Emerging cooperation evaluated evolutionary game theory, experiment with simulation and application

ムハンマド, アーサン, ハビブ

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Emerging cooperation evaluated evolutionary game theory, experiment with simulation and application

Dissertation

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by

MD. AHSAN HABIB

Department of Energy and Environmental Engineering

Interdisciplinary Graduate School of Engineering Sciences

Kyushu University

Japan

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

MD. AHSAN HABIB

ABSTRACT

The entitled of the thesis is," Emerging cooperation evaluated evolutionary game theory, experiment with simulation and application" in which numerous environmental changes or problems that have been recognized as issues of the global perspective. So, the environmental issues can be modelled to optimize by predicting the game aspect. Precisely, it can be said that the environmental issues can be modelled as chicken type game which reveals the several real-world problems based on evolutionary game. The evolutionary game theory (EGT), the most widely known standard structural framework to exhibit a large amount of human behavioral diversity, has turned into prominent structures in environment and social issues to survive and prosper. There have been left several issues which implies the less amount of the fundamental knowledge in the entire field of evolutionary game theory. So, the thinking to start up with PhD study was that the different issues were checked regarding evolutionary game theory, that is what the PhD thesis dedicates. It was thought to start the Ph.D. study was that the evaluation of several challenges are implemented to evaluate which are currently observed in the real field of evolutionary game theory by presuming the 2 × 2 game template that is 2 players and 2 strategy game and the thesis deals with highlighting only 2 × 2 game which is the most prominent and most fundamental template in the field of evolutionary game theory regarding several unclear problems to simplify according to the terminology.

There are several approaches for down-to-earth issues touching with each of the chapters. Let me explain about what the each of the chapter dedicates in my thesis paper. According to the thesis, chapter 1 reveals that the historical context of motivation is needed to look through the study. There are some fundamental concepts of game theory with evolutionary, and behavioral dynamics, as well.

It was thought, concerning on 2 × 2 game template based on chapter 2, focuses on symmetric 2 × 2 game with the universal concept of dilemma strength that was explored by the Professor Tanimoto's script in many years ago. The universal dilemma strength can be defined by consulting the hard process of the mathematics. But still, it can be said that the less amount of the prove that the real human beings behave if he or she is exposed to simplify the 2 × 2 symmetrical game

situations. So, this chapter designs the field survey, say, the experiment to explore what each of the real human beings behave to 2 × 2 symmetric game situations. That means, the design was that obtaining some hard evidence from the real human beings behaving with respect to the universal concept of dilemma strength and dilemma class suggesting from the theoretical point of view. That's the chapter 2 deals with.

The chapter 3, turns to bit different thing as compared to chapter 2 deals with, relies on MAS (multiagent simulation) approach. This chapter mainly concerned on what is called network reciprocity that is one of the five (i.e. kin selection, direct reciprocity, indirect reciprocity, network reciprocity and group selection) fundamental protocols proposed by the Professor Martin Nowak, to emerge the cooperation in the prisoner's dilemma game. For the last several decades, there had been numerous works that proposing new mechanism of enhancing network reciprocity by taking the MAS approach, and this time, the same subject was concentrated in that sense which was bit different than the previous many numerous works had been reported. What chapter 3 reveals that unlike the previous study, the conformity mechanism is able to promote cooperation in network reciprocity mechanism context, and this would dedicate to enrich the idea of template to enhance the network reciprocity.

In chapter 4, comes to also different from previous two chapters; chapter 2 and chapter 3, which concerns on realistic scenario based on 2 × 2 game in terms of the classical game theory. To chapter 4, tries to extend the applications of EGT in certain fields in real sense, but unlike the previous those two chapters (i.e. chapter 2nd and 3rd), chapter 4 concerns on asymmetric 2 × 2 (2 players & 2 strategy) game. Because of the realistic application model build in chapter 4, premises two asymmetric players appeared as power generator system; one of the power generator who is interested in sustainable power generation system like PV, wind turbine system and so forth, whereas another player is introduced as the conventional power generator relying on fossil fuel, coal and so forth. But anyway, the realistic asymmetric 2 × 2 game model was tried to build what precisely analyzed by considering mathematical analysis concerning on equilibrium condition.

Finally, chapter 5 is the summary of the results obtained throughout this work, that shows some novel achievements in the field of game theoretical approach. Apart from this, recommendation and future work has been outlined here and some mathematical formulations with analysis are included in the appendix.

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Research Achievements

Peer-reviewed article

Published article

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Chapter 1

Introduction and outline of thesis

1.1 The approach of socio - physics to human - social - environmental System

We represent a general introduction in this chapter. The concept of socio-physics, one of the growing interdisciplinary-science fields, is required to realize the human – social – environmental system. The environmental system is one of the most important dynamical system that relates to the evolutionary game theory.

1.1.1 Human - social - environmental System

From the Adam-Eve era, the system is a continuous flow till now. In that sense, the system is found all around us, even if we don't know it. Generally, the word "system" is defined as the collection of a series of parts, all of those are connected to form an aggregate element that possess an overall function to achieve a particular goal. Systems have the steps we take in doing a particular job to keep us comfortable and safe. In the real-sense, most real systems evolve with time over a state space according to the rule, i.e., they are called "dynamical systems." A dynamical system has the spatiotemporal structure in the field of science and engineering.

W. J. Karplus had established a new discipline concept of system engineering in 1977, represented the concept as "system rainbow". The spectrum of rainbow shows the modeling and simulation of all models in which "black box model" and "white box model" are prominent of those, shown in Fig. 1.1. In the black box model, human social systems, economical systems, and bio-systems are included. This black box model is used to determine the statistical significance, but not rely on any types of prediction of the result. We must rely on fully black-box model that describes an input-output relationship. By contrast, chemical system, fluid and thermal system, mechanical system, and electrical system are considered as white-box model. In white-box model, an established mathematical model can accurately predict the expected results. Mathematical models give a clear picture of the internal structure of any model system. The quality of the model is determined by the validity and the credibility of the system. As one goes through from the black box model aspect to the white box aspect, there is gradual but steady-state change from the quantitative to the qualitative; guess, prediction, analysis, control, and design. Consequently, according to the Karplus concept, a real complex system based on real-world scenario, can be represented through prediction by using this model.

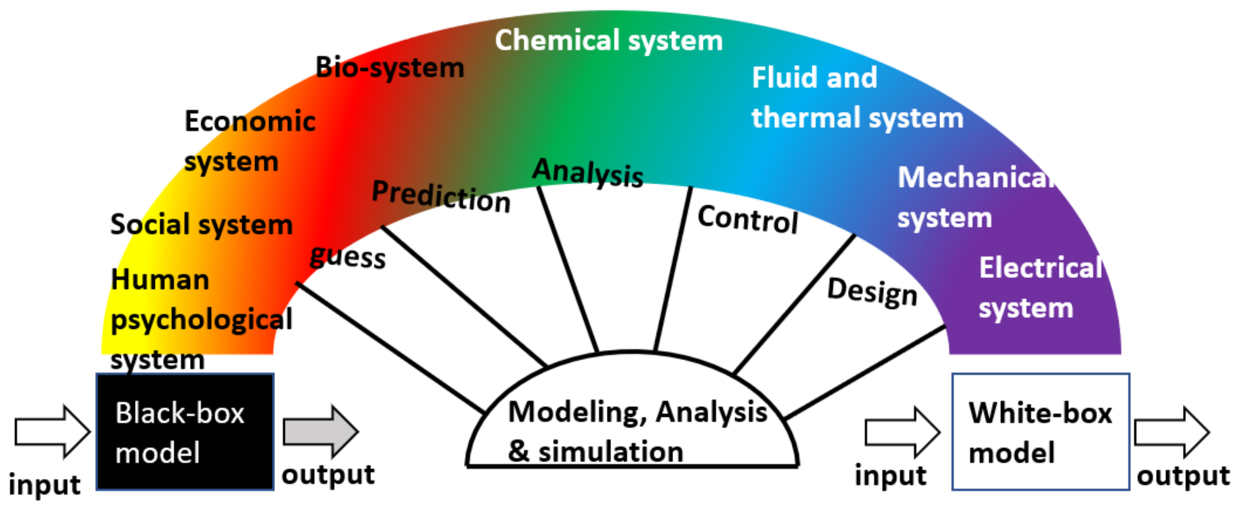
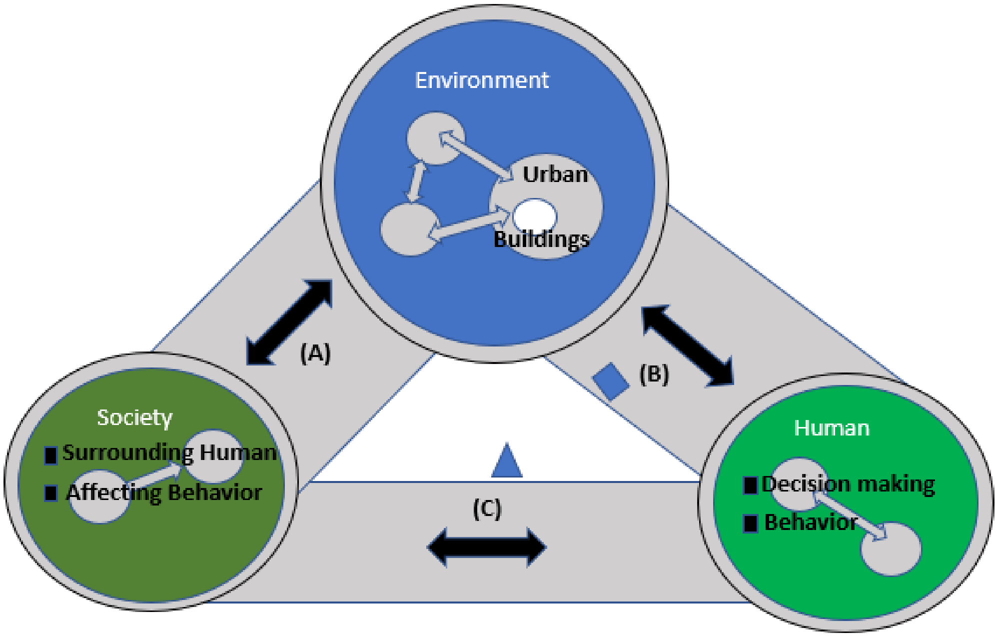


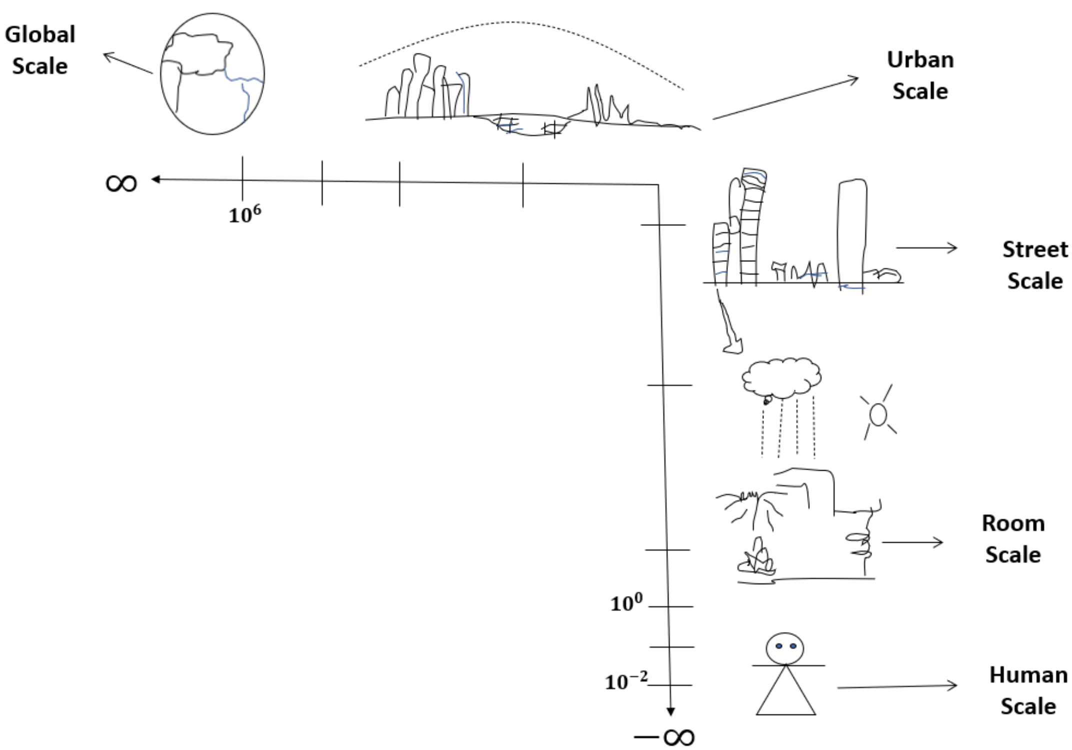
Fig. 1.1: Black-box and white-box models mapped in the System Rainbow proposed by Karplus [1.1]

It is the universal fact that there is strong relation among human, environment and social system. We have tried to create model among human, environment and social system. Human behavior and intension, either supported by rational decision-making process or irrational decision-making process. That means; human overconsumption of fossil fuels over the course of past years, which seems rational for people only concerned with current comfort but seems irrational for those peoples who are care about long term consequences. In seeking to improve environmental problems, one needs to consider complex interactions between physical environmental system and humans as well as social systems as a holistic system of individuals. There are many issues springing up in the complexity of real-world system. Complexity has been defined in various ways in different fields. A system can be complex when the system is composed of many parts that are interconnected in intrinsic ways, [1.2] and [1.3]. The systems become complex when these parts are connected in a non-regular way. Complex systems exhibit chaotic behavior that is characterized by extreme sensitivity to initial conditions, fractal geometry, and self-organized criticality [1.4]. The complexity system can be solved by the stochastic property; higher moments of the system and the probabilistic deviation. What we can guess concerning these processes is not expressed as a set of transparent, deterministic, and explicit equations but black box model, stochastic models. At any rate, in order to solve these problems based on the real life, we must build a holistic model that covers not only environment as physical systems but also human beings and society as complex systems. It is speculated that, human is considered as the white box according to our model. Our approach to modeling human behavior is to consider the human as a device with many internal mental states, each with its own particular control behavior and interstate transition probabilities. Conventionally, physical system can be regarded as the parts of environmental system; urban climate, global weather, or micro indoor environment system. A physical system is involved with many sub-systems by using a set of governing equations to describe the physical principles such as fluid dynamics and heat-transfer theory. Again, human behavior has strong relation with the environmental system to influence the environmental behavior to obtain the desire gain (i.e. payoffs of game theory). This fact inevitably connects the environmental and human systems. A human individual in social system and environmental system are mutually independent or dependent. This heuristic analysis suggests that human, social and environmental systems should be combinedly modeled, which is called human-social-environmental systems.

It is the worldwide tendency to make a balance between the environmental system and the economic growth to achieve a sustainable development strategy for the real-world system. From the ancient period to current position, people are getting much more concern about pollution and energy conservation in the environmental system [1.5]. At present, environmental issues are most important competitive advantage in politics, social, business, etc. The problems based on environment were investigated for the individuals and physical phenomena from the social and psychological perspectives. Figure 1.2 shows the concept of human-social-environmental system. These three systems are followed by different laws, respectively. The environmental systems concentrate on some physical properties, such that, kinetic energy (motion is its potential), heat (main potential is temperature), and various scalars. All of these properties have much more objectives than subjective properties; human emotion, intention, and so on, to drive social system. The issues of environment are considered in different context due to variation that come from the



(a)



(b)

Fig. 1.2: Schematic diagram of relation between (a) the concept of human-social-ecosystem and (b) wide spatial range of scales over ecosystem.

interactions between different environment systems (e.g., human, social and natural) and differences in spatial scale, as schematically explained in Fig.1.2. Our most important question is how we appropriately establish modeling of human motions and social dynamics, which is connected with the echo-system through cross-linkages, shown in Fig. 1.2.

1.1.2 Socio-physics with human - social - environmental system

Man is in the form of knowledge. Knowledge is the condition or fact of knowing something with familiarity gained through experience, association or operations research. Operations research (OR) is the analytical method of the problem solving and decision-making process. The first concept of operations research is aroused during the period of world war II. After that, operations research is applied for statistical physics, business, applied mathematics, artificial intelligence, the government, game theory, and the society. All of these techniques have the goal of solving complex problems and improving quantitative analysis based on social life.

Human societies are a complex and complicated world system. Socio-physics can be considered a new and more precise approach to human behaviour, which include statistical physics, psychological, social, theoretical biology, political, and economic aspects. All these mechanisms are used to seek for many social practical problems and questions in present time. In modern use "socio-physics" refers to using "big data" analysis and the mathematical laws to understand the behaviour of human crowds. So, it is found that socio-physics completely depends on mathematical modelling which is strongly driven by the physics concepts. After that, it is possible to quantify, analyse, and predict a result, even though there is some stochastic deviation or noise. In fact, now-a-days, complex social dynamics and the behaviour of the human agents can be observed and analysed by knowledge-based model using artificial intelligence (i.e., machine learning, genetic algorithm, fuzzy theory, neural networks, and so forth). Socio-physics create an "artificial" world, in which everything is controlled and clearly defined, and the laws of interactions are explicitly written and the range of variations of all the parameters are set, together with the definition of the eventual dynamics of evolution. In a whole, it can be said that socio-physics doesn't claim to reach an exact description of a human group, but instead aims to shed new light on human phenomena. The permanent challenge is to build a model to perform calculations in order to obtain data and results, which in the second step can be compared to the real counterpart of the phenomenon, either via the setting up of experiments, as in physics, or via quantitatively observed trends from the social world. This approach is known as multi-agent simulation (MAS).

This study focuses on the game theoretical approaches coupled with evolutionary game theory, in terms of different dilemmas. The attempt of this thesis shows different models, methods, and analyse to represent the different dilemma situation for the optimal control. This study also represents for estimating change of human attitude, beliefs, decisions, nature, self-concept and environmental activities evolve over time. Consequently, it can easy to predict, realize and recognize the influence of behavioural responses with respect to time. So, it can be said that this thesis paper indicates several important promising approaches to the dilemma situations supported by game theory and EGT, as well. Model verification and validation of the game approaches are done by the experimental, theoretical, and simulation based which provides some critical findings regarding on time series.

1.2 The framework of games

One of the most prominent dissertations, game theory, is the system of modeling the strategic interactions among rational individuals in a condition containing a set of instructions and outcomes to make their decisions. Each individual (player) tries to get his maximum benefit, called payoff, under this game framework [1.6]. So, it can be said that game theory is a discipline to perceive social dilemma situations among the competing players and generate optimal decisions for independent and competing players in strategic settings. The applied disciplines, computer sciences, applied mathematics, statistical physics, political science, social science, business, system science, logic, biology, international relations, information science, etc., have been discussed by the game theory. Game theory was first addressed by Jon von Neumann and Oskar Morgenstern in 1928 regarding human economic behavior [1.7]. They wanted to predict the human behaviors by creating a mathematical framework based on strategic decisions. Consequently, game theory is rendered logistically and mathematically by means of a new concept called evolution. Evolutionary game theory (EGT), branch of game theory, introduced by Jon Maynard Smith and George Price in 1973 by understanding the behavior of animals [1.8]. They searched on strategies and found 'evolutionary stable strategies (ESS)' from the EGT. John Nash had invented a very prominent concept called by 'Nash equilibrium' which is almost same as ESS regarding in non-cooperative games [1.9].As a result, John Nash was rewarded as notable Noble prize in 1994 [1.10].The application of game theory was aroused from the approach of economics and war in 1950s and 1960s [1.11-1.13].After that, ecological approach was come out from the view of Robert May in 1970s.Then, replicator equation based on evolutionary game theory, a most significant role on evolution, was focused by Josef Hofbauer, and Karl Sigmund [1.14].There are some fundamental concepts on game theory as well as EGT, which can be finished-up by the following terms.

1. ***Game:*** a set of situations that depend on the actions of two or more decision makers.
2. ***Player:*** a set of decision makers by rational regarding the game. It can be two or more decision makers in the game called players.
3. ***Strategy:*** a set of plans from the player action arising from the game circumstances. As instance, the outcome of the strategic interactions depends on the choices of the strategy by all the players.
4. ***Payoff:*** The payout of a player takes from their ultimate outcome. The players are very well-known to the defined preferences for the possible outcomes, so that, the payoffs reflecting from these preferences can be assigned for all possible outcomes to all the players.
5. ***Information set:*** all information is available at the particular point in the game.
6. ***Equilibrium:*** a point in the game where the decisions are made by the players, and the outcome is achieved.

1.2.1 Different games regarding game theory

There are different types (symmetric and asymmetric, static and dynamic games, simultaneous and sequential etc.) of games in terms of game theory, cooperative and non-cooperative are very popular game in the real-world conflict scenarios [1.15]. Players try to achieve the maximum payoff in certain and uncertain options in such a game. The classical game theoretical approaches illustrate the situation based on the social issue and other unexpected situation as well [1.16]. Agents rational decision making are made that are fully interdependent with each other by presuming of classical game theoretical approach [1.17]. As a result, classical game theory shows game solution as game equilibrium in the field of science, engineering and others [1.18]. The relevant games based on this study is explained as the following.

1.2.1.1 Cooperative game

Cooperative game theory (CGT) consists of a group of players, collectively form grand coalition. Cooperative games can be found as a competition between coalitions of the players, rather than between the individual players because of the possibility of the external enforcement of cooperative behavior, and the decision-making process. CGT is one of the most rational behavioral models than any other market model. Cooperative game theory presents a simplified approach that allows for the analysis of the game at large without having to make any presumption about bargaining power. Let us consider the feasible coalitions between: coalition 1; combined with 4 subscribers and coalition 2; combined with 3 subscribers, of cooperative game which is shown in Fig.1.3. CGT has been applied in different fields; core of the tree game [1.19], management of high sea fisheries problem [1.20], and cost, benefits resulting from cooperation are allocated to the players [1.21].

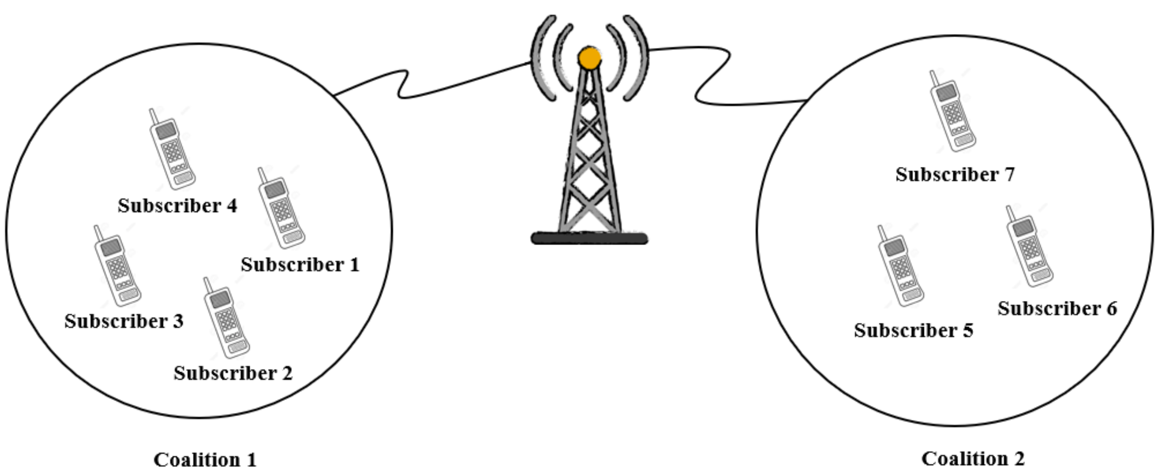


Fig.1.3: Cooperative game

1.2.1.2 Non cooperative game

A non-cooperative game is such a game in which there are a combination of player, actions, strategies, and outcomes. Within the game context, players are those which have the ability to make the decision based on the situation. Actions are considered as the possible movements of the players in the game. Strategies are defined as a complete plan of action of each player adopts their actions in the given set of circumstances within the game. As instance, going to operate the air conditioner in the room, a person has to think what to do, and the options are; turn on and turn off. The possibility strategy would be: “If the room temperature goes below 23^{0}C, then he will turn off the air conditioner, otherwise turn on the air conditioner”. Finally, the outcome of a non-cooperative game shows the pleasure that the player gains through action.

