarding the relationship between evolutionary game theory and a pandemic. To be specific, the game theory used in this study is the Prisoner's Dilemma Game in the COVID-19 pandemic. Previously, not many studies have been done on a world-scaled pandemic in depth. Hence this thesis aims to contribute to the existing knowledge on vaccination strategies amongst a pandemic and develop sufficient understandings pertaining to the vaccine strategies in terms of an epidemic outbreak. Some theorems and corollaries have been studied from the aspects of the theoretical game theory.

Books, journal articles and news articles that are relevant have been studied to expand the knowledge of evolutionary game theory. The book "Game theory Encyclopedia of Information Systems, Volume 2" written by (Turocy & Stengel, 2003), "Game Theory" written by Roger B. Myerson (Myerson, 2013), journal articles published by professionals whose areas of expertise revolve around the evolutionary game theory such as "Vaccination and the theory of games" written by Dr Chris Bauch and David Earn (Bauch & Earn, 2004) , etc have been read and studied.

Up to at least 10 or more journals and books have been read to develop further understanding of game theory and its correlation with vaccination strategies. This is to determine the most relevant and suitable game theory to be used in this case study. The Prisoner's Dilemma Game is found to be the most appropriate game to explain the human behavioural patterns in a vaccination strategy. (AXELROD, 1980)

Due to recent happenings of the COVID-19 pandemic, not much study has been made regarding the human behaviours in this epidemic. Hence, related journals were studied to get a general grasp of how the game theory applies to the transmission of disease. A model is to be built in Python language to simulate the real-life situation of a pandemic and make predictions on the vaccination strategy amidst a pandemic.

1.3 Planning:

In the foreseeable future, more studies are to be done regarding the COVID-19 pandemic in regards to the human behavioural patterns as there will be more publishes anticipated regarding the COVID-19 pandemic.

Task 1:
Expand Literature review and provide more relevant case studies as reference. Review objectives and other different methods used in previous studies to provide a clearer picture to the reader.

Task 2:
Study different simulation models used in vaccination strategies and read up on how to utilize tools to build a simulation model. In the meantime, learn techniques of machine learning by the Python language online via YouTube videos.

Task 3:
Discuss with supervisor on the simulation model and find a suitable dataset. Clean and pre-process dataset to be applied to the model.

Task 4:
Build a suitable simulation model and obtain results that are most optimal and realistic and Revise with supervisor on the model used to better improve and finetune the model.

Task 5:
Analyse the results and provide clear information and proof on the analysis.

2. Literature review

The investigation of evolutionary game theory gave some rather gripping results on vaccination strategies of infectious diseases to interpret the vaccination dilemma among a population. In 2011, (Wu, et al., 2011) conducted a study using a game-theoretic model with an epidemiological process to solve the significant challenge faced by The Administration and Practise of Public Health in ensuring herd immunity by voluntary vaccination, which was rendered much more complex by vaccinations sources that may not be trustworthy. It is also uncertain on the impact of vaccine effectiveness on an individual's vaccination choices. The study perceives that when vaccine efficacy improves, the percentage of people that successfully receives vaccine rises weakens the virus strains from being transmitted. When it comes to vaccination, it is discovered that when the disease is severe, all people are willing to get vaccinated for an intermediate vaccine efficacy due to their self-interests.

Another study administered by (Liu, et al., 2011) conveys that vaccination coverage motivated by self-interest (Nash vaccination) is typically smaller than group-optimal coverage, according to epidemiological game-theory research (utilitarian vaccination). A game theory model is simulated and was extended to the United States and Israel, which have different vaccine programmes, vaccination and care costs, and vaccination coverage ranges. This is to explore the impact of these externalities on the partnership between Nash and utilitarian vaccination coverages for chickenpox. In both the United States and Israel, it is found that when chickenpox severity rises with age, the conventional association between utilitarian and Nash vaccine coverages may be reversed. While vaccine costs are high, the model indicates that incentives or external control can be used to gain herd immunity from chickenpox vaccination.