There are two methods of a non-cooperative game; the extensive form and the normal form. Generally, extensive form is presented by decision tree [1.22] in which nodes as well as branches are available. There are two types of node here; decision node and terminal node. When a player reached at the decision node then he chooses to move. Again, when a player reached at the terminal node then he gains payoff. The extensive form of non-cooperative game represents-

1.The players

2.The game order

3.What choices available for each player when they move on the play

4.What information gathered by all player when they move on the play

5.The payoffs for all players in every combination of the movements.

The instance of extensive form along with normal form of non-cooperative game is revealed as in the Fig.1.4 and Table 1.1.

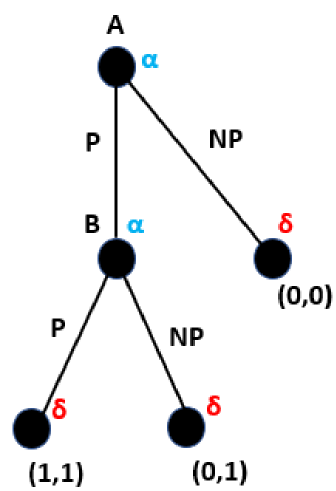


Fig. 1.4: A two player non-cooperative game in extensive form (tree form). Two players as A and B have actions such as P(permit) and not permit (NP). Decision nodes, α and terminal nodes, δ are considered. Here (x, y) shows the payoffs.

The normal form of the extensive form (Fig. 1.4) of the game is shown below:

Table 1.1: Normal form of the extensive form

		B	
		P	NP
A	P	1, 1	0 , 1
	NP	0 , 0	0 , 0

1.2.1.2.1 Nash equilibrium in non-cooperative game

John Nash, Noble prize winner in 1950 for the concept of game theory, proved Nash equilibrium, which is the best way to define the solution of a non-cooperative game combined with two or more players. This concept has applied to analyze several difficult situations, such as various races, wars, etc., and solve that conflict situations by their repeated strategic interaction. Most of the situation, Nash equilibrium elapses with time, that is to say, when once reached its ultimate decision, then it would not possible to deviate from that situation. In other words, Nash equilibrium can be called as no regrets equilibrium because of no player can increase their payoff by switching their decisions unilaterally.

‘Best response’ is one of the most prominent term which is related to non-cooperative game theory. Best response can be defined as the optimal strategy that a player can choose in response to the opponent’s strategies. Leveraging the concept of the best response according to the non-cooperative game theory, Nash equilibrium tries to determine mathematically and logically the actions that players of a game should consider to secure the best results for themselves. Overall, no individual player can receive any benefit from changing actions, presuming the other players remain constant in their strategies. A non-cooperative game can have multiple equilibria or none at all.

1.2.1.2.2 Pareto optimality and Nash equilibrium

Pareto optimality is one of the most important term in game theory. Pareto optimal is such type of strategy in which any one users' payoff can be increased without decreasing payoff of at least one other user. In a non-cooperative game theory, Nash equilibrium does not always show to be a pareto-optimal. The efficiency of the game solution is determined by the Nash equilibrium whereas shows the intuition to the outside viewer whether the final decision is efficient or not [1.22]. The easiest example to understand the difference between Nash equilibrium and Pareto optimality is the prisoner's dilemma in the non-cooperative game theory (Table 1.2). Here, the Nash equilibrium is not pareto optimal due to the better off of the two prisoners by choosing the strategy. [NE; Nash Equilibrium, PO; Pareto optimality, C; Cooperation, D; Defection]

Table 1.2: Relation between Pareto optimality and Nash equilibrium

		Player 2	
		Strategy (C)	Strategy (D)
Player 1	Strategy (C)	$3, 3\ (PO)$	$0, 5\ (PO)$
	Strategy (D)	$5, 0\ (PO)$	$1, 1\ (NE)$

1.3 Symmetric and asymmetric game

1.3.1 Symmetric game

A symmetric game is such type of game in which the payoffs depend only on the other strategies employed for playing a specific strategy, but not on the playing players [1.23-1.24]. In other words, it can be said that without changing the payoff strategies, individual can change the others identity then it is called as symmetric game. The symmetric games are the Prisoner's dilemma, the chicken and the stag-hunt game as the standard presentations. Amid different types of symmetric game, ordinal game and partnership game, are the most common games. The payoff matrix of the symmetric 2 x 2 games is shown below (Table 1.3 (a)). Presuming two players from an infinite and well mixed population are imposed two strategies as cooperation x $(0 \le x \le 1)$ and defection $(1 - x)$, expressed as $= x + (1 - x) = 1$, respectively.

Table 1.3: Symmetric and asymmetric game

		Player 2	
		Strategy (x)	Strategy $(1-x)$
Player 1	Strategy(x)	a, a	b, c
	Strategy $(1-x)$	c, b	d, d

(a)

		Player 2	
		Strategy (y)	Strategy $(1-y)$
Player 1	Strategy (x)	a, b	c, d
	Strategy $(1-x)$	e, f	g, h

(b)

During the play, the payoff strategy of player ‘1’ against player ‘2’ is the same as the payoff strategy of player ‘2’ against player ‘1’.

1.3.2 Asymmetric game

An Asymmetric game is such type of game in which the set of strategy of all the players are not identical. There are most popular asymmetric games, the ultimatum game and the dictator game, which have different strategies for each player. Naturally, asymmetry arises from different situations, such as subpopulations interaction, interactions in interspecies, different assignment roles (i.e., interaction between parent and offspring), interactions in the larger group, sometimes interacting in individuals, and so on, as well [1.25-1.30]. To model such interactions, using evolutionary game theory, which has been applied extensively to study the evolution of cooperation in social dilemmas. A social dilemma is typically modeled as a game with two strategies, cooperation and defection. As instance, if defection pays more than cooperation if the opponent is cooperator, then the social dilemma comes from the game due to conflict of interest between the groups and the individual. Discussion of asymmetric model which is not possible to describe from the model of the symmetric matrix. So. these asymmetric conditions can be properly analyzed by the realm of continuous strategy, adaptive dynamics in the evolution system. The payoff matrix of asymmetry is reflected in Table 1.3(b) in which two players are considered from an infinite and well mixed population using two strategies as player 1 has the cooperation $x(0 \leq x \leq 1)$ and defection *(1-x)* strategy, in contrast, player 2 belongs to the cooperation as y $(0 \leq y \leq 1)$ and defection *(1-y)*, respectively, which can be expressed as $= x + y$, and $0 \leq x + y \leq 2$, respectively. The payoff strategy is not identical for each of them. That is to say, the payoff strategy of player '1' against player '2' is $c,\ d$ which is the different from the payoff strategy of player '2' against player '1' is e, f, during the play.

Asymmetric game approaches are natural models in terms of the certain world scenarios that show the real insight inspection of the human beings. The real-world game players have different concepts to apply asymmetry game effectively. The asymmetric interactions and evolutionary game theory with different strategies, seem more natural and realistic for the game players to percept the different behaviors of people belong to the large population. The simplified asymmetric game model can justify and amplify the actual behavior of the humans evolving with the game application. The application to the asymmetric game based on real-life is elucidated by the several examples, including animals, environment; water, wind, and solar, pollution, in different enterprises, cyberspace, electrical grid system and so forth. Besides, many potential applications are highlighted to exhibit the human behavioral approaches as well, regarding game theory.

1.3.3 2 player and 2 strategy (2 × 2) game

The magnum opus of game theory by Neumann and Morgenstern, was first inaugurated in 1944 entitled by "Theory of games and economic behavior" [1.31]. A basic framework structure based on human's rational decision-making process regarding game theory, can deal with different diverse fields like applied mathematics, economics and so forth. The most prominent standard template is called 2 × 2 game (2-player and 2-strategy game) in which two players are presumed from an infinite and well mixed situation and two strategies are imposed as cooperation x and defection $(1 - x)$,respectively . So, the standard payoff matrix is shown as (Table 1.4),

Table 1.4: Symmetric 2 × 2 game

		Player 2	
		Strategy (x)	Strategy $(1 - x)$
Player 1	Strategy (x)	a	b
	Strategy $(1 - x)$	c	d

where *a (d)* provides the payoff when mutually cooperating (defecting), b *(c)* reveals the payoff of the focal player when he cooperating (defecting) but his opponent defecting (cooperating).Many models dedicated to game theory as well as evolutionary game theory, have been applied to the application of evolution of cooperation with respect to social dilemmas. Social dilemmas occur due to the conflict between the individual's and the groups interest, as an instance, when cooperation pays less than defection and the cooperator acts as opponent then the social dilemma situation is aroused. The nature of this social dilemma relies on the ordering of a, b, c, and d. The most important rankings of the games are illustrated as the prisoner's dilemma (PD) ($c > a > d > b$), the chicken game (CH) ($c > a > b > d$), the stag-hunt (SH) game ($a > c > d > b$), and the trivial game ($a > c > b > d$). The dilemma strength for the 2 × 2 game is addressed as,

$$D_g = c - a \qquad (1.1)$$

$$D_r = d - b \qquad (1.2)$$

where D_g indicates the gamble-intending dilemma (GID) — the inclination of two equal players to exploit each other, while D_r gives the risk-aversion dilemma (RAD) — the inclination of equal players trying never to be exploited.

1.3.3.1 Evolutionary mechanisms with replicator dynamics

In 1973s, the concept of evolutionary game theory (EGT) was first addressed by John Maynard Smith and George Price [1.32]. EGT has referred grown up evolutionary models based on behavior. The aspects of behavior of agents or individuals from the large population has strongly connected each other by the strategic interactions. The strategy in terms with the evolution of cooperation, has become an invaluable important tool for the mathematical, statistical, and computational approach to biology [1.33]. That is to say, the framework of this novel plays a prominent role to the behavior of the human and animal, as well [1.34-1.36]. There are three essential approaches to evolutionary game theory. First of all, the word "evolution" refers to the cultural evolution that shows the change of beliefs and strategy over time. Second one," rational" presumption by EGT is more applicable in real world system. Third and last one, "evolutionary game theory", is more realistic dynamic system in real sense due to consider the population instead several players.

1.3.3.1.1 Evolutionary stable strategies (ESS)

Evolutionary stable strategy (ESS), addressed by John Maynard Smith and George R. Price in 1973, is such a strategy in which population can accept this, after that any alternative strategy cannot change that strategy. ESS are strongly inspired from the Nash equilibrium. So, it can be said that the modified version of Nash equilibrium is ESS. The application of ESS is applied for the evolution of human biological system, cultural evolution, anthropology, philosophy, political science, and economics. Finally, it is figured out that ESS is used to illustrate the human behavioral system very clearly, as well.

1.3.3.1.2 Replicator dynamics (RD)

Replicator dynamics (RD) indicates the evolution of a population strategies. Peter Taylor and Leo Jonker introduced replicator dynamics as a dynamic process used in EGT in 1978 [1.37]. RD can be achieved biologically as a model of natural selection. Usually, RD provides a replicator equation in terms of mathematics. The replicator equation (in discrete and continuous form) is applied to the EGT that satisfies the stability of the equilibria of the equation. The solution of the concept is almost found from the evolutionary stable states of the population. Let's presume, there are n strategies. The payoff of strategy i interacting with j strategy is expressed as $n \times n$ matrix, $A = [a_{ij}]$,known as the payoff matrix. Consider an infinite well mixed population ($N \to \infty$) and denote $x_i(t)$ as the frequency of strategy i at time t, the expected payoff of strategy i is given by

$\pi_i = \sum_{j=1}^{n} x_i a_{ij}$.

Hence, the average payoff is given by

$$\bar{\pi} = \sum_{i=1}^{n} x_i f_i$$

The replicator dynamics can be written by,

$$\dot{x}_i = x_i(\pi_i - \bar{\pi}) \quad i = 1,2..,n \qquad (1.3)$$

1.3.3.1.3 Example of dynamic analysis of the 2 × 2 game

The games are played among the individuals that represent pairwise interactions between players with two behavioral strategies, cooperation and defection. Presume, a typical 2 × 2 game combined with two players (i.e. player 1 & player 2) taking strategies x and $1 - x$, respectively, which is shown in Table 1.5. The following payoff matrix is shown.

Table 1.5: Payoff matrix of 2×2 game

		Player 2	
		Strategy (x)	Strategy $(1-x)$
Player 1	Strategy (x)	a	b
	Strategy $(1-x)$	c	d

It is found from the above matrix that player 1 achieves payoff a playing against another player 1 and gets payoff b playing against player 2. Again, player 2 achieves payoff c playing another player 1 and gets payoff d playing against another player 2. The expected payoffs for player 1 and 2 are,

$\pi_1 = ax + b(1-x),$

$\pi_2 = cx + d(1-x).$

The replicator equation is as,

$x^* = x(1-x)[(a-b-c+d)x + b - d]$ (1.4)

This equation has three equilibrium points,

$x^* = 0, x^* = 1$ and $x^* = \frac{d-b}{a-c+d-b}$; for or $d < b$ and $a < c$ or $d > b$ and $a > c$.

Four different cases are found according to the equation (1.4) to investigate the behavior of non-linear dynamics. It is noted that the equilibrium dynamics can be achieved from their values. These equilibria represent several cases which are described in below [1.38-1.39]. In addition, it should be mentioned that there are two scaling measurement parameters for dilemma strength which can be defined as $D_g = c - a$ and $D_r = d - b$,respectively.

Case-1: Dominance strategy

When the condition $d > b$ and $c > a$ satisfies, then $D_g > 0$ and $D_r > 0$ is achieved, which show the prisoner dilemma game, that focus player 2 dominates the player 1. In this case, at the point $x^* = 0$ presents the stable point, whereas, at $x^* = 1$ provides unstable point. On the contrary, if $c < a$ and $d < b$, then $D_g < 0$ and $D_r < 0$ is obtained, that indicate trivial game which illustrate player 1 dominates player 2. In this case, at point $x^* = 1$ is stable and at point $x^* = 0$ is unstable equilibrium.

Case -2: Bi stability

Let's presume, $c < a$ and $d > b$ that present $D_g < 0$ and $D_r > 0$ which represents stag hunt game. the at points $x^* = 0$ and $x^* = 1$ are both stable but at the point $x^* = \frac{d-b}{a-c+d-b}$ is unstable equilibrium.

Case-3: Coexistence

When $c > a$ and $d < b$ then we get $D_g > 0$ and $D_r < 0$ which refer as a chicken type game. The fixed points at $x^* = 0$ and $x^* = 1$ present both unstable and $x^* = \frac{d-b}{a-c+d-b}$ is stable.

Case-4: Neutrality

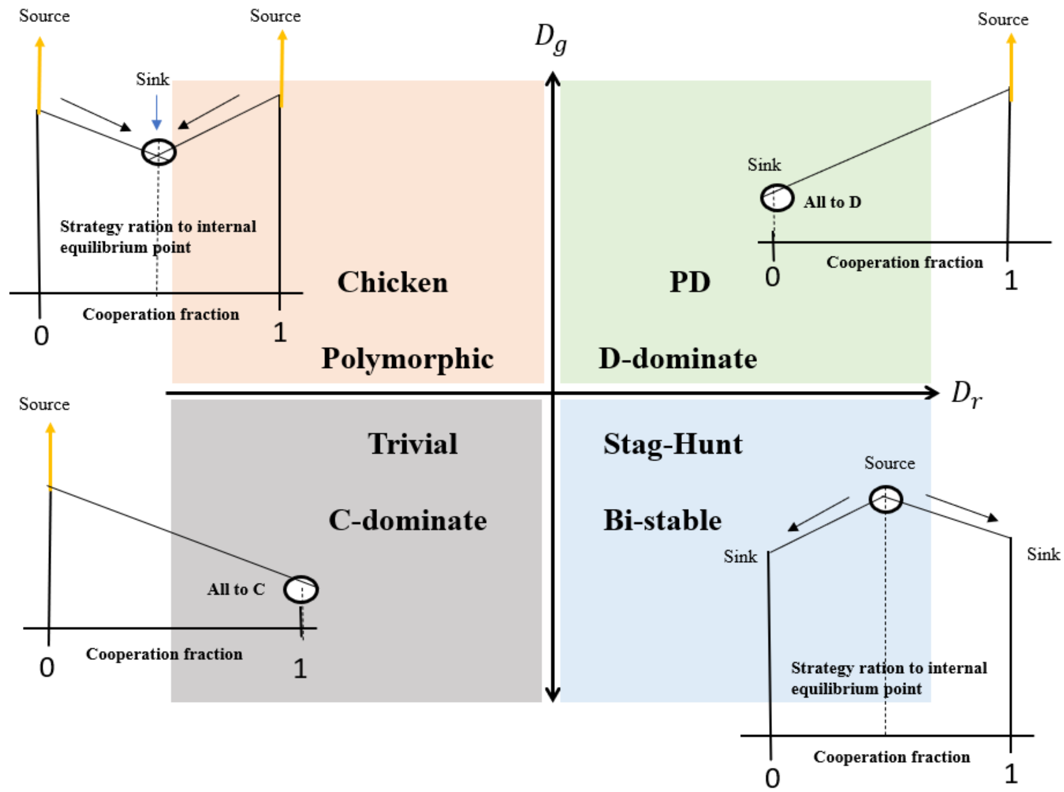
In this case, if $c = a$ and $d = b$ which represent $D_g = 0$ and $D_r = 0$ .That is to say, if you are playing with your game opponent in this game , then no matter what you adopt as a strategy, then the payoff will be same as opponent. you would always have exactly the same payoff as your opponent

1.3. 3.1.4 Dilemma analysis based on different games

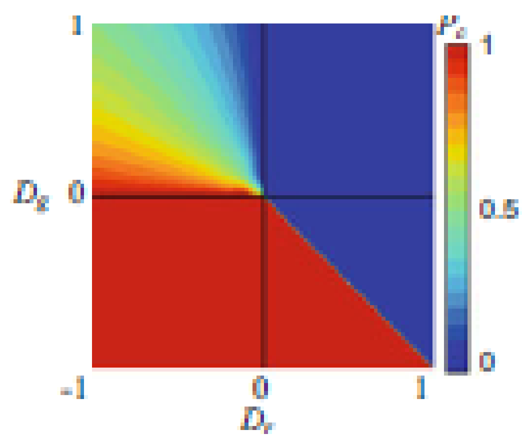
The summarization of the dilemma situations of the different game classes; Prisoner's dilemma, Chicken, Stag-hunt, and Trivial game are depicted as follow (Table 1.6 and Fig. 1.5).

Table 1.6: Different phase of various game classes regarding 2×2 game.

Game class	**Phase**	$\mathbf{D_g(GID) > 0}$ **?**	$\mathbf{D_r(RAD) > 0}$	**Dilemma Situation?**
Prisoner's dilemma (PD)	D-dominate	Yes (+)	Yes (+)	Yes (+)
Chicken (Snow Drift; Hawk-Dove)	Polymorphic	Yes (+)	No (−)	Yes (+)
Stag Hunt; SH	Bi-stable	No (−)	Yes (+)	Yes (+)
Trivial	C-dominate	No (−)	No (−)	No (−)



(a)



(b)

Fig. 1.5: Dynamical phase diagram by D_g and D_r of 2×2 game and (a) the description of dynamic of each game class and (b) Cooperation fraction at equilibrium point. At that situation, presumed an infinite and well mixed population system with replicator dynamics in which initial cooperation fraction,P_c is 0.5.The color of PD and trivial is blue and red, respectively, in which D-dominate phase and C-dominate phase are set up. In chicken game area, the cooperation fraction is shifting

and becomes polymorphic phase at equilibrium position. In SH game, bi-stable presents two-fold phases, either absorbed all cooperation or all defection.

1.3.4 Multi-player games as public goods game

To get the more realistic scenario, the multi-player games are presumed which is treated as public goods game (PGG) [1.23-1.24]. Presume, N players take part in a single multi-player game in which the number of cooperator is denoted by n_c. After taking the donations from all co-operators among the N players, the total pooled donation is multiplied by the amplifying factor, r. Thus, the public good game has been amplified. The results of the public good game are equally distributed to all the game participants irrespective of whether the players are collaborators or not. In this sense, a defector can be called a free rider. An important point is that the payoff of the defectors is always bigger than that of the cooperators. The discrete cooperation fraction is denoted by,

$$P_c = \frac{n_c}{N}$$

The condition that meets the satisfy for the multi-player game is written as

$$\pi_D = (n_c - 1) > \pi_c(n_c).$$

Payoff structure for the cooperator and defectors are,

$$\pi_c = r\frac{n_c}{N} - 1 \quad (1.5)$$

$$\pi_D = r\frac{n_c}{N} \quad (1.6)$$

Here, a cooperator has no incentive to keep cooperating at any cooperation fraction, and so that the cooperation fraction is always declining. As a result, Nash equilibrium is absorbed by an all defectors state i.e., $P_c = 0$. On the other hand, the maximum social payoff, or fair Pareto optimum, appears at all co-operators state, $P_c = 1$. For that reason, we can call it a multi-player Prisoners dilemma game as PGG.

1.3.5 Universal scaling for dilemma strength games

A dilemma is expressed from mathematical modeling whenever the pareto optimum does not match with the Nash equilibria. In PD, Chicken, and SH, the fair pareto optimums do differ from the Nash equilibria.SH indicates only a partial match but makes dilemma because the other results are possible. When the value of D_g and D_r are fixed, then the evolutionary dynamics are determined easily. But when a certain specific reciprocity mechanism is addressed into a game, such as spatial prisoner's dilemma game on the lattice network with degree as 8, at that situation, D_g and D_r are not sufficient for indicating correctly the situation of dilemma strength . Consequently, presuming a finite set of population combining with any reciprocity mechanism defining a new set of parameters of GID (gamble-intending dilemma) and RAD (risk-averting dilemma) as $D_g{}'$ and $D_r{}'$, called as universal scaling for dilemma strength , respectively, [1.39] are used to express the dilemma situation properly.

$$D_g{}' = \frac{c-a}{a-d} = \frac{D_g}{a-d}, D_r{}' = \frac{d-b}{a-d} = \frac{D_r}{a-d} \qquad (1.7)$$

1.3.6 Social viscosity; reciprocity mechanism

Presuming an infinite and well-mixed population along with the dynamics of a symmetric 2-strategy game, will increase cooperation level among the agents if a pair of agents is randomly selected from infinite population. Besides, in animal societies, such as insects, birds and mammals, in which cooperation is emerged from their collective action based on the real-world scenario. Cooperation and dilemmas are interrelated with each other in the social world's life. The dilemma situation is aroused from transportation to the restriction of the action of human behavior [1.39] and restriction of human behavior can affect the ant's behavior and even though in viruses, as well, which causes dilemmas in the environmental issue. So, many researchers from many disciplines have tried to solve the dilemmas situation in the perspective of the evolution of cooperation.

To eliminate the social dilemma situation and maintain the stable cooperation, Nowak proved that, there are five fundamental protocols: Direct Reciprocity, Indirect Reciprocity, Kin Selection, Group Selection and Network reciprocity, to mitigate or cancel social dilemmas. These mechanisms are called as social viscosity. If we presume a battle repeated game field, then direct reciprocity expresses the battle between a pair of individual, indirect reciprocity shows the importance of the opponent behavior ;cooperation or defection, can be recognized ,the network reciprocity indicates that a player achieve the information relating to the strategy of his neighbors when a player plays against his neighbors player. All the social dilemmas can be solved and create a cooperative world. That means, these mechanisms open up to reduce the anonymity from the infinite and well-mixed population and shed light on to form a cooperative society.

1.4 Network reciprocity

Network reciprocity is obtained by the connectivity between cooperative players. Alternatively, it can be said, when a cooperator connects with cooperator neighbor then the cooperation level is increased. The most important effects coming from the network reciprocity are: (1) mutual cooperation is increased when the number of game opponents is few; and (2) cooperation can be enhanced if a player adopts the strategy from a neighbor as a cooperator through network. These two features illustrate how cooperators survive in PD's network game, although players only need to utilize the simplest strategy either cooperation or defection [1.40]. Network reciprocity is applied to different diverse fields, like statistical physics, theoretical biology, and so on.

Different types of networks have been considered according to the population structure. Social networks have been incorporated as a spatial arrangement of relationship, that can express the interactions between individuals [1.41]. As a basis, homogeneous well-mixed population to be for the stochastic models. According to the real-world scenario, it is better to represent the population as a network under homogeneous topology (e.g., a ring or square lattice, which refer as regular networks) as Erdös-Rényi random networks [1.42] ,heterogenous network topology (e.g. scale-free network) [1.43], heterogeneous small world network [1.44], or other topologies [1.45]. From the network point of view, evolutionary games are not only played on regular network, but also on complex networks that have different degrees. The affect of network node changes over time for each round and a node presents individuals, or an agent or seldomly a population in the usual network. There are some factors such as update rules, update dynamics, average degree, and population size influence network reciprocity.

1.4.1 Strategy update rule

In the line with network topology, an agent updates his strategy synchronously by considering the accumulated payoffs with all his neighbour in each round. There are the four update rules have been studied widely.

1)Imitation Max (IM): A focal player copies the strategy which has the largest payoff among all the strategies chosen by the focal player and his immediate neighbours.

$$S_i = \begin{cases} S_i \; if \; \pi_i > \max\{\pi \; \in \; N_i\} \\ S_j \; if \; \pi_j = \max\{\pi \; \in \; N_i\} \end{cases} \tag{1.8}$$

Here, S_i is the strategy of the ith agent and N_i is the neighbour agents of i(focal agent). π_i indicates the accumulated payoff, respectively, of the ith (focal)agent. π_j presents the accumulated payoff of j(neighbour agent).

2)Fermi-PW(F-PW): A focal player i chooses a randomly player j's strategy with probability calculated considering the Fermi function. A F-PW process determines the probability of her imitating strategy, depending on differences in payoff.

$$P_{S_i \leftarrow S_j} = \frac{1}{1 + \exp\,[(\pi_i - \pi_j)/k]} \tag{1.9}$$

Here, π_i and S_i indicate the accumulated payoff and strategy, respectively, of the ith (focal)agent. The parameter k in the Fermi function is set to 0.2. $P_{s_i \leftarrow s_j}$ is the probability of i's strategy being overwritten by $j's$.

3)Linear-PW(L-PW): The strategy of a player j is chosen as in Fermi-PW, but the probability is given by a linear function and operates as follows:

$$P_{S_i \leftarrow S_j} = \frac{\pi_j - \pi_i}{\max\,(k_i, k_j)\;[max(T,1) - \min\,(S,0)]} \tag{1.10}$$

Here, k_i indicates the degree of the ith(focal)agent.

iv)Roulette (RS): A focal player chooses one among the strategies adopted by the focal player and her immediate neighbours with a probability proportional to the payoff and operates as follows:

$$P_{S_j \leftarrow S_i} = \frac{\pi_j - \underset{k \in N_i}{min}[\pi_k]}{\sum_{j \in \{N_i\}}\left(\pi_j - \underset{k \in N_i}{min}[\pi_k]\right)} \tag{1.11}$$

where $\{N_i\}$ presents the set of neighbours for the focal agent i and himself.

1.4.2 Effect of the initial fraction of cooperators on cooperative behavior in the evolutionary prisoner's dilemma game

Two update options for dynamics have been considered here. One is synchronous updating in which update its strategy at every play of the games and another one is asynchronous updating, a randomly chosen player plays the game immediately followed by his /her strategy update; following that, another randomly chosen game player plays and updates. These two update dynamics have power to influence the results, according to the work reported by Grilo and Correia (2007) [1.46]. As the de-facto standard for the simulation of the game, initially 50% cooperators population and 50% defectors population are considered, which randomly assigned in the network. As a result, generating evolutionary characteristics from the model are called as the dynamical systems. This characteristic shows the stable cooperative phase or vulnerable against the invasion of defectors in the context of the application of the biological system. For that reason, we would like to discuss the significant reason whether choosing the initial cooperators of network reciprocity have a great influence or not.

Enduring and expanding Periods

The enduring (END) period and expanding (EXP) period are introduced, which is shown in Fig.1.6. Presuming, initially 50% cooperation and 50% defectors in the evolutionary course, there very two important crucial processes have been found: END and EXP period. In the END period, cooperators try to endure defectors invasion (or cooperators avoid learning defection from neighbours), that means, the period of END is characterized by a rapid downfall of cooperation. On the other hand, the expanding (EXP) period; since cooperators who successfully survive in the END period by forming cooperative clusters (C-clusters), expand their area by converting defectors into cooperators which shows the evolutionary trail is increased in the level of cooperation. Somehow, weak dilemma represents the low cooperation fraction starting from the EXP period regarding evolutionary characteristics.

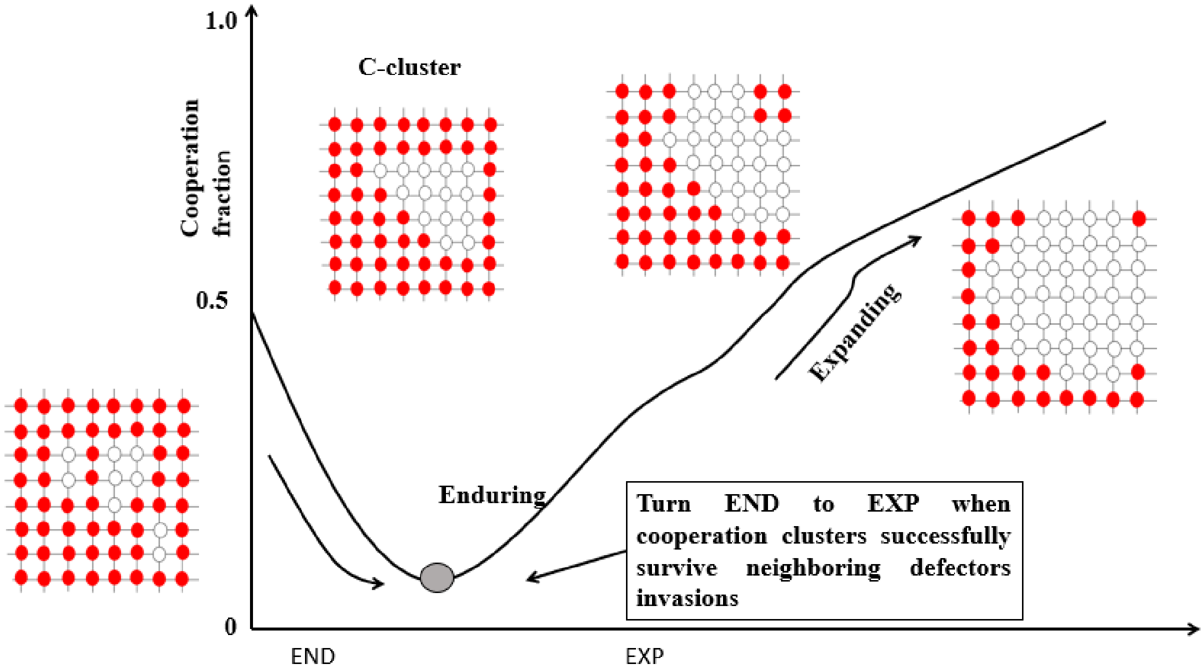


Fig.1.6: The schematic diagram of spatial prisoner's dilemma game with END and EXP concepts, Enduring (END) period: Initial cooperators will quickly be looted by defectors, leaving only a few cooperators to form a compact C-clusters. Expanding (EXP) period: C-clusters begin to expand, since a cooperator on the clusters border can attract a neighboring defector into cooperator.

1.5 Experimental work

Experimental game is one of the most interesting game approaches to interactivity between the theory and the clarification. That is to say, the experimental game is such type of game which represents the experiment that relates to the basic instincts of the strategic behavior of the human beings in real-life. First and foremost, the experimental game generates the observation of the behavior of the participants with the rationality manner. Experimental participants reveal their feelings or thinking's according to game design. The design of the experimental game depends on two factors; the need for the information about the principles of strategic behavior, and the advantages of the experiments providing in it. As a result, most of the games in terms of application arise questions predicting strategic behavior by the combination of the empirical knowledge and the theory. The prediction of game theory—specially noncooperative game theory, which underlies the most applications—is reflected in the observed behavior in different fields, such as; the laboratory works which can control and observe by the experimental technique to allow for a decisive advantage to identify the relationship between the environment and the strategic behavior.

1.6 Conformity

Competition in the group can make selection pressure for the ability to acquire group norms (specially enhancing cooperation), that led to a successful interaction within group regarding gene-culture coevolutionary theory [1.47-1.48]. Going through this theory, group norms create cooperation, which is achieved through imitation and conformity. We can say conformity is such kind of characteristic of human beings which has strong impact to change in believe or behavior to go along with normative society. People adapt exceptional skills for imitating other people which will conform as well as the approve of conformity. As instance, people have a strong tendency to align within the group member's answer to a question, even though they know the answer is not correct [1.49]. So, it can be said, social conformity can be achieved in terms of attitudes, beliefs, actions, perceptions, cooperation, trust, imitation, prestige-biased learning, and so-forth in any complex and awkward situation.

1.7 The statement of problem

In our real society, human beings are very closely connected to others by social-relationship specially morality, social fairness, cooperation and competition. The competition comes from the people mind based on the nature of the social dilemma situation. We can say competition is often occurred by the social dilemma situation—sometimes the dilemma makes patterns through which we can be good and sometimes we are nevertheless rewarded being selfishness. The selfishness resulting from the personal beneficial choice due to social dilemmas whether the opponent/others are benefited or not, for the time being. So, People are lured into short-term self-interest, seemingly without presuming the long-term potential behavior, such as environmental pollution. Because the long-term outcome (global dramatic climate change) is poorer for every individual in the group. Each individual can use the public goods for themselves, whereas the best result for the group is to explore the resources very slowly with wisely.

Decision making strategies by people based on dilemmas can use to optimize the outcome. So, the most significant behavior of decision-making during dilemma situation is aroused from game theory. We can say, game theory can be applied to elucidate the complex behavior of the human regarding mathematical model which represents the responses of the people in dilemma situation. Moreover, EGT is presumed as perfect dynamic system to model for the decision-making of individuals facing some situations like social dilemmas. We tried to adopt the EGT in our study to utilize, analyze, evaluation, and so forth to find out the best optimal system.

1.8 Thesis flow diagram

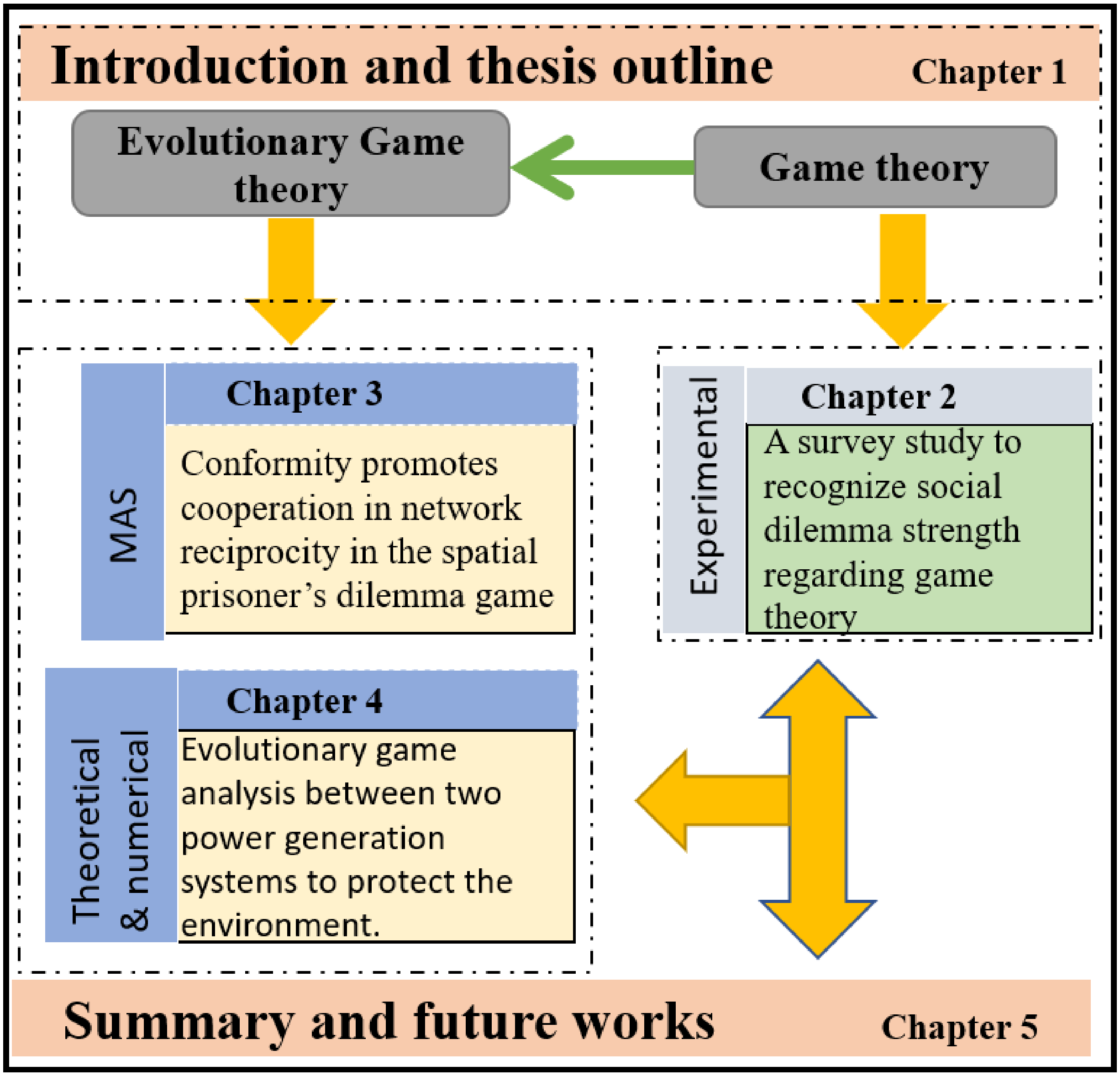


Fig.1.7: Structure of the thesis

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Chapter 2

A survey study to recognize social dilemma strength regarding game theory

2 Abstract

In order to recognize the dilemma classes and its strength, the current study shows a verification test of four game classes; Prisoner's dilemma, Trivial, Chicken, and Stag-Hunt accompanied with a cross sectional survey through website. Based on cooperative and defective behavior, we presumed a multiple set of 2 × 2 games for two game classes regarding game opponents: whether he is an intimate friend or an unknown person in the questionnaire. There are total 375 respondents participated in this study. It is found that Prisoner's dilemma and Trivial game are easily recognized by the respondents, but they are not aware of the dilemma strength and difference of game opponent's attribute whether the opponent is a close or unknown one.

2.1 Introduction

From birth, human is endowed with some innate characteristics preferring; cooperation and defection, that help people to lead a meaningful life, in real sense. Cooperation is respected since childhood to death, generally. Meanwhile, the set of cooperation(C) and defection (D) is regarded as the common scenario in the game theory, which is called strategy [2.1]. A game is defined as a set of strategy and payoff structure that models the human decision-making process with the premise that a player intends to maximize her own benefit. Alternatively, it can be said that game theory is a theoretical framework to strategic decision-making process in any situation in the real life.

John Von Neumann and Oskar Morgenstern first introduced game theory [2.2], that provides a quantify model based on human decision-making process in a basic pattern with respect to the real-life scenario. So, the so-called pattern is named as symmetric 2-player and 2-strategy game, called 2×2 game, where two unacquainted players out of infinite and well-mixed population (that is an environment without any 'social viscosity' [2.3], are imposed to choose whether C or D, of which game structure is denoted by the payoff matrix; $\begin{bmatrix} R & S \\ T & P \end{bmatrix}$, where R (P) indicates the payoff when mutually cooperating (defecting), S (T) means the payoff of the focal player when he cooperating (defecting) but his opponent defecting (cooperating). Although there have been many precursors dedicated to the stock of game theory as well as evolutionary game theory (EGT), recently a new idea to quantify 'dilemma strength' for 2×2 games was introduced [2.4-2.5] in which,

$$D_g = T - R \qquad (2.1)$$

$$D_r = P - S \qquad (2.2)$$

$$D_g^{/} = \frac{D_g}{(R - P)} \qquad (2.3)$$

$$D_r^{/} = \frac{D_r}{(R - P)} \qquad (2.4)$$

where D_g indicates the gamble-intending dilemma (GID) — the inclination of two equal players to exploit each other, while D_r indicates the risk-aversion dilemma (RAD) — the inclination of equal players trying never to be exploited. Tanimoto and his colleagues [2.4-2.5] further introduced D_g' and D_r' that are defined as respectively normalized D_g and D_r ,because the dilemma strength with a certain mechanism adding social viscosity is quantitatively affected by R - P.

Table 2.1: Summary of the general design

Focal point	**Detail**
Game structure	Symmetric 2 × 2 game
Game class	Whether a responder can understand game classes: Prisoner's dilemma (PD), Trivial (TR), Chicken (CH) and Stag-Hunt (SH). In CASE I, PD and Trivial are paired, while in CASE II, CH and SH are paired.
Game dilemma strength	Whether a responder can distinguish dilemma strength: D_g (D_r) and D_g' (D_r').
Social viscosity resulting from the assumption of a game-opponent	Whether a game-opponent is an *intimate friend/unknown person* to a responder.

Evolutionary game theory, the application of game theory, is quietly recognized worldwide and several studies have been related with its theoretical aspect or taking simulation approaches to solve down-to-earth questions; as examples, why cooperative behavior has been evolutionally favored in many animal species from human being to nature [2.6-2.20]. The experimental works vis-à-vis theory and simulation have been extensively studied, many pioneers have tried to validate the game theory by intrigued experimental efforts. Only with respect to recent experimental studies on 2 × 2 game, we can itemize as below: Leonie et al.[2.21] shed light on mixed strategy setting in their experimental setting, Valerio et al.[2.22], studied on how social preference influencing the relationship between the ratio of benefit vs cost and cooperation level, Filippos et al. [2.23] focuses on how the short-range mobility of people affecting cooperation, and Alberto et al. [2.24] introduced experimental version of spatial game setting. Fort et al. [2.25] focused on the update rule which enhances cooperation, Jelena et al. [2.26] stated the impact of the cooperation on the moody and heterogeneous situation, and more; Normann et al. [2.27], and Hauert et.al.[2.28]. Other than 2 × 2 game settings, there have been affluent experimental works concerning Public Goods Game [2.29-2.49] , experimental economics across subject populations [2.50-2.52], when faced with a new game, participants use strategies that reflect both behavioral spillover and cognitive load effects [2.53], subjects with low accuracy do not tend to retaliate more than those with high accuracy [2.54], the different strategy of the world's appear, help to create a more cooperative world [2.55-2.64] , in experimentally, the more cooperative is raised when the dilemma situation becomes less [2.65-2.69] , the cooperation of the partner increases in the repeated games for a long horizon and no significant distinguish over time [2.70-2.72], experience subjects play the vital role for the emergence of cooperation in the repeated prisoner's dilemma games [2.73-2.76], subjects appear to use a "loss-avoidance" selection principle: they expect others to avoid strategies that always result in losses [2.77], characteristics of interaction partner (i.e., a long-term partner or a stranger) affect human cooperation and punishment in public goods experiment in which increasing the cooperation level, punishment is reduced due to potential free riders [2.78-2.83], long-term interaction is a well-known factor to maintains cooperation; it has been known as theory of direct reciprocity or reciprocal altruism in the network of social life [2.84-2.95] , the affects of incentive attributes to the cooperation level [2.96-2.98], competition contributes cooperation level [2.99-2.100] ,strong correlation between wealth inequality and the cooperation level [2.101-2.102]. The taxonomy of the literature in case of experimental works with the decision making of game theoretic approach is shown in Fig.2.1.

Human decisions are based on the accumulating ample evidences over time for 2 × 2 experimental games, but it is needed to make clearly validate the plausibility of game theory, especially recognize dilemma strength by the mass people in the real life scenario. This study has explained the result of our preliminary experimental trial having threefold; whether people fairly recognizing dilemma class; either Prisoner's Dilemma ($D_g > 0$ & $D_r > 0$), Chicken ($D_g > 0$ & $D_r < 0$), Stag Hunt ($D_g < 0$ & $D_r > 0$) or Trivial ($D_g < 0$ & $D_r < 0$), whether people correctly recognizing the dilemma strength, and whether cooperation level observed being dependent on anonymous or not-anonymous situation.

The remaining part of this manuscript consists as below. Section 2.2 describes experimental design, Section 2.3 reports result and give discussion, and conclusive remarks would be noted in Section 2.4.