According to another study coordinated by (Bhattacharyya & T. Bauch, 2011), the Nash equilibrium model explores the results of two strategic interactions between I) the proportion of vaccination in a well-mixed population and the vaccination cost and II) the number of individuals vaccinated and the virus-infected probability of susceptible individuals. The Nash Equilibrium strategy demonstrates the “wait and see” motive whereby individuals who choose not to receive vaccination pins their hopes on the vaccine co-operators for herd immunity not to mention waiting on the vaccinated to “test the waters” on the safety of the vaccines. The study concluded that the “wait and see” behaviour contributes to the lengthened duration of the epidemic peak, and further explains that the Nash equilibrium model shows not only feedback mechanisms but also feed-forward mechanisms where the initial presumed costs of vaccination perpetuate the future perceived costs of vaccination and determines the vaccine coverage in a population for as long as the outbreak of the pandemic may last.

For good measure, according to (Chapman, et al., 2012), individuals with age are more susceptible to transmission of disease as there is a higher mortal rate among elder individuals. With that said, they are found best protected from the transmission of diseases through the vaccination of young individuals, who are said to be the biggest contributors to the spread of disease. The study targets 2 groups: younger groups and older groups, pay-out incentives were offered in the game individually and by groups. When players are paid individual points, it shows that a higher percentage of the older group received vaccines compared to that of the younger group due to their self-interest behaviour. Whereas group benefits were prioritized when players were given points according to group point totals, more younger players received vaccines compared to the older group, achieving a higher point total. This study was conducted to learn their behavioural pattern in the vaccination strategy and concludes that the payoff in a vaccination strategy is dependent on the decisions everyone makes cumulatively as some act on self-interest and others are willing to act at a cost to benefit the group as a whole.

On top of that, an experimental study has also been orchestrated regarding the free-riding behaviour of individuals when making decisions regarding vaccinations. In 2014, (Ibuka, et al., 2014) experts interpreted that vaccination choices made of an individual are likely to affect the choices of their peers as well. The study conducted investigated the effect of the vaccination decision of an individual in a group setting for a notional disease known as "influenza" with a hypothetical vaccination for said disease with the aid of a computerized probe game. The experiment carried out had controlled conditions by certain parameters on the characteristics of both the vaccines and the disease. Descriptive statistics were used to evaluate the results gained from the experimental design on the relationship between the proportion of participants who choose to receive the vaccine and the parameters such as cost of vaccines, risk of infection and severity of influenza. On another hand, researchers used multilevel logistic regression models to study the free-riding behaviour within the group and found that when the proportion of vaccination of participants in the group increases, the less likely an individual would choose to get vaccinated in the following round. This insinuates a free-riding motive regardless of the conditions or parameters of both the influenza and vaccine. The study also concluded that the chances of a participant receiving the vaccine are higher when the participant had higher exposure to influenza.

According to (Li, et al., 2017), the new prediction model and vaccination strategy proposed for infectious diseases also take into account the network properties such as clustering coefficients and degrees that affect a person's ability to influence the decisions others make and the density of a network, known as clustering coefficients. They have found that these are two important factors on a disease' widespread among a population while making allowance for instances of when the vaccine fails, i.e., vaccine infecting vaccinated individuals. The prediction model deduced in the study exhibits that vaccination strategies of infectious diseases are affected by the social network structures and the initiatives people take to receive a vaccine due to individual differences.

According to an interview (Roberts, 2020) carried out, an epidemiologist and director of the Yale Centre for Infectious Disease Modelling and Analysis, Alison Galvani also states that self-interest-based decisions cause a rather insignificant coverage within the society collectively. Hence it shows that human behavioural patterns show a significant impact on vaccine decisions made.