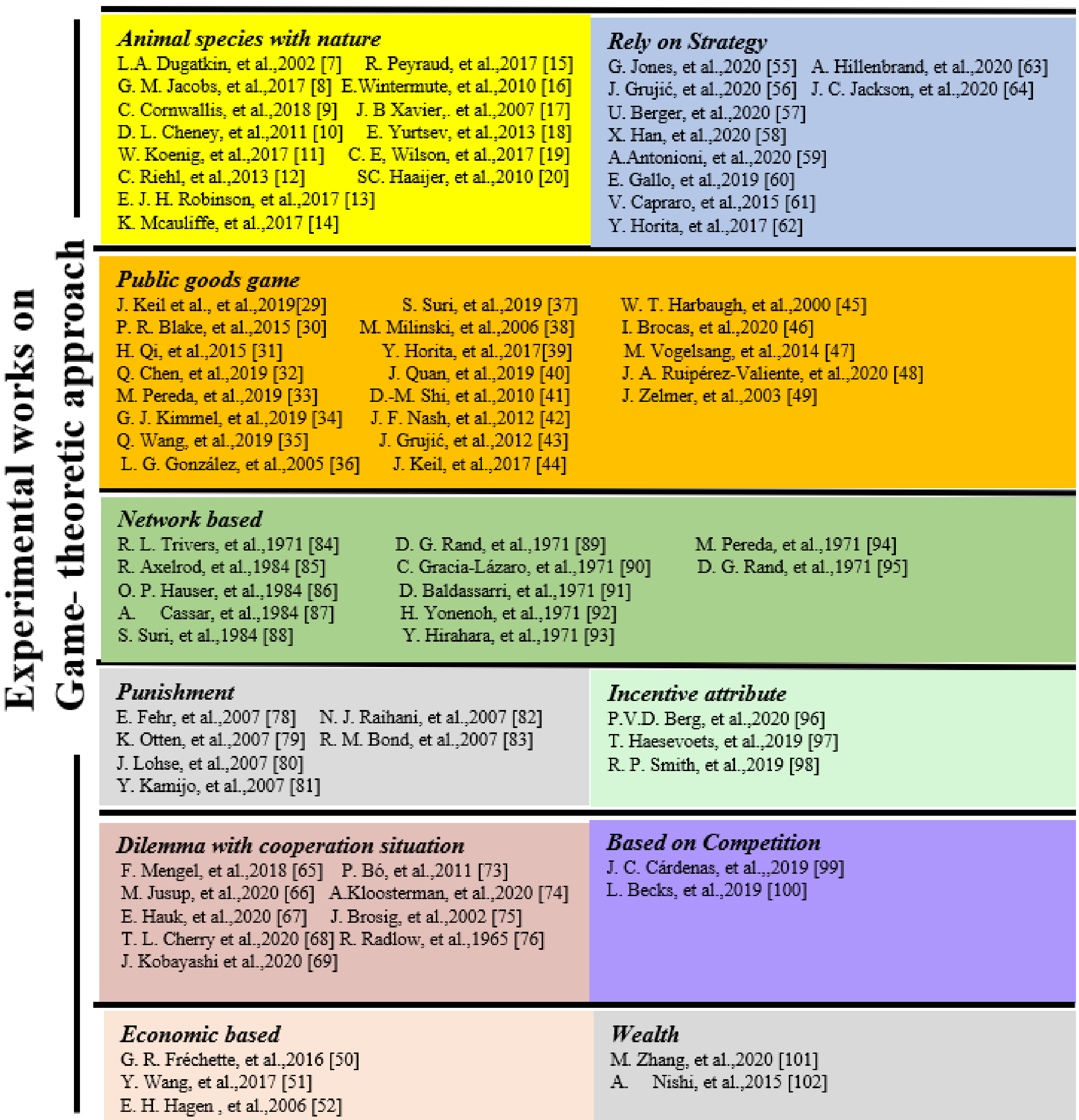

Fig. 2.1: Taxonomy of present literature in experimental works with game theoretic approach.

2.2 Experimental design

A simple 2×2 games are presumed for the questionnaire survey based on the social interactions according to the real contexts.

2.2.1 General design

Presume a symmetric 2×2 game from an infinite and well-mixed situation has been applied to a query for recognition of four game classes in addition to dilemma strength either be comprehensible for the participants or otherwise in the experiment with(out) social viscosity. In a nutshell, going through the summary of the general design (Table 2.1), we were concerned on; how game class, dilemma strength, and assumption of a game-opponent respectively influence on respondents' cooperation level.

2.2.2 Questionnaire design

We made a questionnaire-based experimental survey in which repeated, and one-shot 2×2 games are played according to the impact of real-life social dilemmas. This survey is designed as a structured cross-sectional survey using multiple choice answers through a web-based survey. This is implemented through Google form which offers a simpler solution as below. In the case of field survey, data are collected through face to face interviews.

There is an overview of the questionnaire in Fig.2.2 that shows the *INTRODUCTION*, which belong to either CASE (I) or CASE (II) after the part where demographic questions were posed. The portion of *INTRODUCTION* pertains to CASE (I) to provide explanation for the Prisoner's dilemma (PD) and Trivial games while the portion of introduction or pertains to CASE (II) to explain Chicken (CH) and Stag Hunt (SH) games, and also gives the general background of game setting when participants went through the questionnaire. There are 8 questions, i.e. (a) to (h), for both CASE (I) and CASE (II) in which PD vs Trivial, or CH vs SH games are compared. In the *INTRODUCTION*, a participant was asked his/ her game-opponent to be either an intimate friend or an unknown person. To this end, a participant was asked to select either A (indicating Cooperation) or B (indicating Defection) as his/ her option. The 8 questions were sequentially given to each of the participants, of which order amid (a) to (h) are fully randomized. We introduced such two settings: (i) we ask participants through this experiment to consider game opponent from among unknown people, (ii) allowing participants to choose game opponent from intimate friends. Perfectly, in this anonymous world, a game opponent is given as a man on the street as unknown (zero chances to play again with the same opponent i.e. the one- shot game) ensure zero social viscosity. On the other hand, in the case of an intimate friend, such a game setting has a certain level of social viscosity.

Here, Table 2.2 illustrates different dilemma strength parameters that satisfy $\boldsymbol{D_g}$ $(= \boldsymbol{D_r})$and $\boldsymbol{D'_g}$ $(= \boldsymbol{D'_r})$ for CASE (I) and different for CASE (II)

CASE (I) (Prisoners Dilemma(PD) & Trivial game)

PD game

(a)

You \ Opponent	A	B
A	100, 100	-500, 600
B	600, -500	0, 0

(b)

You \ Opponent	A	B
A	500, 500	-500, 1000
B	1000, -500	0, 0

(c)

You \ Opponent	A	B
A	100, 100	-100, 200
B	200, -100	0, 0

(d)

You \ Opponent	A	B
A	500, 500	-100, 600
B	600, -100	0, 0

Trivial game

(e)

You \ Opponent	A	B
A	1500, 1500	100, 1400
B	1400, 100	0, 0

(f)

You \ Opponent	A	B
A	2000, 2000	300, 1700
B	1700, 300	0, 0

(g)

You \ Opponent	A	B
A	300, 300	100, 200
B	200, 100	0, 0

(h)

You \ Opponent	A	B
A	400, 400	300, 100
B	100, 300	0, 0

CASE (II) (Chicken (CH) & Stag hunt game(SH))

CH game

(a)

You \ Opponent	A	B
A	100, 100	500, 600
B	600, 500	0, 0

(b)

You \ Opponent	A	B
A	500, 500	500, 1000
B	1000, 500	0, 0

(c)

You \ Opponent	A	B
A	100, 100	100, 200
B	200, 100	0, 0

(d)

You \ Opponent	A	B
A	500, 500	100, 600
B	600, 100	0, 0

SH game

(e)

You \ Opponent	A	B
A	500, 500	-100, 400
B	400, -100	0, 0

(f)

You \ Opponent	A	B
A	100, 100	-100, 0
B	0, -100	0, 0

(g)

You \ Opponent	A	B
A	500, 500	-500, 0
B	0, -500	0, 0

(h)

You \ Opponent	A	B
A	100, 100	-500, -400
B	-400, -500	0, 0

Fig. 2.2: Each of the case (both (I) and (II) has eight questions. PD and CH have (a), (b), (c), (d) question, and Trivial and SH have (e), (f), (g), (h) question.

Table 2.2: Summary of the dilemma strength for the CASE (I) (PD vs trivial game) and CASE (II) (CH vs SH game).For CASE(I), D_g $(= D_r)$ and $D_g^{/}$ $(= D_r^{/})$in addition to CASE (II) has different dilemma strength.

Case (I)	**PD setting**	**(a)**	**(b)**	**(c)**	**(d)**
	D_g $(= D_r)$	500	500	100	100
	$D_g^{/}$ $(= D_r^{/})$	1	5	0.2	1
	Trivial setting	**(e)**	**(f)**	**(g)**	**(h)**
	D_g $(= D_r)$	-300	-300	-100	-100
	$D_g^{/}$ $(= D_r^{/})$	-0.75	-0.15	0.067	-0.33
Case (II)	**CH setting**	**(a)**	**(b)**	**(c)**	**(d)**
	D_g (D_r)	500 (-500)	500 (-500)	100 (-100)	100 (-100)
	$D_g^{/}$ $(D_r^{/})$	1 (-1)	5 (-5)	0.2 (-0.2)	1 (1)
	SH setting	**(e)**	**(f)**	**(g)**	**(h)**
	D_g (D_r)	-100 (100)	-100 (100)	-500 (500)	-500 (500)
	$D_g^{/}$ $(D_r^{/})$	-1 (1)	-0.02 (0.02)	-5 (5)	-1(1)

2.2.3 Subjects

There are total 375 survey participants; subjects, or respondents, whose trail in detail is shown in Table 2.3.

From May 2019 to July 2019, our field survey chosen randomly, in this regard had been conducted with direct questions at Kyushu University, Japan while a web-based survey had been conducted at Begum Rokeya University, Rangpur, Bangladesh. The questionnaire was provided to the participants through a link and were requested to fill out the demographic data, e.g. gender, age, occupation etc.

2.3 Results and discussion

2.3.1 Statistics of demographic characteristics

With Table 2.3 presents the socio-demographic characteristics of participants, fraction of male and female, occupation and age distribution. Most of them were college-age students.

Table 2.3: Survey of participants in different games (M = Male, F = Female, S = Student, J = Job) (Total = 375).

Game		Gender (%)	Occupation (%)	Age year (%)
Case (I) (PD+ Trivial)	Unknown person (150)	M = 73.3 F = 26.7	S = 98.4 J = 1.6	15-20 (14.8) 21-25 (80.3) 26-30 (4.1) 36-40 (0.8)
	Intimate friend (169)	M = 24.3 F = 75.7	S = 85.3, J = 14.7	15-20(21) 21-25(51.7) 26-30(11.9) 31-35(3.5) 36-40(1.4) ≥ 40(5.6)
Case (II) (CH + SH)	Unknown person (28)	M = 82.1 F = 17.9	S = 46.4, J = 53.6	15-20(3.6) 21-25(14.3) 26-30(28.6) 31-35(25) 36-40(25) ≥ 40(3.6)
	Intimate friend (28)	M = 85.7 F = 14.3	S = 89.3 J = 10.7	21-25(21.4) 26-30(42.9) 31-35(25) 36-40(10.7)

2.3.2 Result of test

2.3.2.1 PD versus Trivial

The outcome of how the respondent's cooperation fraction along dilemma strength influencing both Prisoner's Dilemma (left) and Trivial (right) games are shown in Fig 2.3. Here the combination of normalized dilemma strength and original dilemma strength; $(D_{g,}^{/} D_g)$, were varied as (5, 500), (1, 500), (1, 100), (0.2, 100), (- 0.067, -100), (- 0.15, -300), (-0.33, -100), (-0.75, -300) in plots (a) to (h), respectively. The label of panels; (a) to (h), is consistent with that for Case (I); (a) to (h), explained in Fig 2.3. We presumed $D_g^{/} = D_r^{/}$ $(D_g = D_r)$.

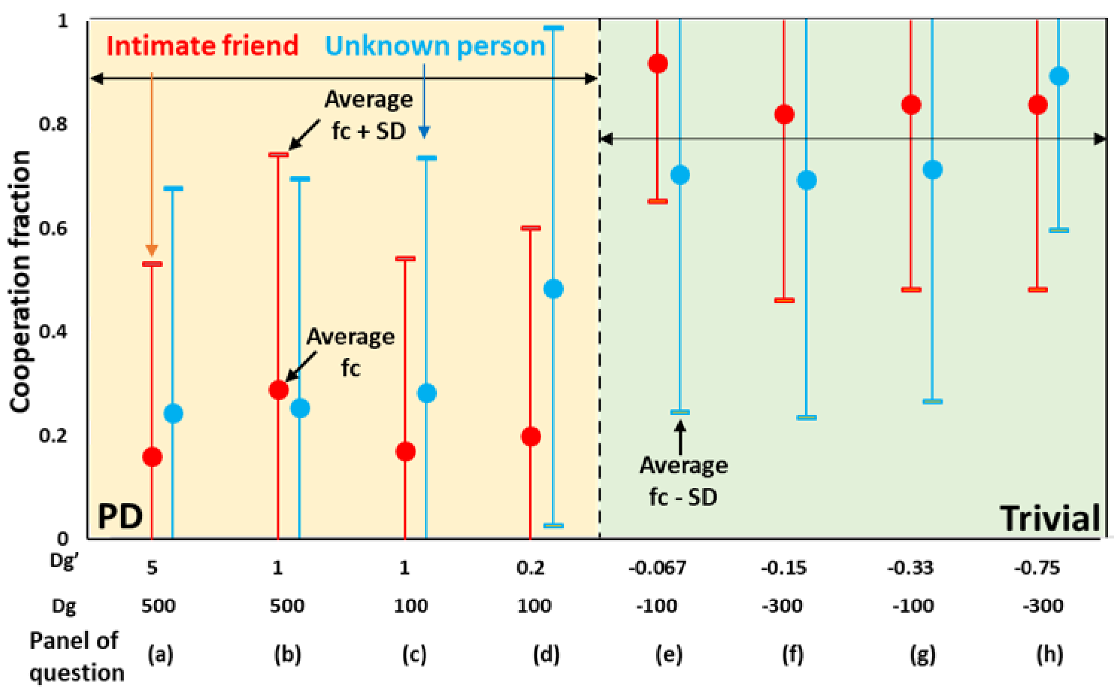

Fig. 2.3**:** Graphical representation of average cooperation fraction for intimate friend and unknown person in case of PD vs trivial game over dilemma strength $(D_g\ , D_g^{/})$. There are 8 questions in which first four i.e. (a), (b), (c), (d) belongs to PD and remaining four i.e. (e), (f), (g), (h) are from trivial game.

Obeying to what the evolutionary game theory [4] quantitatively predict, the cooperation fractions for all of PD ((a) – (d)) and Trivial ((e) – (h)) in case of 'unknown person' must be consistent with

0 and 1, respectively. But the result showed somehow cooperative (less than 0.5) in case of PD, and not perfectly cooperative in case of Trivial. This is because a real situation, usual people exposed in daily life, cannot be ideally similar to what the theory premises as perfectly well-mixed and infinite population.

The result of 'intimate friend' was expected to observe more cooperation than that of 'unknown person', because the assumption of whether intimate or unknown may affect people's recognition of anonymity. In fact, as many previous studies based on the theory and simulations validated, when the game environment implements a certain mechanism to add 'social viscosity' lessening anonymity amid agents, reciprocity such as; direct, indirect, network reciprocity, etc, can be observed even in a severe PD situation, which leads to a higher cooperation. In our result, although there can be observed slightly more cooperation of 'intimate friend' case in a Trivial setting, the difference between 'intimate friend' and 'unknown person' for both PD and Trivial seems unclear, perhaps can be said no different when noting quite large standard deviations. Also, the difference resulting from varying dilemma strength seems unclear, although more cooperation can be observed with the decrease of $D_g^{/}$ in the case of 'unknown person', which is consistent with the theoretical prediction [2.4-2.5]. The only thing we successfully confirmed is the difference of cooperation fractions between PD and Trivial. It implies that people were able to be cognizant of dilemma class differences, i. e., whether he/ she is exposed to PD; a strong dilemma situation, or Trivial; non dilemma situation.

2.3.2.2 Chicken versus Stag Hunt

Table 2.4 shows average and standard deviation of observed cooperation fractions in Case (II); (a) – (d) for Chicken, and (e) – (h) for Stag Hunt. According to what the theory predicting as long as a well-mixed and infinite population for players, cooperation fraction should be 0.5 for all of the settings (a) – (h) because of $D_g^{/} = -D_r^{/}$ ($D_g = -D_r$), irrespective to whether it coming to Chicken or SH, and irrespective to the dilemma strength. However, all of the observed average cooperation fractions except for (f) and (g) presuming 'intimate friend' setting show more than 0.5. Although this might result from the instinct of human tendency that he / she decently behaves to others, it would be said that the observed result is unclear if noting a larger standard deviation against average.

Table 2.4. Summary of the subjective responses according to the questionnaire for CH and SH game by intimate friends and unknown people go through different dilemma strengths (D_g , D_r , $D_g^{/}$, $D_r^{/}$). There are 8 questions in which the first four i.e. (a), (b), (c), (d) belongs to CH and remaining four i.e. (e), (f), (g), (h) are from SH game (fc ± SD = Average cooperation fraction ± standard deviation) .

	CH				**SH**			
	(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
D_g , D_r	500, -500	500, -500	100, -100	100, -100	-100, 100	-100, 100	-500, 500	-500, 500
$D_g^{/}$, $D_r^{/}$	5, - 5	1, -1	1, -1	0.2, -0.2	-0.2, 0.2	-1, 1	-1, 1	-5, 5
Intimate friend (fc ± SD)	0.53 ± 0.50	0.64 ± 0.48	0.6 ± 0.49	0.6 ± 0.49	0.5 ± 0.5	0.46 ± 0.5	0.42 ± 0.5	0.78 ± 0.41
Unknown person (fc ± SD)	0.53 ± 0.50	0.85 ± 0.35	0.6 ± 0.49	0.6 ± 0.48	0.53 ± 0.5	0.57 ± 0.5	0.57 ± 0.5	0.75 ± 0.44

2.3.3 Statistical analysis

We represent Table 2.5 as the summary of the statistical analysis of the χ^2 (Chi-square) test for four different games: PD, Trivial, CH and SH with an intimate friend as well as an unknown person along with dilemma strength. This test quantifies whether the cooperation fraction at each dilemma strength can be seen as significantly different or not. The statistical hypotheses for all the eight cases are denied. It implies that subjects did not recognize the dilemma strength implemented by different $D_g^{/}$ and $D_r^{/}$ (D_g and D_r).

We show Table 2.6 as the statistical analysis of the PD versus Trivial and CH versus SH game by using the T-test. This T-test quantifies whether the average cooperation fraction of all of PD settings are significantly different from that of Trivial or not; and whether the average cooperation fraction of all of CH settings are significantly different from that of SH or not. The result confirms that subjects clearly distinguish the game class difference if both PD and Trivial are imposed but did not for the case comparing CH and SH.

Table 2.5. χ^2 (Chi-square) test is used to determine the dilemma strength but none of them are significant.

Game	**playing with**	**P-value**	**If P-value < 0.05 then**
PD	Intimate friend	0.99696	not significant
	Unknown person	0.98901	not significant
Trivial	Intimate friend	0.99998	not significant
	Unknown person	0.99816	not significant
CH	Intimate friend	0.99971	not significant
	Unknown person	0.99278	not significant
SH	intimate friend	0.98549	not significant
	Unknown person	0.99723	not significant

Table 2.6. T-test: two-sample assuming unequal variances to recognize the different game classes.

Game	**P-value**	**If P-value < 0.05 then**
PD versus Trivial	1.93×10^{-08}	significant
CH versus SH	0.33	not significant

2.4 Conclusion

The most prominent archetype of evolutionary game theory, 2 by 2 game, which is motivated by the current attribute of study for both theoretical and simulation aspects, we dare back to the simplest question; whether a human fairly recognizes social dilemma class and its strength. To answer this question, we designed a quite simple questionnaire survey based on 2 by 2 games with the four game classes. The results suggest that people did not recognize the dilemma strength and showed none of the significant difference in cooperation fraction when premised whether 'intimate friend' or 'unknown person' is a game opponent. But it confirmed that they clearly recognize the difference of game class between and Prisoner's dilemma with sever dilemma and Trivial game with none dilemma game in the perspective of social scenario.

Advocates of our result justification which is diverged from the prediction of the theory show that our game setting to the subjects did not achieve the comprehensive results compared to the social dilemma game setting, i.e., pizza game [2.44] and realistic public goods game [2.45] settings, was employed.

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Chapter 3

Conformity promotes cooperation in network reciprocity in the spatial prisoner's dilemma game

3 Abstract

A new spatial prisoner's dilemma game, conformity, is proposed by considering lattice with underlying network and pairwise Fermi (PW-Fermi) as update rule to enhance network reciprocity mechanism. According to the conformity protocol, a neighbor with more weight resulting from the conformity would be more likely selected as a pairwise opponent in the PW-Fermi updating process instead of random selection the conventional model presuming. A series of systematic simulations confirms that our model realizes more enhanced network reciprocity than the conventional SPD model. This mechanism was explained by presuming the concepts of the END period (the initial time that reduced the global-cooperation fraction from its initial time) and EXP periods (the period, following to END period, the increase in global cooperation fraction) which effectively elucidating how cooperative clusters survive in initial period and extend to defective regions.

3.1 Introduction

From the Darwin era to the current situation, every people are trying to survive themselves at any cost to sustain in the moral society. Usually, people along with researchers from the diverse fields are very interested to know how to sustain '*survival*' among all species (i.e. from life to lifeless beings) within the human and animal societies over dilemma situations throughout the universe [3.1]. In the real-world scenario, these dilemma situations are resolved by Nowak's social viscosity [3.2]. Nowak's social viscosity is classified into the five fundamental mechanisms. Network reciprocity is one of the most important mechanisms for adding 'social viscosity' that is a framework to lessen anonymity amid anonymous game players, i.e., agents. Network reciprocity [3.3-3.5] can be implemented by a simple mechanism, where each player is connected with the underlying social network with limited number of game-opponents who are neighbors. In the network reciprocity, there are two main effects working behind: one is the local gaming mechanism with neighbors, and another is the local adaption mechanism; copying process from neighbors. Those two effects as a whole ensure cooperators' prosperity vis-à-vis defectors by reducing the social dilemma [3.6-3.7], although the model itself presumes the simplest strategy setting; either cooperation (C) or defection (D) — it does not require sophisticated characteristics (i.e., memory and learning mechanisms). So, the so-called prisoner's dilemma (PD) class (e.g., spatial prisoner's dilemma (SPD)) is premised here.