Over and above that, (Brüne & Wilson, 2020) have reviewed relevant evolutionary insights as to how people react to a pandemic and the repercussions of a pandemic in the absence of a vaccine. In this case, the Coronavirus SARS-CoV-2 is modelled on the grounds of evolutionary game theory to mock situations in which individuals decide to cooperate or defect. Public Goods Game was used in the disquisition as the researchers found it most relevant regarding the research where public health is treated as "Public Good". The game works by involving any number of players with a fixed number of tokens who will then invest their tokens in a common pool, also known as the public good, at the same time. The game host then redistributes the token in equal shares, benefiting all players equally, regardless of how many tokens were first invested by each player (Brandt, et al., 2006). Dr Brüne and Dr Wilson revised the social behavioural patterns in terms of the pandemic with the Public Good Game and predicted that cooperation (in terms of complying with sanctions such as keeping social distance and wearing face masks) will decrease over time in the absence of public health regulations. The research shows that the main adaptive responses to the pandemic are behavioural immune system (BIS) and sickness behaviour (SB).

3. Preliminary results

3.1 Methodology/ Model

This research involves the study of the relevance of game theory in vaccine strategizing. In this case, the Prisoner's Dilemma game is used to simulate the pandemic as a game. The target players of this study are individuals of a large population with two strategies known as "cooperate" and "defect".

	Co-operator	Defector
Co-operator	P	Q
Defector	R	S

The above is the payoff matrix of the evolutionary Prisoner's Dilemma game. The evolutionary Prisoner's Dilemma is usually framed in terms of benefits *b* and costs *c*, where *b* is when players choose to receive the vaccination to reap the fruits and *c* represents the risks players take to co-operate in receiving vaccination such as the side effects that they may face or the possibilities of their body rejecting the vaccines.

Co-operators are players who choose to receive vaccination voluntarily and benefits the defectors who opt-out from receiving vaccinations.

When both players co-operate and receive vaccination, the payoff is represented by P, where P = $b - c$. This shows that mutual co-operation produces fair results for both players as players are putting in the same amounts of effort to receive the same benefits, which is the reduced risk of coronavirus transmission between both players. On the contrary, when both players are defectors and opt-out from vaccinations, the spread of the virus remains unruly and intractable, represented by S, where both players are not benefited at zero costs.

Nonetheless, when one co-operator decides to receive the vaccine and the other player decides to defect, the payoff of the defector will be represented by R, where R = *b*. This is said as the defectors do not have to take risks to turn to the co-operator's advantage, the reduced transmission of coronavirus while the co-operator's payoff is rendered as Q,

where Q = $-c$, bearing the risks of receiving vaccination that dominates over the benefits received. (Turocy & Stengel, 2003)

According to (AXELROD, 1980), the defector always receives the highest payoff when the corresponding player co-operates. However, when both players choose to defect, both players receive the worst payoff which is nothing. Hence the payoff matrix satisfies the argument where R > P > S > Q and 2P > R + Q.

Replicator dynamic is the mathematical tool that can be used to apply the evolutionary game theory to our behavioural model. It can describe the evolution of frequencies of each fraction of strategies by taking into consideration their fitness and mutual influence. The replicator equations of our behavioural model are:

$$\dot{x}_i = x_i[f_i - \overline{f}],$$

$$\begin{bmatrix} \dot{x}_C \\ \dot{x}_D \end{bmatrix} = \begin{bmatrix} x_C \\ x_D \end{bmatrix} \cdot \begin{bmatrix} f_C - \overline{f} \\ f_D - \overline{f} \end{bmatrix}$$

Where:

- f_D and f_C represents the average population payoff of defectors and co-operators respectively, which is also known as fitness.
- Average population payoff: $\bar{f} = X_C f_C + X_D f_D$
- Average payoff of co-operators: $f_C = X_C(b-c) + X_D(-c)$
- Average payoff of defectors: $f_D = X_C(b) + X_D(0)$

By rearranging the equation,

$f_C = X_C b - c$ and $f_D = X_C(b)$ where X_D = 1- X_C

3.2 Classification/Discussion:

It was considered a rather challenging task to start off with the study of the project with bare minimum knowledge regarding this area of expertise – the evolutionary game theory. However, after more readings were done, the flow of the research seemed to be getting on track. As mentioned earlier, it was difficult to access journal articles that were specified in the situations involving a worldwide pandemic, hence, understandings towards this research were gained from many different sources and journal articles.

Building a model is still on hold as more information is to be gathered and learned in the coming stages of study.

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