There is less amount of experimental [3.8-3.9]works to enhance the cooperation regarding social dilemmas and many simulation [3.10-3.61] works are performed , as well. In particular, there have been quite a few works concerning network reciprocity, presuming SPD [3.62] as the baseline framework. In line with real world applications, some of those implemented social complex networks as underlying topology [3.63-3.77]. Recently, some works [3.78-3.97] found the central mechanism of network reciprocity whose key idea is that an evolutionary course going from an initial random state to a final equilibrium state can be divided into two temporal periods; END and EXP periods. The term 'enduring period', denoted by END, refers to an initial period in which the global-cooperation fraction, P_c, decreases from its initial value, usually given as a random state of equal numbers of cooperators and defectors (i.e. $P_c(t = 0) = 0.5$). Since initially placed cooperators are exploited by neighboring defectors and immediately become to defector, P_c

decreases in END period. Yet, some cooperators, who successfully form a robust C-cluster such as 'Perfect C-cluster' [3.78] meaning a 3 by 3 cooperators-square on a lattice graph, can survive. Because of this, in 'expanding period'; denoted by EXP, following to END period, those cooperators surviving in END start to grow by letting neighboring defectors to cooperators, which brings the cooperation fraction increasing in EXP period. However those previous works highlighting on END and EXP periods presumed Imitation Max (hereafter, called IM) as strategy updating rule, in which a focal agent deterministically adopts the strategy of one neighbor (amid all his neighbors and himself). There has been another rich history of simulation works for SPD models presuming a stochastic strategy updating rule. Pairwise Fermi (hereafter called PW-Fermi) [3.98-3.100] is most representative one, in which a focal agent copies one of his neighbor's strategy with the probability quantified from none-linear function, Fermi function, of which argument is the payoff difference between him and the specific neighbor he selecting. The neighbor is randomly chosen from the set of all neighbors the focal agent has. Generally, PW-Fermi has been more heavily applied in the previous SPD works as strategy updating rule than IM, because human's adaptation process seems rather stochastic than deterministic. A relatively few studies presuming PW-Fermi with the concept of END and EXP period on the network reciprocity have been discussed.

According to the conformity with PW-Fermi, we have found twofold components; one is stochastically drawing one of neighbors (fixing a pairwise opponent) and another is quantifying the copying probability by referring to Fermi function. A new SPD model is proposed to enhance network reciprocity by means of PW-Fermi rule dovetailed with the so-called conformity rule instead of random pairwise opponent selection in our current study. The conformity is the concept of similarity of strategy a focal agent has in comparison with those of his neighbors. Thus, the original concept of 'conformity' implies that a focal agent takes either cooperation or defection depending on whether cooperation or defection is majority in his neighborhood, which is literally 'conformity' rule. There have been studies implemented the conformity concept and its derived ideas into strategy updating rule [3.101-3.105]. What our model assuming is that a focal agent tends to choose a neighbor having more reliability as a pairwise opponent. Observing the real-world scenario, it seems more realistic than the selection from random choose. The classification of literature review along with MAS with respect to game theoretic approach is shown in Fig.3.1.

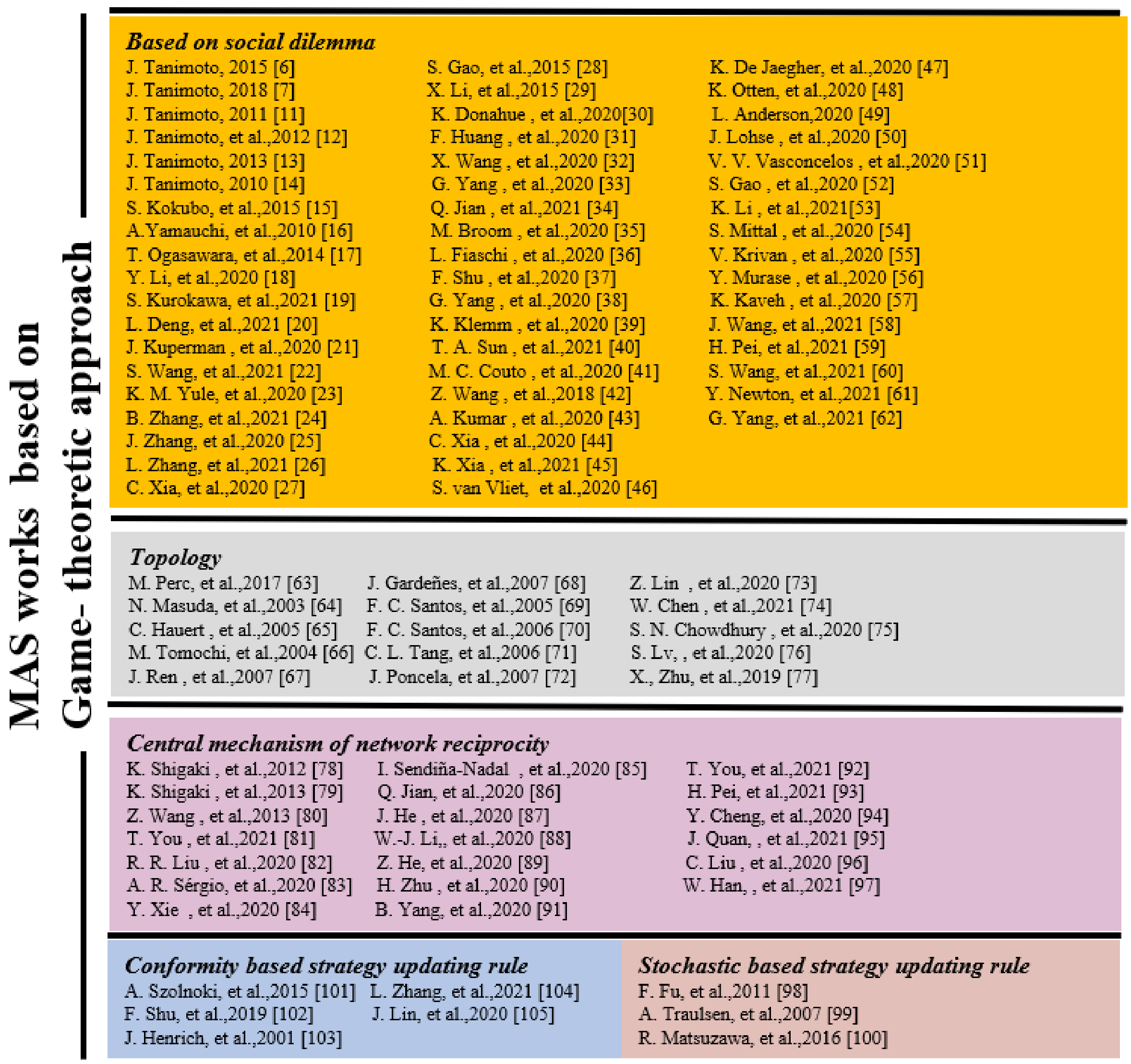

Fig. 3.1: Literature review’s taxonomy based on MAS regarding game-theoretic approach

The remaining part of the paper is organized as follows: Section 3.2 explains our new model and the simulation procedure, Section 3.3 represents and discusses the results, and Section 3.4 presents the conclusions.

3.2. Model description

A two-dimensional (2D) lattice graph is presumed for the underlying topology with a lattice of 100 ×100. The four boundaries of the domain are mutually looped. Thus, the total number of agents was set to N = 10^4, which was confirmed to be sufficiently large to yield simulation results that were reasonably insensitive to system size. Each agent had eight neighbors, which implies the network obeying to Moore neighborhood. After each game, each agent synchronously updates his strategy by referring to one of his eight neighbors, according to the modified update rule, described as below.

As long as agent's interaction, i.e., game, is concerned, let us presume a 2 × 2 (two-player and two strategy) game as an archetype. Each player can adopt one of the two strategies; Cooperation (C) or Defection (D). Players are rewarded (R) for mutual Cs and punished (P) for mutual Ds. If one player chooses C and the other D, the latter receives a temptation payoff (T), and the former is indicated as sucker (S). We define the Chicken-type dilemma as $D_g = T - R$ and the Stag Hunt-type as $D_r = P - S$, respectively [3.106-3.108]. Without losing mathematical generality, PD game is confined by assuming $P = 0$ and $R = 1$ as follows:

$$\begin{pmatrix} R & S \\ T & P \end{pmatrix} = \begin{pmatrix} 1 & D_r \\ 1 + D_g & 0 \end{pmatrix}. \qquad (3.1)$$

In Prisoner's Dilemma (PD) games, the elements are presumed to satisfy $T > R > P > S$ and $2R > T + S$ [3.6-3.7]. The range of both type dilemmas varies within $0 \le D_g(D_r) \le 1$. At each time step, a player occupying a vertex on the network plays PD games with his/her eight neighbors. The total payoff of Agent i; π_i, used for the strategy updating process as below, is obtained by accumulating over eight games he does at each time step.

The key point discussed in this study is the mechanism through which each agent updates his strategy. Traditionally the PW-Fermi rule has been most commonly presumed, where the focal agent i randomly chooses one of his neighbors, say agent j, as his pairwise opponent. agent i

compares his own payoff with that of his opponent (π_j), and the probability that agent *i* copies agent *j*'s strategy is represented by:

$$P_{i \leftarrow j} = \frac{1}{1 + \exp\left(\frac{\pi_i - \pi_j}{\kappa}\right)}, \qquad (3.2)$$

where π_i and π_j indicate the accumulated payoff of the Agent *i* (focal) and Agent *j* (opponent), and the thermodynamic temperature (κ) in the Fermi function is set to 0.1 as a widely accepted value in the previous studies [3.3][3.78][3.80][3.99]. With increase of temperature, $P_{i \leftarrow j}$ approaches to 0.5, meaning the random situation of whether it comes to copying from his opponent or keeping his own strategy.

Instead of random selection, our model obeys to the following process to draw one of agent *i*'s neighbors as his pairwise opponent.

Let us define Conformity to index how agent *j* is reliable (or say, popular, stable) in his neighborhood. Suppose Agent *i* as focal has k_i neighbors. agent *j* ($j\epsilon$ {k_i neighbors}), one of k_i neighbors of agent *i*, has k_j neighbors. Let agent *j*'s strategy be s_j. agent *j*'s conformity in our framework is defined as;

$$Conf_j = \frac{n_{s_{l;l\epsilon\{k_j\}}=s_j}}{k_j}, \qquad (3.3)$$

where the numerator means the number of *j*'s neighbors who have same strategy agent *j* has. Calculate the weight according to the following condition;

If $\pi_j > \alpha \cdot \pi_i$ then $w_j = Conf_j$ otherwise $w_j = 0$. (3.4)

The model parameter α indicates weighting factor. This conditional statement imposes Agent *i* to count up Agent j 's Conformity, defined by Eq. (3.3), to *Weight* only when agent *j* obtains α-time more payoff than agent *i* earning. To this end, we define the probability of agent *i* choosing agent *j* as his pairwise opponent as below;

$$P_{i,j} = \frac{w_j}{\sum_{\ell\in\{k_i\}} w_\ell}. \qquad (3.5)$$

Let alone, if $\sum_{\ell\in\{k_i\}} w_\ell$ is zero, Agent *i* does not copy from any of his neighbors, and does keep his current strategy.

It is worthwhile to note that a neighbor (say j) having less payoff than that of the focal agent (agent i) would be one of possible pairwise opponents if presuming $\alpha < 1$. But this only suggests agent j is ‘eligible’ to be selected. Whether he is really selected or not is another question, which is fully dependent on agent j’s conformity.

Our concept above-formulated might be justified as below. One tends to learn from a neighbor who is evaluated more ‘reliable’. Such ‘reliability’ can be estimated by the fact how he is consistent with his surrounding neighbors, which is called *Conformity* in our model. To grantee more solid ‘reliability’, another condition in terms of payoff should be added, i.e., the focal agent only accounts his neighbor’s *Conformity* if that particular neighbor is prosperous, which is formulated by Eq. (3.4) as the constraint. This is a metaphor that an economically prosperous person who is accommodative with his neighbors would be approximately regarded as ‘socially reliable’.

The procedure of a single simulation episode is presented as follows. In the beginning, equal number of cooperator and defector ($10^4/2$) are randomly generated, which are distributed on different vertices of the network. A single simulation episode runs until the frequency of cooperation reaches a quasi-equilibrium level. The results shown in the following sections are provided from 100 independent simulations, which means our analysis is based on the assemble average of 100 realizations.

3.3 Results and discussion

Fig. 3.2 shows cooperation fraction in PD region within $0 \leq D_g(D_r) \leq 1$. Panel (A) confirms the result of traditional SPD game presuming the conventional PW-Fermi (hereafter called by default model), which realizes a relatively meager network reciprocity. Unlike the case presuming IM and lattice, this setting, where a stochastic strategy updating rule based on PW-Fermi is combined with lattice, inherently has less potential of network reciprocity [3.108]. The result from the present model shows much better than the default model. Therefore, we would be able to say that the present model enhances network reciprocity than the default SPD game. Despite slight difference, with increase of α, the network reciprocity becomes little bit more. Color drawn in the heat-map for our model (panels (B – D)) is observed as more dark than that in panel (A), which implies that the present model attains higher level of cooperation than the default model does.

One notable thing is that the network reciprocity brought by the proposed model more significantly stretches along with D_g-direction than D_r-direction. This fact can be paraphrased that the present model more effectively works for resolving Chicken-type dilemma than Stag Hunt-type dilemma. To solve the puzzle just above, let us take further insight as below. We deliberately explore the case of $\alpha = 1.5$. In practice, we highlight two specific game structures in which the present model brings considerable network reciprocity. One is both Chicken-type and Stag Hunt-type dilemma co-existing; $D_g = D_r = 0.14$, denoted by the red circle in Fig. 3.2 (D), which belongs to what-is-called Donor & Recipient game [3.6-3.7], sub-class of PD. Another is only Chicken-type dilemma existing; $(D_g, D_r) = (0.4, 0.0)$, denoted by the blue triangle in Fig. 3.2 (D).

Fig. 3.3 gives time-evolution of all 100 realizations in case of $D_g = D_r = 0.14$. Fig. 3.4 provides snapshots of representative time-steps from initial chaotic random world via END period to EXP period, which results from one of the 100 realizations highlighted by the red line in Fig. 3.3.

Fig. 3.5 and Fig. 3.6 are counterparts for Fig.3.3 and Fig. 3.4 in case of $(D_g, D_r) = (0.4, 0.0)$.

One thing we should confirm is that the averaged cooperation level in case of $D_g = D_r = 0.14$ is less than that of $(D_g, D_r) = (0.4, 0.0)$.

In case of $D_g = D_r = 0.14$, the valley value of global cooperation fraction; P_c, taking place at the end of END is observed more than 0.1 (Fig. 3.3), which is much more than that in case of $(D_g, D_r) = (0.4, 0.0)$ (Fig. 3.5). This is because relatively larger number of C-clusters surviving until the end of END (see panel of *t* = 9, Fig. 3.4) than that observed in Fig. 3.6. When C-clusters start to expand surrounding defective zone in EXP period, plural C-clusters, if it is too much, mutually hamper to grow more, since defectors among those C-clusters can exploit plural cooperators, thus such defectors could be persistent. This mechanism consequently brings relatively lower cooperation level in case of $D_g = D_r = 0.14$ (Fig. 3.3).

In a nutshell, it would be more favorable if the number of C-clusters surviving in END period would be less. In ideal, only one C-cluster exists at the end of END period, it would be able to smoothly extend to neighboring defective zone in EXP period attaining to a highly cooperative equilibrium. Yet, one can easily suppose that a certain mechanism to bring such ideal situation might be counterproductive, just because a C-cluster surviving as an 'only-one survivor' may/ may not be destroyed by surrounding defectors before starting EXP period. If it is the case; going to extinction, that particular episode ends up with all- defectors- state at somewhere in END period. That is to say; seeking 'ideal' too much, you may 'lose everything'.

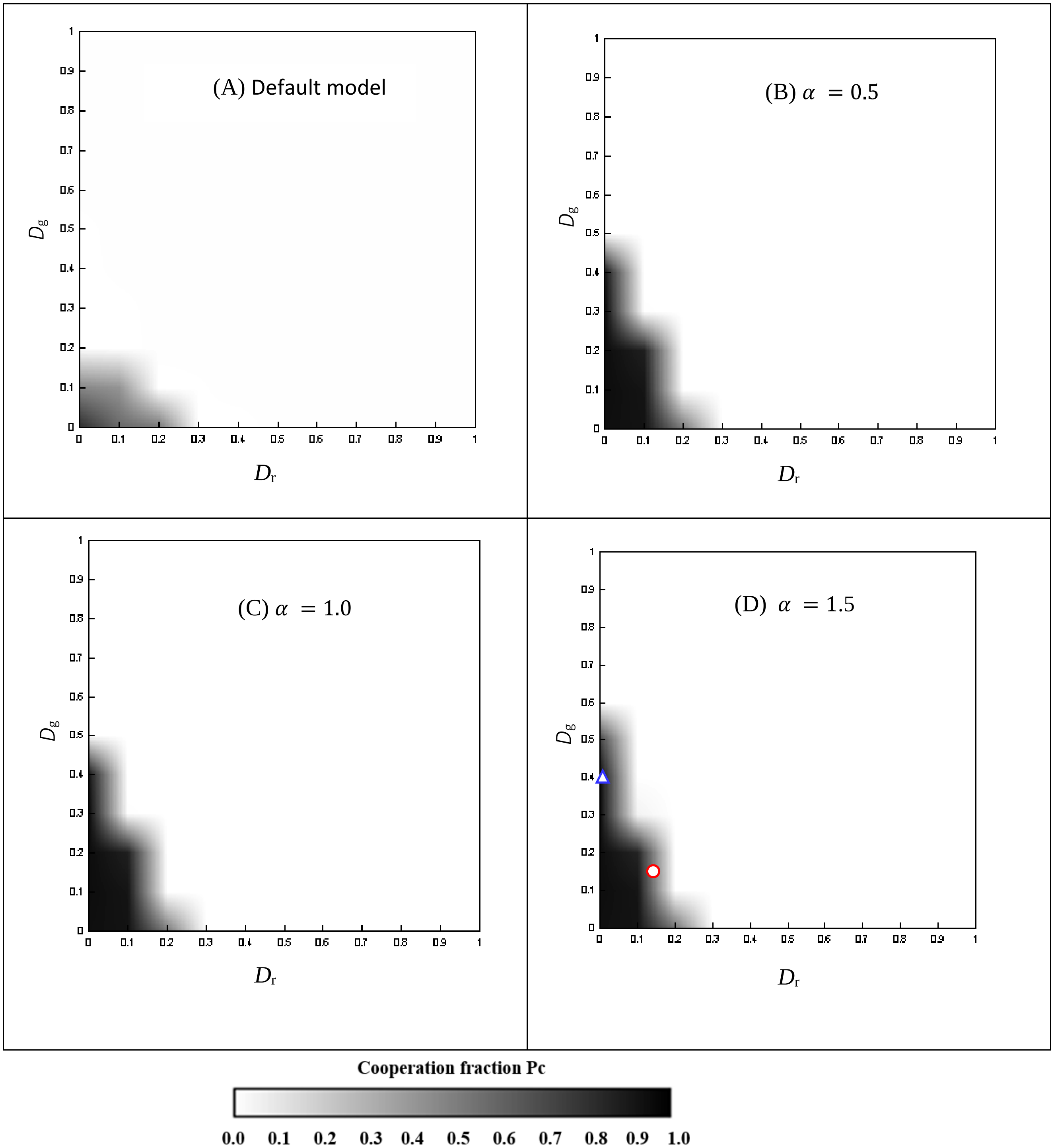

Fig. 3.2: Averaged cooperation fraction over varying dilemmas under the influence of conformity. Games are played with the different parameters of α within the range of $0 \leq D_g(D_r) \leq 1$ on an 8-neighbors lattice (k = 8) with 10000 agents. All contours are drawn from an average of 100

realizations. Equilibrium fraction of cooperators in $D_r - D_g$ diagrams for (A) the default PW-Fermi model, (B) $\alpha = 0.5$, (C) $\alpha = 1.0$, and (D) $\alpha = 1.5$. Red circle and blue triangle respectively point $D_g = D_r = 0.14$ and $(D_g, D_r) = (0.4, 0.0)$, deliberately explored in Figs 3.3 & 3.4 and Figs 3.5 & 3.6.

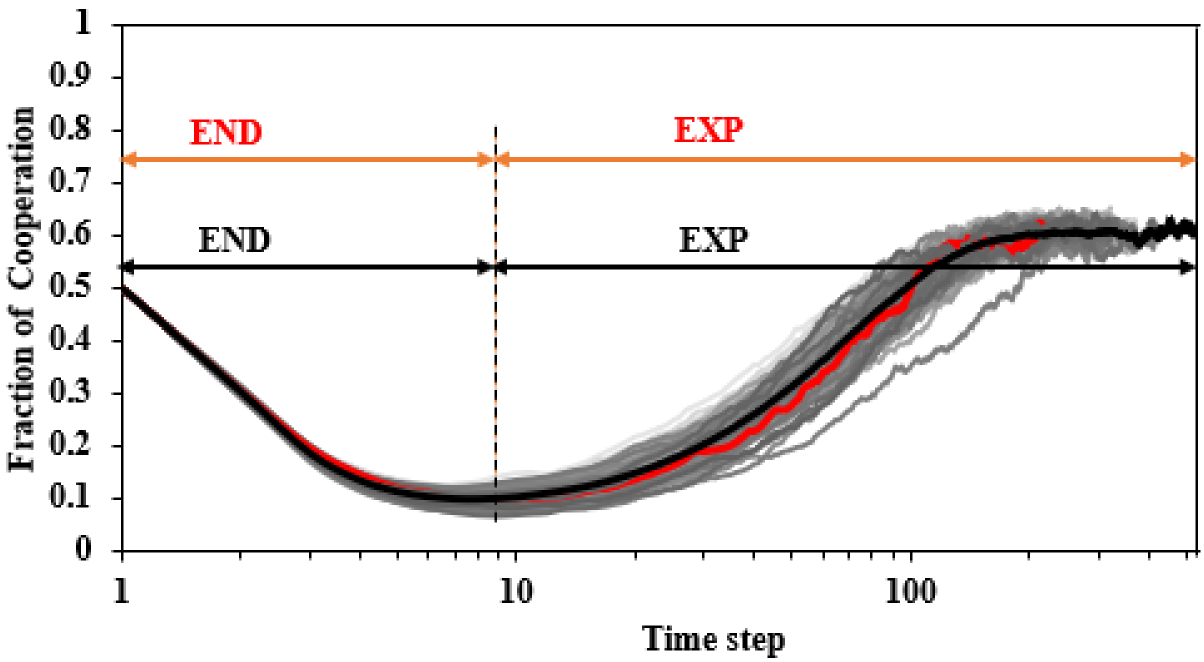

Fig. 3.3**:** Time evolution of the cooperation fraction with conformity-driven players for $\alpha = 1.5$, and PW-Fermi along with lattices are presumed at $D_g = D_r = 0.14$ that was suggested by the red circle in Fig. 3.2 (D). All 100 paths (gray lines) are drawn for END and EXP periods. Black line represents the attainment of average time-evolution. Red line gives the time-evolution of the case discussed in Fig.3.4. Two set arrows to highlight 'END' and 'EXP' are for those for average time-series and that in Fig.3.4.

On the contrary, if another certain mechanism supports letting many C-clusters survive in END period like the panel of t = 9, Fig. 3.4, it certainly becomes less likely to end up with the situation of all-defectors-state in END period abovementioned, but also has less power to let surviving C-clusters grow in EXP period. This trade-off situation can be likened as; seeking 'certainty' (i.e., strongly avoiding all-defectors-state in END period), you may lose chance of 'triumph' but must be satisfied with a 'reasonable win' (i.e., average level of cooperative equilibria observed in Fig. 3.3 cannot be comparable with that in Fig. 3.5).

One thing we should note is that the present model introducing the conformity idea into PW-Fermi does encourage the first effect; less number of C-clusters surviving in END that bringing a high P_c in EXP period, when the environment imposes a stronger Chicken-type dilemma.

More importantly, although the default model could not allow cooperation surviving if a social dilemma becomes more severe with a larger Chicken-type dilemma (refer to the case of $(D_g\ , D_r\ ) = (0.4\ , 0.0)$ and see Fig.3.2 (A)), our new model is able to let cooperation be prosperous. As long as carefully observing Fig.3.5, quite ironically, because of stronger Chicken-type dilemma, i.e. more sever dilemma situation, much higher cooperation can be finally established at equilibrium vis-à-vis Fig. 3.3; the case of $D_g\ = D_r\ = 0.14$. This is because our new model helps cooperators surviving in END period, and subsequently brings small number of cooperative survivors due to the larger dilemma.

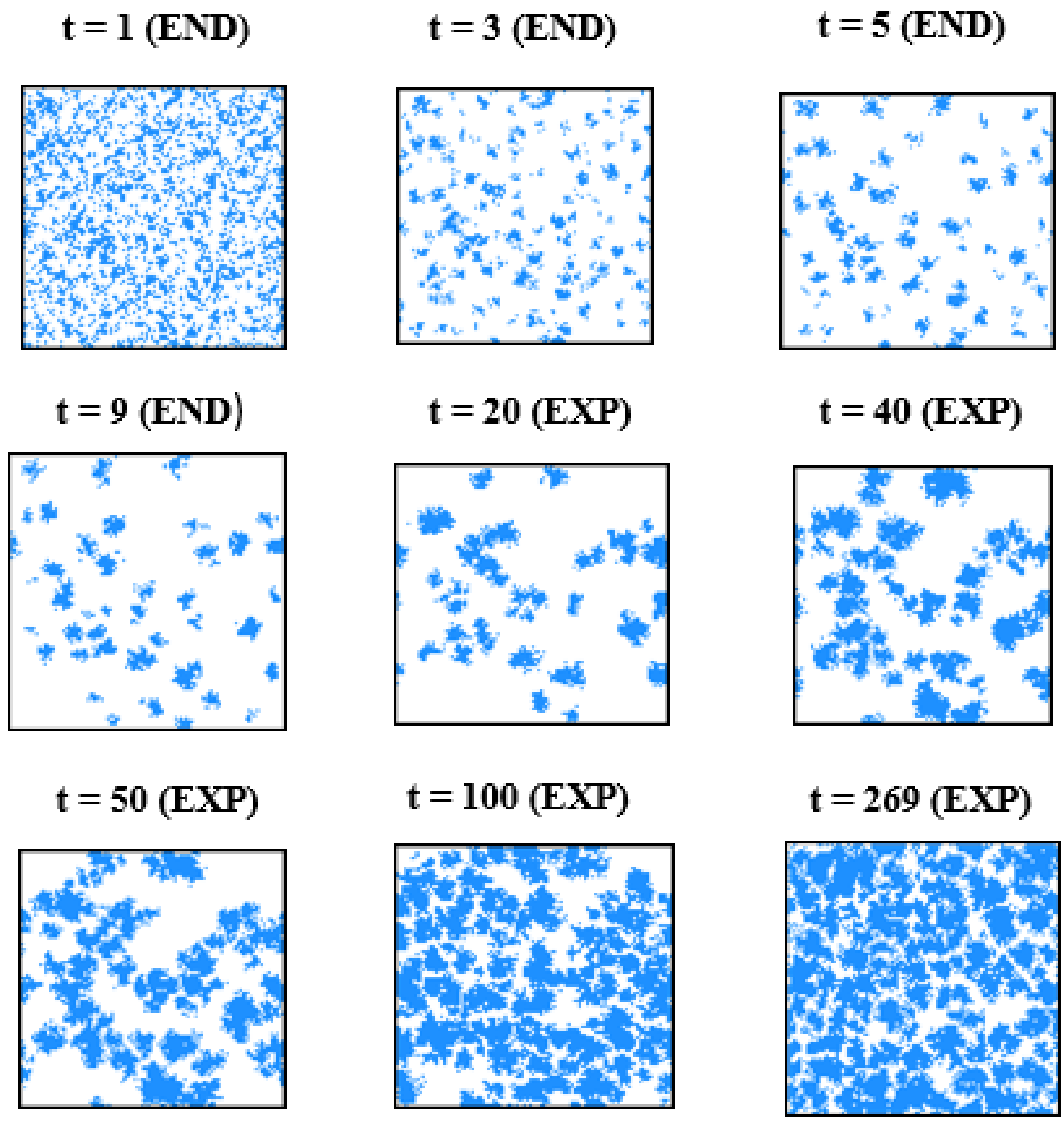

Fig.3.4: Snapshots of cooperators (blue) and defectors (white) over representative episodes for $D_g = D_r = 0.14$ presuming $\alpha = 1.5$, of which time-evolution is given by the red line in Fig. 3.3.

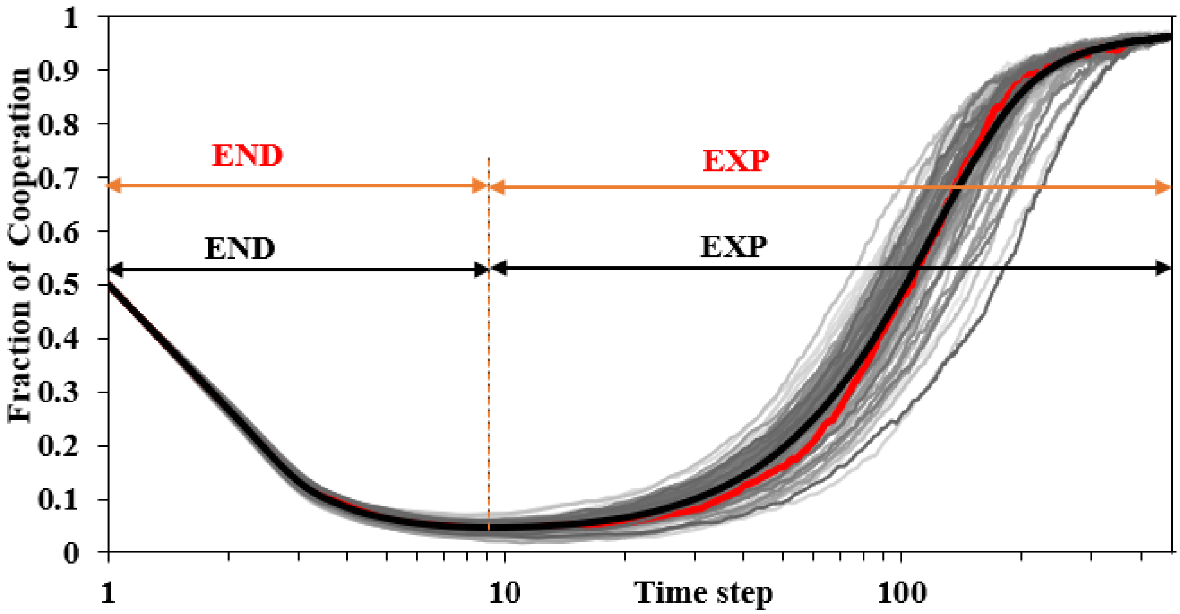

Fig. 3.5**:** Time evolution of the presentative episodes for the cooperation fraction with conformity-driven players for $\alpha = 1.5$, and PW-Fermi along with lattices are presumed at $(D_g, D_r) = (0.4, 0.0)$ that was suggested by the blue triangle in Fig. 3.2 (D). All 100 paths (gray lines) are drawn for END and EXP periods. Black line represents the attainment of average time-evolution. Red line gives the time-evolution of the case discussed in Fig.3.6. Two set arrows to highlight 'END' and 'EXP' are for those for average time-series and that in Fig.3.6.

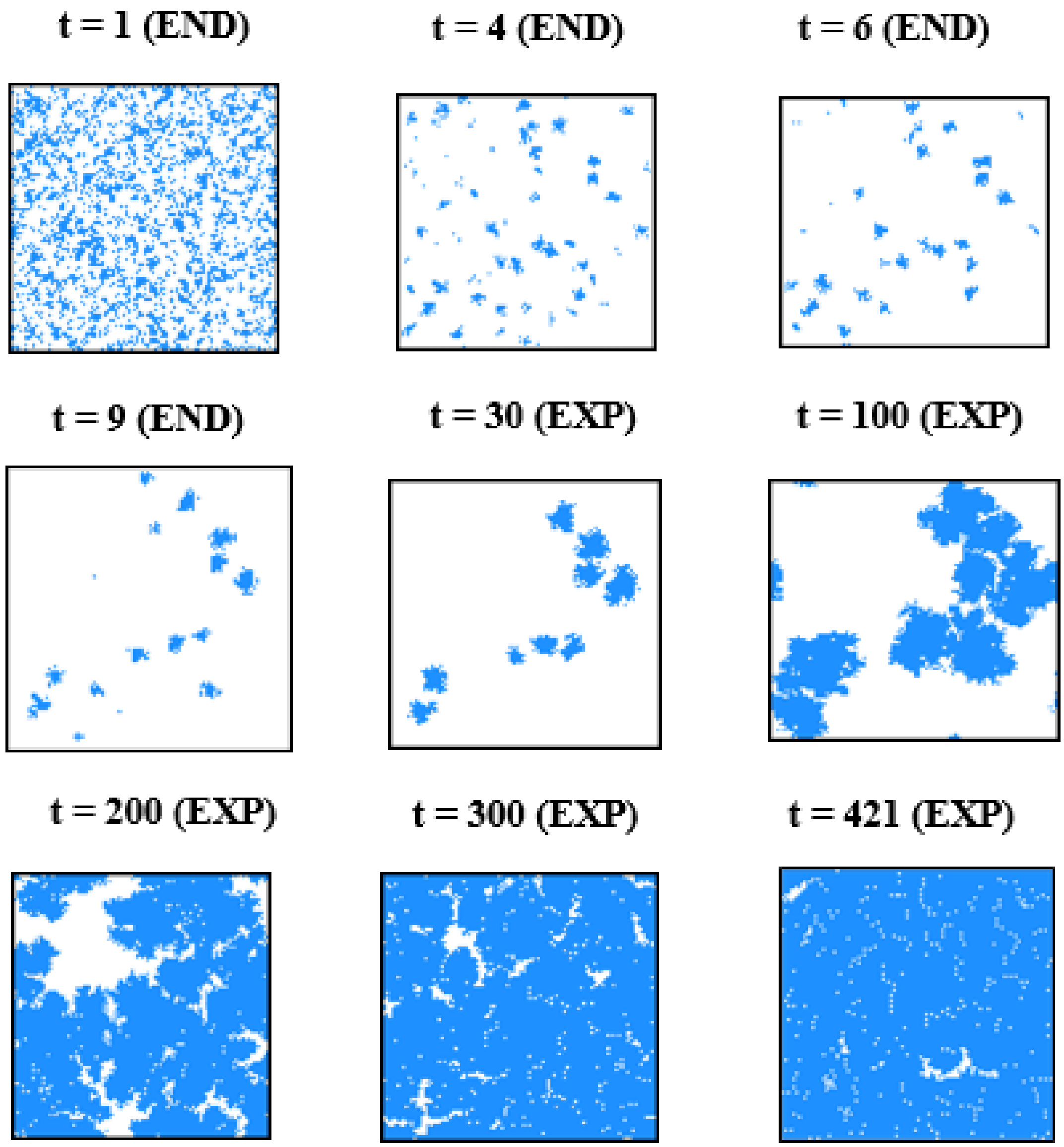

Fig. 3.6: Snapshots of the evolutionary process of the spatiotemporal distribution of cooperators (blue) and defectors (white) at $(D_g, D_r) = (0.4, 0.0)$ presuming $\alpha = 1.5$, of which time-evolution is given by the red line in Fig. 3.5.

A further question coming up here is why the present model helps emerging such additional as well as specific network reciprocity. One conceivable justification is as follows. Suppose a focal cooperative agent, taking a strategy updating, stands on a border of cooperator-defector, i.e., he faces with defective neighbors but still has cooperative neighbors around him because he belongs to a C-cluster. Reminding the model mechanism, where a focal agent strategy-updating tends to choose a high conformity neighbor to reference for the Fermi process, we would say that, if the size of C-cluster being more, this focal cooperator more likely selects a stable cooperative neighbors who lives in the central side of the C-cluster obtaining a high payoff brought by mutual cooperation. It compels him staying cooperation never shifting to defection. And as more importantly, such an event would be more likely if agents are exposed to high D_g than high D_r. It is because Chicken-type dilemma gives advantage to a defector exploiting his cooperator (by allowing T) but never reducing the payoff of a cooperator exploited by neighboring defector that is quantified by none of Stag Hunt-type dilemma. Thus, the reference cooperator to whom the focal cooperator on the border references would keep high level of payoff even if he has small number of defective neighbors.

3.4 Conclusion

A new game model, spatial prisoner's dilemma game, was built from the inspiration by observing the real world scenarios [3.109], where a focal agent, stochastically strategy-updating based on Fermi function, tends to choose a neighbor with a high conformity as the reference of Fermi process.

The simulation judgement showed that the current SPD model is able to realize more enhanced network reciprocity than the conventional default SPD model does. That highly cooperative situation would be more addressed in the region of high Chicken-type dilemma imposed than Stag Hunt-type dilemma.

We explained the mechanical working behind such specific network reciprocity effect by Consulting with the concept of END and EXP periods. The central point is that such stochastically skewed selection mechanism screening a PW-Fermi opponent based on our conformity framework gives advantage to a larger size of C-cluster in END period, which only makes robust C-clusters (perhaps less number) survive in END period when exposed to a larger Chicken-type dilemma, and weed-out weaker C-clusters (perhaps large number).

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Chapter 4

Evolutionary game analysis between two power generation systems to protect the environment

4 Abstract

The demand of power generation has appeared as the major issue for the developed as well as developing countries with the perspective of the real-world scenario. Many factors influence power-producing sectors, including government incentives, customer demand, production cost, eco-friendly, and investors investment to meet up the energy demand. To analyze the cost-benefit-subsidy in power generator system under the evolutionary game setting, we considered two asymmetric game structures by coupling the photovoltaic (PV) power system and coal-fired (CF) power system. To model the asymmetric games for PV and CF, Game-1 considers respective cost and benefit, whereas, Game-2 deliberates cost, benefit, and government subsidy. We present both analytical and numerical approaches within this framework and find that the cost and benefit significantly impact the stable evolutionary strategies. In addition, the power generation system with improve technique can lead to maximize with the help of government policy.

4.1 Introduction

One of the most prominent energy systems, the Photovoltaic (PV) power system, shows that this power system can reduce the power demand. By using the solar potential for power generation system, the PV system shows benefits such as low maintenance, minimum environmental effect, and moderate power generation costs [4.1-4.3]. Besides this, the PV system needs high investment for the installation of the PV panel. Another resource is the coal-fired (CF) power system that meets our demand for energy through power generation. For example, coming to the real-world scenario, the power production structure in china, more than 70% of the coal power system [4.4]. However, the CF system inevitably releases SO_2, dust, CO, etc. As a result, ozone layer destruction, climate warming, acid rain, air pollution, water pollution, and health risks increase day by day. Also, the government plays another vital role in power generation. The government provides subsidies for the PV power system and the CF power system to protect the environment. With the growing fierce global market competition, PV and CF have supported the market environment and meet consumer needs in their interest. So, it can be more flexible in the context of PV and CF system in terms of social and environmental sustainable development [4.5].

Over the last decades, evolutionary game theory (EGT) [4.6] pays more attention and has promoted the significant development. Moreover, the concept and its application of EGT have been expanded swiftly. The more focus of the evolutionary game theory was on the dynamics of strategy (Cooperation or Defection) change as influenced by the various competing systems' in different situations of dilemma game [4.7-4.13]. The essence of the dilemma game precisely describes by Tanimoto and Sagara [4.14] in which they investigated and revealed the idea of GID (gamble-intending dilemma) and RAD (risk-aversion dilemma) to express the social dilemma game [4.15 - 4.21]. At present, EGT is widely recognized as a prominent tool to signify the different characteristics of games such as firm and industry behaviors, broader biological and dynamical systems, economic growth theory, etc., accompanied with the games of symmetric and asymmetric.

The important branch of the game, the symmetric game, is a such type of game in which all the players have the same action, and symmetric payoffs provide in each activity. On the other hand, asymmetric games are such types of games in which players do not share their gains equally, in EGT. Here, different options contract to each player. So, it can be said that the asymmetry games are aroused from the individual differences, phenotype variations such as size, speed, strength, wealth, and environmental variation, based on evolutionary game theory, which is observed in nature. There was substantial development in the study of symmetric games [4.7-4.8] that helped promote sustainable development and improved the ecological conditions. Besides, there was a lot of application on asymmetric games, such as parasitic relationships [4.22], the battle of the sexes [4.23], animal conflicts [4.24], and social variation [4.25-4.33]. Many researchers had conducted their research and analysis on behavior of the environment [4.34-4.39], pollution [4.40-4.47], enterprise [4.48-4.61], electronic collaboration system [4.62-4.64], river with water [4.65-4.69], wind-water system [4.70], electronic devices system [4.71-7.79] ,banks with farms [4.80-4.86], corruption [4.87-4.91],economic field [4.92-4.93], knowledge based share [4.94], and agricultural case [4.95-4.97] with respect to the evolutionary game theory. The phenotype of different articles is elucidated in Fig. 4.1.

We applied the EGT to investigate the behavioral characteristics; cost-benefit-subsidy of the asymmetric games, to the environmental case. Chengrong Pan and Young Long [4.98] established the game model between the microgrid and conventional grid, concluding that the probability of their positive choice correlates with direct and indirect benefits, government subsidies but reciprocal with costs based on evolutionary game theory. The application of game theory studied in the hybrid energy system between PV and wind [4.99]. Again, CF used different technology types to power generation based on the analysis of evolutionary game theory [4.100-4.101]. The previous studies found that PV and CF game models have rarely been studied based on the evolutionary game analysis. Our research's focus depends on strategy selection in the evolutionary game analysis in terms of the environment. Strategies selection are determined by their decision-making behavior within the entire players [4.102].

This study provides the models of the asymmetric evolutionary game to evaluate PV and CF systems' interaction by considering consumer benefits, manufacturers' cost, environmental sustainability, and government subsidy. We have developed two asymmetric game models. First, in Game 1, only cost and benefit for both PV and CF systems are presumed. Both systems compete with each other to keep consumers' maximum benefit and sustainable environment. Next, in Game 2, we assume the cost, benefit, and government subsidy for PV and CF power generation systems. In this context, both systems play with each other for environmental aspects and the government sustainability criteria to get the maximum subsidy. To examine the effect of interaction, we

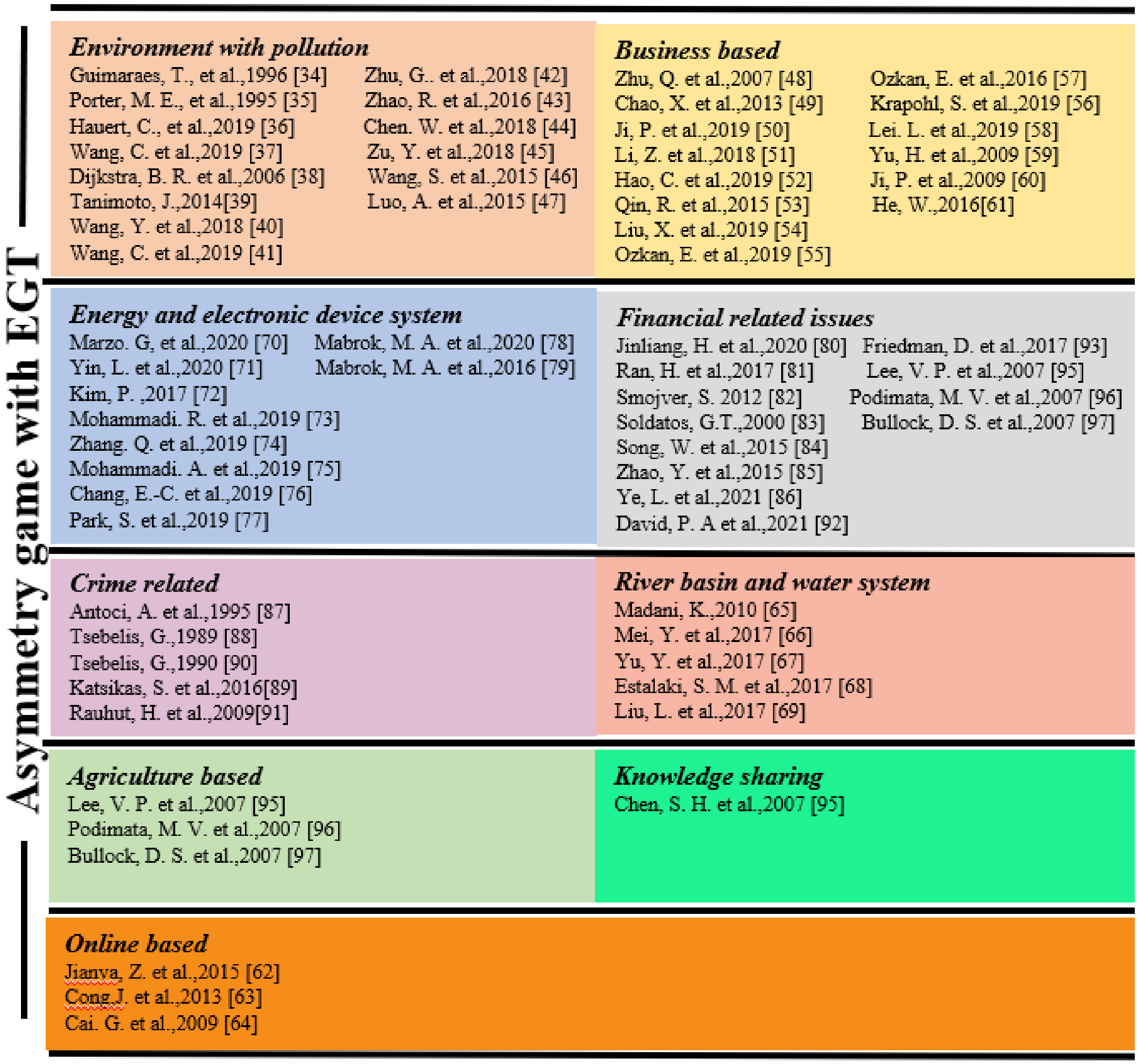

Fig. 4.1: Selected different articles of asymmetric evolutionary games.

perform theoretical analysis as well as numerical simulation to show various stability conditions for different parameter variations.

The remaining part of the paper proceeds as follows: Section 4.2 introduces the model for game 1 with results and discussion; Section 4.3 establishes the model for game 2 with results and discussion; Section 4.4 is the research conclusion.

4.2 Model for game 1

This paper sheds light on the asymmetric game, like Game 1. In this game, PV plays with CF for common parameter resources: cost and benefit.

4.2.1 Game 1

Electricity demand of the consumers to meet up from the power generation has been a crucial point regarding save the environment sustainability. According to the game model, we presume two players: PV and CF power generator systems on the framework of asymmetric evolutionary game theory. Each player adopts two strategies; either cooperation or defection. Cooperation shows that mutual benefits are exchanged with each other instead of competing. Here, 'cooperation' refers to such behavior in which all necessary equipment and requisite things are prepared and utilized to protect an environment that gets consumer benefit and attention. The term 'benefit' means the income of revenue received through the power industry, whereas 'cost' refers to the spend in which the two players burden environmental provision to attract consumers. Being environmental-oriented preference, consumers favor choosing that industry based on the environmental-friendly power generation systems for sustainable development. Although it should be mentioned that the demand level of consumers is flexible, not a fixed value. The interaction between PV and CF power industries with two strategic types, cooperator and defector, can be characterized by a 2 × 2 asymmetric game with the following payoff matrix:

$$\begin{array}{cc} & \begin{array}{cc} \boldsymbol{CF\ (C)} & \boldsymbol{CF\ (D)} \end{array} \\ \begin{array}{c} \boldsymbol{PV\ (C)} \\ \boldsymbol{PV\ (D)} \end{array} & \begin{pmatrix} B_p - C_p, B_c - C_c & \frac{B_p}{2} - C_p, \frac{B_c}{2} \\ \frac{B_p}{2}, \frac{B_c}{2} - C_c & 0, 0 \end{pmatrix} \end{array} \quad (4.1)$$

In this game, if both PV and CF cooperate in maintaining environmental sustainability, they spend the cost, (C_p, C_c), and both receive the benefit (B_p, B_c) of being able to attract consumers. If both game players defect, each pays no cost and receives no benefit. Thus, Game 1 can be explained as follows:

(a) PV and CF, both cooperate: If both systems cooperate, consumers notice that both power generators pay their maximum effort to protect the environment. Therefore, two power industries will get benefit (B_p, B_c) from consumers and spend the costs (C_p, C_c) related to the electric power to meet environmental sustainability (B_p= benefit of PV, B_c= benefit of CF, C_p= cost of PV and C_c= cost of CF). Here, x and y represent the frequencies of cooperation for PV and CF, respectively. However, $1 - x$ and $1 - y$ denote for the frequencies of defection for PV and CF. Here, $(0 \leq x \leq 1, 0 \leq y \leq 1)$.

(b) PV and CF, both defect: If both power generator industries do not pay any attention to protect the environment, the consumers do not purchase any power from those two players. Therefore, both players obtain none of the benefits and pay no cost.

(c) PV cooperates but CF defects and vice versa: If PV cooperates and CF defects, then PV is wished to pay the cost C_p; in contrast, CF is requested to pay the cost C_c, when CF cooperates and PV defects. Meanwhile, both systems share the benefit, (B_p, B_c), equally. This implies that if one of the power systems pay attention to reduce the environmental problem, consumers will see what happened in those two industries. For example, when one of the power generator industry (PV or CF) cooperates and another one defects, the consumer consumes electric power from both systems. Thus, PV and CF share the benefits equally; denoted by $B_p/2$ and $B_c/2$, respectively. Consumers inherently know that one of the power generators does not pay attention to a sustainable environment; however, another pay effort by spending cost.

4.2.2 Result and discussion for game 1

Here we develop a framework for two power generator systems: PV and CF on the framework of asymmetric games in which the payoffs depend on the cost, benefit, and subsidy of the players as well as their strategies. We perform both analytical and numerical analysis to show the interaction between two systems and their corresponding varying parameters.

Analytical approach for game 1

In the framework of Game 1 (equation 4.1), if x and y represent the cooperation fraction of PV and CF, respectively, then the replicator equation can be expressed as follows (see appendix),

$$\frac{dy}{dt} = y(1-y)\left(\frac{B_p}{2} - C_p\right) \tag{4.2}$$

$$\frac{dx}{dt} = x(1-x)\left(\frac{B_c}{2} - C_c\right) \tag{4.3}$$

According to the stability criteria of the Jacobian matrix (see appendix), when $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$, we obtained four equilibria as $(x, y) = (0,0), (0,1), (1,1)$ and $(1,0)$. The equilibria and corresponding ESS (evolutionarily stable strategy) are summarized in Table 4.1. Also, the phase portrayed is displayed in Fig. 4.2 for four equilibrium points.

From Table 4.1, we observe four equilibrium points and corresponding stability conditions (ESS, saddle and unstable). Consequently, figure 4.2 presents four equilibria for various conditions, such as, $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$, (b) $C_p > \frac{B_p}{2}$, $C_c < \frac{B_c}{2}$, (c) $C_p < \frac{B_p}{2}$, $C_c > \frac{B_c}{2}$ and (d) $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ along PV and CF. Here, O, A, B, and C show the equilibria points (0,0), (0,1), (1,1) and (1,0), as, $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$, (b) $C_p > \frac{B_p}{2}$, $C_c < \frac{B_c}{2}$, (c) $C_p < \frac{B_p}{2}$, $C_c > \frac{B_c}{2}$ and (d) $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ along PV and CF. Here, O, A, B, and C show the equilibria points (0,0), (0,1), (1,1) and (1,0), respectively. Detailed of the evolutionary mechanism and stability conditions for Game 1 is described as follows,

Table 4.1: Stability of local equilibrium points for different condition for Game 1.

Equilibrium points (x,y)	$C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$	$C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$	$C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$	$C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$
(0,0)	$-,-$ **ESS**	$-,+$ Saddle	$+,-$ Saddle	$+,+$ Unstable
(0,1)	$+,-$ Saddle	$+,+$ Unstable	$-,-$ **ESS**	$-,+$ Saddle
(1,0)	$-,+$ Saddle	$-,-$ **ESS**	$+,+$ Unstable	$+,-$ Saddle
(1,1)	$+,+$ Unstable	$+,-$ Saddle	$-,+$ Saddle	$-,-$ **ESS**

a) When $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$ (i.e., when the cost of PV is greater than the benefit of PV then it adopts cooperation strategy, in contrast, the cost of CF is greater than its benefit then it adopts cooperation strategy), there are four equilibrium points in the system (Table 4.1) , and it can be inferred from Fig. 4.2(a). Both parties adopting defective strategy is an evolutionary stable strategy (ESS), as the system converges to O (0,0) (shown in Figure 4.2(a)).

b) When $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$ (i.e.,the cost of PV is greater than its benefit when it adopts cooperation strategy, the cost of the CF is less than its benefit when it adopts cooperation strategy), there are four equilibrium points in the system which converges to C(1,0),as seen from Table 4.1 and Fig. 4.2(b).It suggests that PV adopts cooperative strategy and CF chooses the defection strategy ,this point is called as an ESS point.

c) When $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ (i.e., while the cost of PV is less than its benefit when it adopts cooperation strategy, the cost of the CF is greater than its benefit when it adopts cooperation strategy), there are four equilibrium points in the system which converges to A(0,1),as seen from Table 4.1 and Fig. 4.2(c). It suggests that CF chooses cooperative strategy and the PV adopts the defection strategy, this equilibrium point is as ESS point.

d) When $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ (i.e.,the cost of PV is less than its benefit when it adopts cooperation strategy, the cost of the CF is less than its benefit when it adopts cooperation strategy), there are four equilibrium points in the system which converges to B(1,1),as seen from Table 4.1 and Fig. 4.2(d). It suggests that cooperative strategy for both parties is actually an ESS point.

Numerical approach for game 1

To validate our theoretical simulation (Fig. 4.2) by using deterministic method to determine numerical analysis. Numerical simulation is carried out through C/C++ programming to make an in-depth analysis of the evolution of cooperation between PV and CF power system under four cases. The horizontal and vertical axis show the different initial conditions$x(0)$ and $y(0)$ with respect to time. We presume for PV and CF system are (Fig. 4.3);

a) $C_p = 0.5$, $B_p = 0.6$, $C_c = 0.5$, $B_c = 0.7$ ($C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$ **):** This condition will converge to 0 for both, PV and CF (Fig. 4.3(a)). At this situation, PV and CF tends to present defection to generate the electricity.

b) $C_p = 0.3$, $B_p = 0.4$, $C_c = 0.2$, $B_c = 0.5$ ($C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$**):** This system will toward point to 1 for PV and 0 for CF (Fig. 4.3(b)). Thus, this result shows that the tendency of PV allows the cooperation, while CF represents the defection to produce electricity.

c) $C_p = 0.2$, $B_p = 0.5$, $C_c = 0.3$, $B_c = 0.4$ ($C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ **):** This assumed parameters will meet to 0 for PV and 1 for CF (Fig. 4.3(c)). This situation presents cooperation for CF whereas PV is in reverse strategy.

d) $C_p = 0.2$, $B_p = 0.5$, $C_c = 0.2$, $B_c = 0.5$ ($C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ **):**This condition will support 1 for PV and CF both (Fig. 4.3(d)). Both resources provide cooperation to generating electricity.

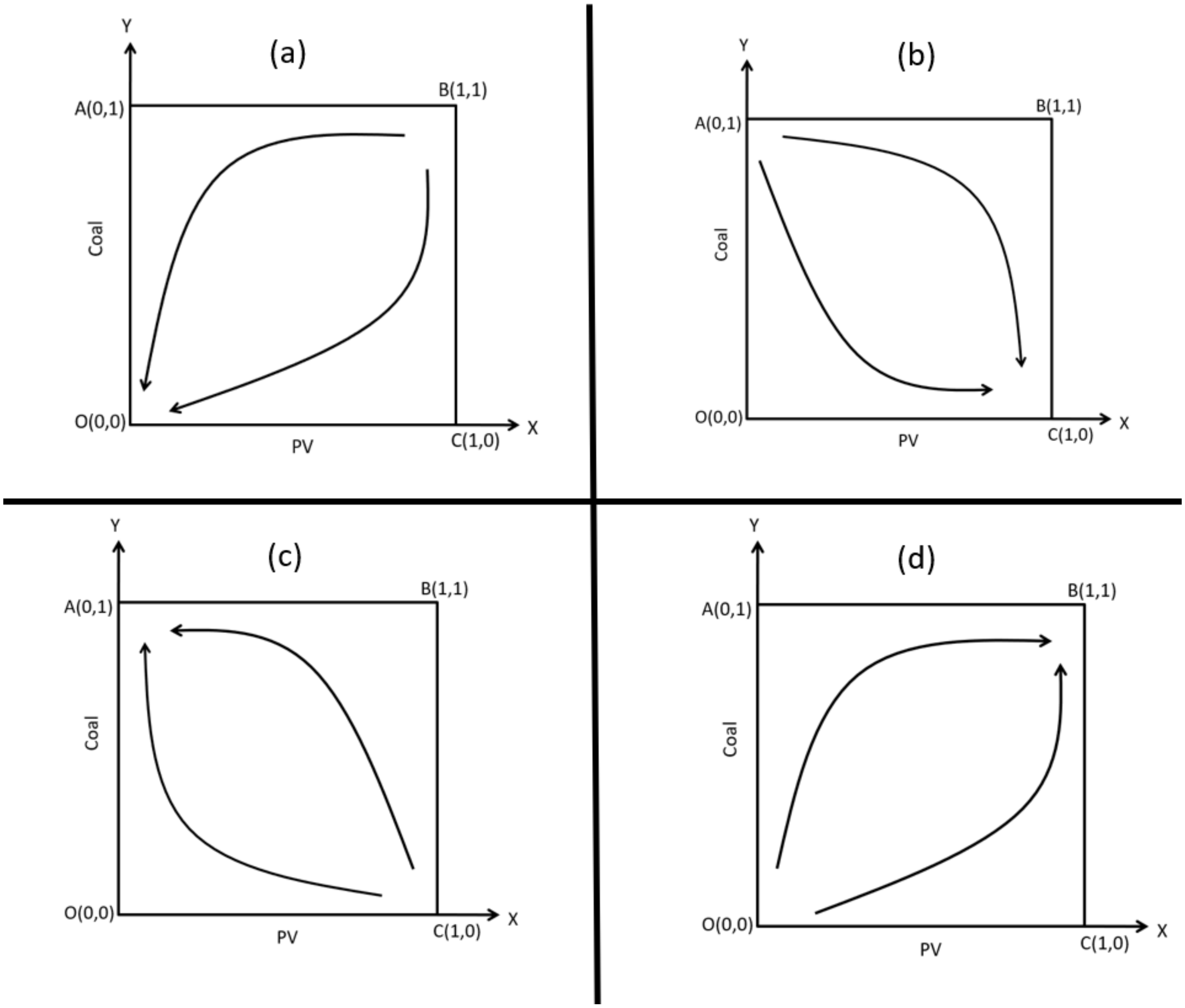

Fig. 4.2: Schematic diagram of dynamic evolution for different conditions; (a) $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$, (b) $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$, (c) $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ and (d) $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ for figures (a), (b), (c) and (d), respectively.

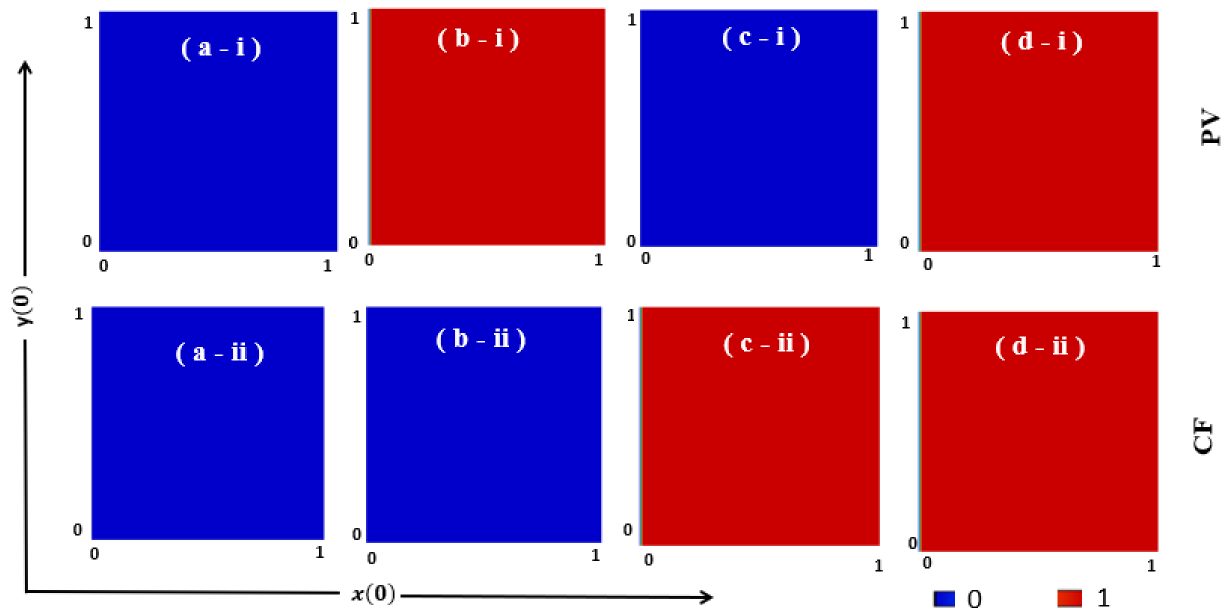

Fig. 4.3: Evolutionary different game phase diagram of PV $(* - i)$ and coal $(* - ii)$ system; (a) $C_p = 0.5$, $B_p = 0.6$, $C_c = 0.5$, $B_c = 0.7$ ($C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$), (b)$C_p = 0.3$, $B_p = 0.4$, $C_c = 0.2$, $B_c = 0.5$ ($C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$) , (c)$C_p = 0.2$, $B_p = 0.5$, $C_c = 0.3$, $B_c = 0.4$ ($C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$) and (d) $C_p = 0.2$, $B_p = 0.5$, $C_c = 0.2$, $B_c = 0.5$ ($C_p < \frac{B_p}{2}$, $C_c < \frac{B_c}{2}$).

4.3 Model for game 2

This study provides the asymmetric game; Game 2. In game 1 as well as game 2, PV plays with CF for common parameter resources: cost and benefit. However, in Game 2, one additional parameter called "government subsidy" is introduced to meet the sustainable environment given by government.

4.3.1 Game 2

The game 1 model showed that the PV and CF power generation system under asymmetric EGT has been considered cost and benefit, which often depends on consumers' interest and environment issue. Thus, it is constructive to introduce government subsidy or reward based on sustainable environment preference. If the government declares the subsidy or reward package for power industries to keep eco-friendly power generation systems for sustainable development, then formulate 2 × 2 asymmetric games (Game 2) as,

$$\begin{array}{cc} & \begin{array}{cc} \boldsymbol{CF\ (C)} & \boldsymbol{CF\ (D)} \end{array} \\ \begin{array}{c} \boldsymbol{PV\ (C)} \\ \boldsymbol{PV\ (D)} \end{array} & \begin{pmatrix} \frac{B_p}{2}+\frac{S}{2}, \frac{B_c}{2}+\frac{S}{2} & 0, B_c + S \\ B_p + S, 0 & \frac{B_p}{2} - C_p, \frac{B_c}{2} - C_c \end{pmatrix} \end{array} \tag{4.4}$$

According to the game, there are two game players (PV and CF) and two external players as consumers and the government. The government provides subsidies for the power industry to protect the environment. Therefore, if both PV and CF cooperate, they support each other and shared the benefit and the government allowance equally. However, both pay the cost to attract consumers and not get any subsidy from authorities when both defects. Game 2 can be summarized as follows:

a) PV and CF, both cooperate: If both players cooperate to protect the environment, they shared their benefits and subsidies equally, $\left(\frac{B_p}{2}+\frac{S}{2}, \frac{B_c}{2}+\frac{S}{2}\right)$.

b) PV and CF, both defect: If both two players do not agree to cooperate to protect the environment, the government imposes some fine or rules to maintain the environmental sustainability. As a result, additional costs termed as C_p and C_c are required, which can be regarded as a government penalty. Thus, if both players defect bring a worse situation for the consumer as well as the government side.

c) PV cooperates and CF defects or vice versa: If one player adopts to cooperate and other agree to defect, the co-operator helps the defector sacrifice both benefit and subsidy. In this situation, PV decides to give his entire allowance and benefit to CF due to a very altruistic mind to save the environment.

4.3.2 Result and discussion for game 2

We have made model for two power generator systems: PV and CF with respect to asymmetric games in which the payoffs rely on the cost, benefit, and subsidy of the players and their strategies. Both analytical and numerical analysis is done to show the interaction between two systems and their various related parameters.

Analytical approach for Game 2

The evolutionary game model for PV and CF, describes the progressive process for the transformation of both sides favorable strategy. Both sides are not adjusting their strategies at the same time. One side needs to decide its strategy by considering the other side's strategy and the payoff the strategy brings. From the evolutionary game theory's perspective, the payoff matrix in the gaming can be expressed as shown in equation 4.4.

Based on these, if PV and coal both choose cooperation strategy, the replicator dynamics differential equation (variant with time) is (see appendix)

$$\frac{dy}{dt} = y(y-1)\left(x\left(\frac{S}{2}+C_p\right)+\frac{B_p}{2}-C_p\right) \tag{4.5}$$

Again,

$$\frac{dx}{dt} = x(x-1)\left(y\left(\frac{S}{2}+C_c\right)+\frac{B_c}{2}-C_c\right) \tag{4.6}$$

According to the evolutionary stability condition of the Jacobian matrix (see appendix), when $\frac{dy}{dt}=0$, $\frac{dx}{dt}=0$,there are the five equilibrium points that can be found as $O(0,0), A(0,1), B(1,1)$, $C(1,0)$ and $E(x^*,y^*)$. From equation (A17) and (A18), the evolutionary strategy matrix concerning between PV and CF is conducted. The equilibrium stability point of the evolution system can be found by analyzing the stability of Jacobian matrix of the system. The Jacobian matrix is expressed as in equation (A19). The equilibrium stability points are obtained (Table 4.2) from the equation (A22-A31) (see appendix). Detailed analysis of the evolutionary game is described as follows.

Table 4.2. Equilibrium stability points for different conditions from equation (A22-A31) for game 2.

Equilibrium point (x,y)	$C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$	$C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$	$C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$	$C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$
(0,0)	$+,+$ Unstable	Saddle	Saddle	$-,-$ **ESS**
(0,1)	$C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$	$C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$	$C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$	$C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$
	$-,-$ **ESS**	$-,-$ **ESS**	Saddle	Saddle
(1,0)	$-,-$ **ESS**	Saddle	$-,-$ **ESS**	Saddle
(1, 1)	$+,+$ Unstable	$+,+$ Unstable	$+,+$ Unstable	$+,+$ Unstable
$\left(\frac{C_p - \frac{B_p}{2}}{C_p + \frac{S}{2}}, \frac{C_c - \frac{B_c}{2}}{C_c + \frac{S}{2}}\right)$	$C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$	$C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$	$C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$	$C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$
	Saddle	Saddle	Saddle	Saddle

a) When $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$ $, S > 0$ (i.e., the cost of PV is greater than its benefit when it adopts cooperative strategy, while the cost of CF is greater than its benefit then it chooses cooperative strategy, the government subsidy is positive), According to the Fig. 4.4 (a) and Table 4.2, A and C are in evolutionary steady-state (ESS), O and B are unstable points, and E is a saddle point. At that situation, the initial state reaches in the upper left area of the system formed by $OABE$, the system converges to the $A(0,1)$. That is to say, CF adopts cooperation strategy and PV chooses non-cooperative strategy, the system goes to stable confrontation state as $A(0,1)$. Again, when the initial states fall in the bottom right area of the system formed by the $OCBE$,the system reaches to $C(1,0)$,that means, PV chooses cooperative strategy and CF chooses defective strategy, as a result, $C(1,0)$ shows a stable confrontation state.

b) When $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$ $, S > 0$ (i.e., the cost of PV is greater than its benefit when it chooses cooperative strategy, while the cost of CF is less than its subsidy when it adopts cooperative strategy, the government subsidy is positive), there are equilibrium points in which meets to A(0,1),as seen from Table 4.2 and Fig. 4.4(b).It suggests that PV adopts defective strategy and CF chooses the cooperative strategy ,the system is an ESS point.

c) When $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ $, S > 0$ (i.e., the cost of PV is less than its benefit when it adopts cooperative strategy, while the cost of CF is greater than its subsidy when it adopts cooperative strategy, the government subsidy is positive), there are equilibrium points in the system which converges to C(1,0), as seen from Table 4.2 and Fig. 4.4 (c). It suggests that PV chooses cooperative strategy and CF adopts the defective strategy, the system is an ESS point.

d) When $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$ (i.e., the cost of PV is less than its benefit when it adopts cooperative strategy, while the cost of CF is less than its subsidy when it adopts cooperative strategy, the government subsidy is positive), there are equilibrium points in the system which converges to O(0,0), as seen from Table 4.2 and Fig. 4.4 (d). It suggests that both parties adopt defective strategy.

Numerical approach for game 2

As we did as above, the horizontal and vertical axis show the different initial conditions $x(0)$ and $y(0)$ with respect to time. We presume different conditions for PV and CF system are (Fig. 4.4);

a) $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$: Through the condition $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$,we have done several analyses.

(i) When the subsidy, S is increased

All these setting parameters (i.e., $C_p = B_p = C_c = B_c = S = 0.5$) other than subsidy, S (i.e. 1, 3 and 10) is symmetric. So, there is no difference on the structure of equal size of the basin for those two players (Fig. 4.5).

(ii) Changing the cost of PV, C_p

We varied C_p. With respect to C_p, there is some sorts of inequality comes up as compared with C_c. If we back to the case of C_p=0.5 and other parameters $B_p = C_c = B_c = 0.5$ and $S = 1$ which recovers totally symmetric case (Fig. 4.6(a)). So perfectly gridline appears again in which equal basins appearing for both two players PV and CF. If we increase the magnitude only for PV in skewed manner which implies C_p= 0.8, because of this, basin of PV decreases like Fig. 4.6(c). In contrast, if we consider C_p = 0.3 the basin of PV increases like Fig. 4.6 (b).

(iii) Changing the benefit of coal, B_c

We changed the magnitude of B_c. After varying B_c, we found some sorts of inequality comes up as compared with B_p. If we adopt the case of B_c=0.5 and other parameters $B_p = C_c = B_c = 0.5$ and $S = 1$ which shows totally a symmetric case (Fig. 4.7 (a)). So, both two players PV and CF show perfectly equal basin. If the benefit only for coal is increased in skewed manner which implies that B_c=0.9, because of this, basin of PV decreases like Fig. 4.7 (c). On the contrary, if we presume B_c=0.2 then the basin of PV increases like Fig. 4.7 (b).

In those comparisons (Figs. 4.5 to 4.7), one may think that why a so-called internal equilibrium does not appear. Let us reference to Fig. 4.6 (c) again for instance. By consulting with the concept of universal dilemma strength [4.1- 4.21], we can confirm that both Chicken-type dilemma strengths, or GIDs, are positive; $D_g|_{PV} = (B_p + S) - \left(\frac{B_p}{2} + \frac{S}{2}\right) = \frac{B_p}{2} + \frac{S}{2} > 0$ and $D_g|_{CF} = (B_c + S) - \left(\frac{B_c}{2} + \frac{S}{2}\right) = \frac{B_c}{2} + \frac{S}{2} > 0$, whereas both Stag Hunt-type dilemma strengths, or RADs, are negative; $D_r|_{PV} = \left(\frac{B_p}{2} - C_p\right) - 0 = \frac{0.5}{2} - 0.8 < 0$ and $D_r|_{CF} = \left(\frac{B_c}{2} - C_c\right) - 0 = \frac{0.5}{2} - 0.5 < 0$. Because of this numeric evaluation, one may expect to observe an internal equilibrium like what can be in a symmetric Chicken game. But we could not see such tendency at all in Fig. 4.6 (c). The observed equilibrium is, instead of polymorphic, bi-stable; either $(x, y) = (1,0)$ (denoted by 'PV' indicating PV to fully cooperative; while CF to fully defective), or $(0,1)$ (denoted by "CF' indicating CF to be fully cooperative). This is because, unlike a symmetric game where quite strong constraint; $x + y = 1$, is imposed, in an asymmetric game like the current model presuming, x and y independently range [0,1], which loses the attraction by internal equilibrium as above and leads to appear a bi-stable equilibrium as we could observe. This is quite common in such an asymmetric game, although most of the previous studies have missed out to discuss.

b) $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$: We presumed the value as; $C_p = 0.2$, $B_p = 0.2$, $C_c = 0.2, B_c = 0.2, S = 0.5$. This condition supports 0 for PV and 1 for CF (Fig. 4.8(a)). This result shows the tendency of PV adopts defection strategy and CF supports cooperation strategy.

c) $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$: We presumed the value as; $C_p = 0.1$, $B_p = 0.5$, $C_c = 0.2, B_c = 0.2, S = 0.5$. This condition converges to 1 for PV and 0 for CF (Fig. 4.8(b)). This result shows the tendency of PV adopts cooperation strategy and CF supports defection strategy.

d) $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$: We presumed the value as; $C_p = 0.2$, $B_p = 0.5$, $C_c = 0.2, B_c = 0.5, S = 0.5$. This condition supports 0 for PV and CF both (Fig. 4.8(c)). At this situation, PV and CF tend to support defection strategy to generate electricity.

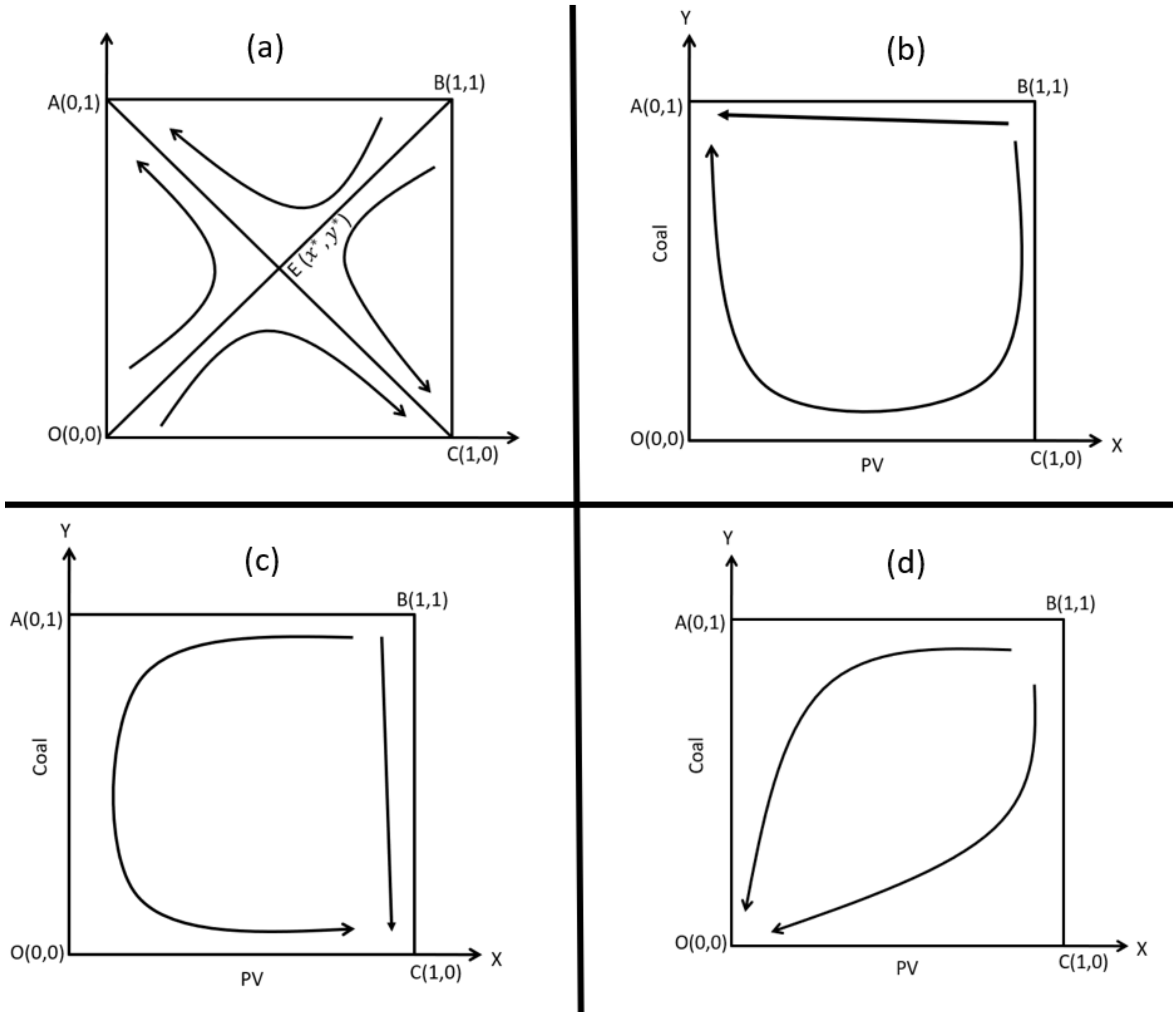

Fig. 4.4: Schematic diagram of dynamic evolution for different conditions; (a) $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$,(b) $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$, (c) $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$ and (d) $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$ for figures (a), (b), (c) and (d), respectively.

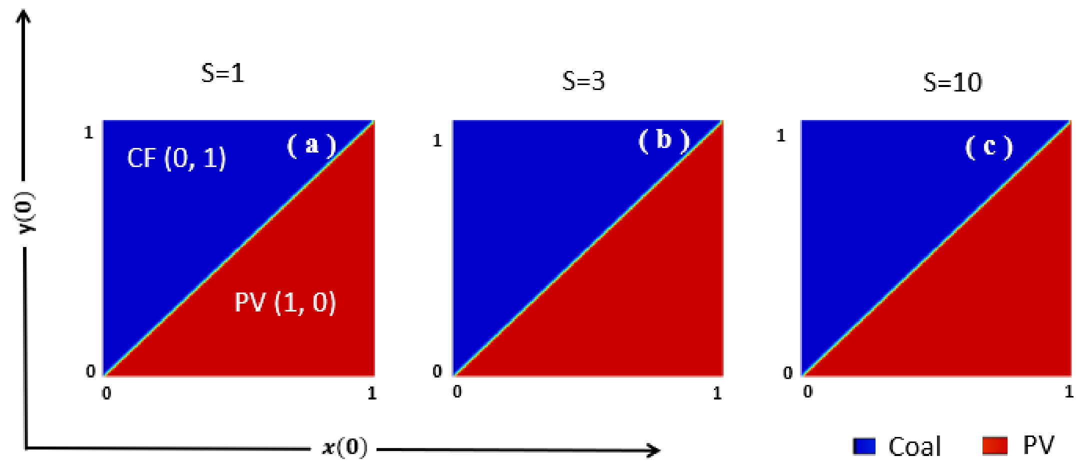

Fig. 4.5: Phase diagram of the evolutionary game analysis between PV and coal; (a) $C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1$ (b) $C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 3$ (c) $C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 10$.

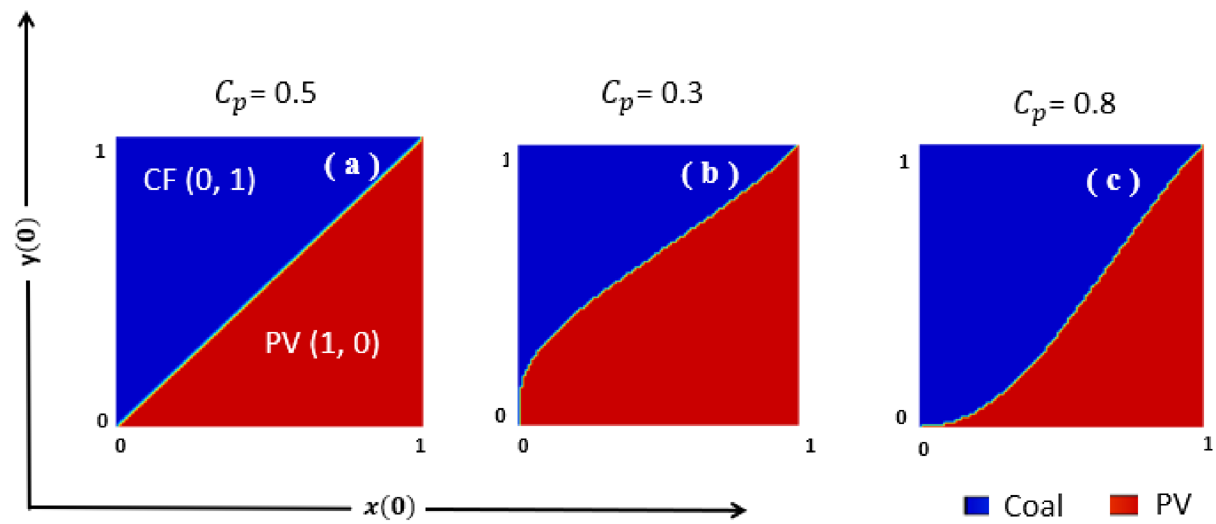

Fig. 4.6: Phase diagram of Evolutionary game analysis between PV and coal; (a) $C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$ (b)$C_p = 0.3$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$ (c) $C_p = 0.8$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$.

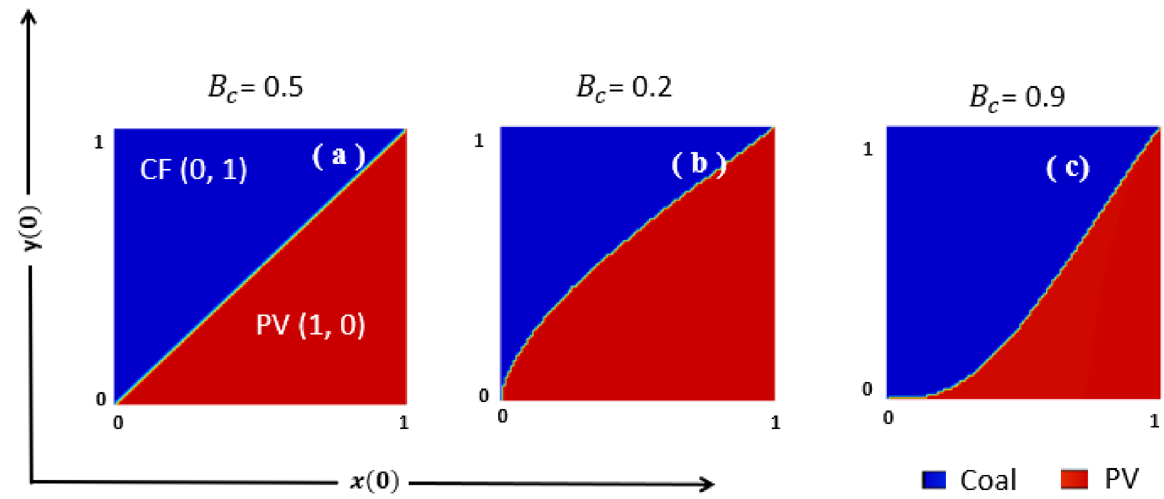

Fig. 4.7: Phase diagram of the evolutionary game for PV and coal system; (a) $C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$ (b)$C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.2, S = 1.0$ (c)$C_p = 0.5$, $B_p = 0.5, C_c = 0.5, B_c = 0.9, S = 1.0$.

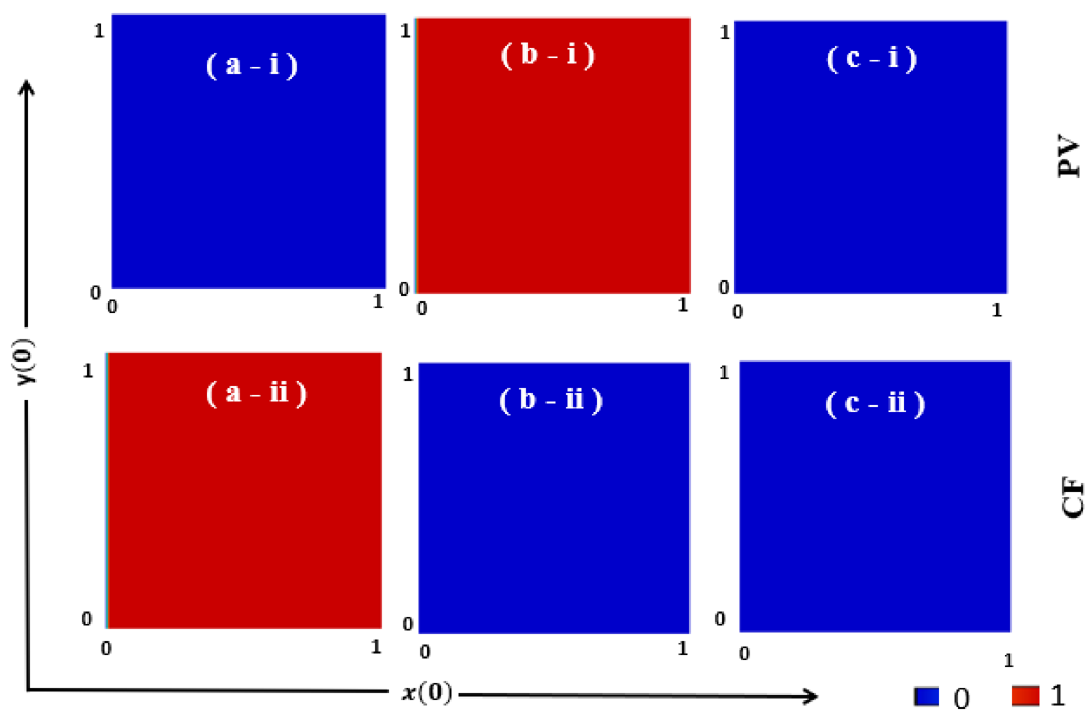

Fig. 4.8: Evolutionary different game phase diagram of PV $(* - i)$ and coal $(* - ii)$ system; (a) $C_p = 0.2$, $B_p = 0.2$, $C_c = 0.2, B_c = 0.2, S = 0.5$ ($C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$) , (b)$C_p =$

0.1 , $B_p = 0.5$, $C_c = 0.2, B_c = 0.2, S = 0.5$ ($C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$, $S > 0$) and (c) $C_p = 0.2$, $B_p = 0.5$, $C_c = 0.2, B_c = 0.5, S = 0.5(C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$, $S > 0)$.

4.4 Conclusion

This article employs the evolutionary game theory to suggest the contribution to the power generation system. According to the evolutionary game theory, two games; game 1 and game 2, are played between two players (PV and CF). Benefits and costs are the presumed parameters for game 1, whereas, in game 2, benefits, costs, and government subsidies are considered for the game players. We explored their impact on evolutionary behaviour between PV and CF. As a result, we tried to find out ESS regarding the different conditions of the games. Furthermore, we verified the theoretical results with numerical simulation.

The research proposal for game 1 is describes as follow.

The adaption of strategic for power generation by PV and CF is correlated with benefits and costs, shown in our game model. According to the simulation analysis, we find that the costs and benefits have more significant impacts on the evolutionary game approach's evolutionary trend.

The suggested proposals for game 2 are as follows.

According to the game model analysis based on evolutionary game theory, government subsidies are useful for motivating power generation. If the government subsidies are increased, then an equal share will be distributed. When the cost of PV is higher than that of CF, so, the consumers tendency will go for CF system to purchase the power. That means the cooperation rate of CF is higher. Furthermore, as CF's benefit is decreased, it becomes lower than that of a PV system, meaning the CF system's has lower cooperation rate to power generation system.

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Chapter 5

Summary and future work

5.1 Conclusive summary

Human life in the society has been facing social dilemmas from the historical period to till now. As a result, many researchers from different diverse scientific fields, are still now affording to recognize the different game classes and to realize the dilemma strength, as well. So, the reactions from human by the behavioral traits show a most important role to understand dilemmas to improve the control efforts. Finally, evolutionary game theory (EGT) is appeared as one of the prominent role model to make the decisions of the rational individuals.

The different rendering approach model regarding EGT was proposed in this doctoral thesis to assess the influence of behavioral changes in response to social dilemma situation, evaluating the potential effects from social dilemmas situation. This study represents the proof of comprehensive analysis of game theoretical models to percept the internal significance and to predict the human possible solutions to survive. The purpose of this thesis is summarized the current studies, and provide recommendations and future research directions, as well. The current study introduces some holistic contributions; mathematical models with different agents, application, advantages and disadvantages, and proposed model has been demonstrated in relevant technical views.

Chapter 1 shows some fundamental features of modeling on behavioral mode, game theory and social dilemma with their strength. Deeply inspired by the study of ancestry, this study tries to capture the basic aspect on behavioral modeling based on human-decision making regarding game theoretical approach.

The experimental game model is the most widely applied models regarding realistic scenario, in which the population is presumed to be well-mixed situation. Chapter 2 is devoted to an experimental 2×2 game model to verify the validity of the game theory with respect to social dilemma aspect. To know the experimental evidence on behavior in social dilemma situations of different game classes: Prisoner’s dilemma (PD), Trivial, Chicken (CH), and Stag-Hunt(SH), a questionnaire based experimental survey is conducted as a structured cross-sectional survey using multiple choice answers through a web-based survey; google form, and field survey; face to face interview. The statistical analysis suggests that subjects clearly distinguish the game class difference if both PD and Trivial are imposed but not for the case of CH and SH game. The experiment outcomes reveal that Prisoner's dilemma and Trivial game are easily acknowledged by the respondents, but the respondents are unable to determine the dilemma strength and the difference of game opponent's attribute whether the opponent is a close or unknown person.

Going through the implementation of basic concepts of EGT, chapter 3, the approach introduced a framework of conformity with spatial prisoner's dilemma (SPD) 2×2 (two-player and two strategy) game model by considering lattice networks. In addition, a stochastic strategy updating rule based on PW-Fermi has been chosen to describe the network reciprocity effects. Based on high conformity, following by fermi process rules, the tendency of a focal agent adopts her neighbors obeying by Moore neighborhood rule. So, to promote the enhancement of cooperation level using the conformity-driven network reciprocity is in-depth explained by a multi-agent simulation (MAS)approach with proper evaluation test. Simulation shows that our stochastic model has more enhanced cooperative situation in the network reciprocity than the conventional model of SPD achieved. This mechanism is due to the concept of END period (the initial period in which global cooperation fraction decreases from its initial value) and EXP period (the period in which global cooperation increases by following END period) that substantially elucidates the survive of cooperative clusters from initial period to defective zones .

To unveil the presence of sustainable environmental situation based on power generation systems in the perspective of human behavior under evolutionary game theory, in chapter 4, we developed asymmetric game model. Here, we focus on two types of asymmetric games; 'Game 1 and Game 2', in which PV (Photovoltaic) works with CF (Coal-fuel) as two common players that relates with two common criteria, such as cost and benefit. Besides, in Game 2, one another parameter called "subsidy" is addressed to meet the sustainable environment supported by the government. We investigated their influence on evolutionary behaviour between PV and CF. Consequently, we endeavoured to figure out ESS (evolutionary stable strategy) with respect to the game's different conditions. Moreover, the theoretical results are verified by the numerical simulation. The numerical simulation results of game 1 suggest that costs and benefits have a more significant effect on the approach of the evolutionary game trend and moreover, the results of game 2 regarding numerical simulation show that government subsidies are very helpful in motivating power generation.

The existence of the above-mentioned chapters, a number of vital significant aspects in many contexts considered by EGT, has been introduced and tried to make the model better with some proposed mechanisms aspects. Finally, people can get help from some divining suggestions getting from these models reckoning with respect to the game theoretical approach, to evaluate the better estimation in the perspective of diverse situation.

5.2 Recommendation and future research direction

This doctoral thesis clarified the successful strategies of the game-theoretic approaches modeling the coupled dynamics of the various situations involving social dilemma game situations, individuals' decision making, and contemplating the strategies of several interventions to realize about the dilemma situations from the observation in the real communities. Experimental models, easier and better perceiving models in real sense of human being, predicting on dilemma games have the potential benefits of performing theoretical examination. Network models of games regarding human contact patterns, can be parsed by the experimental procedure, and build simulation. Besides, relying on game theoretical models of mathematical models, developing a conceptual model, evaluation and validation, not only assist us to recognize the system, but also explore to yield insight into the complex processes involved in the behavior of the system by some important presumption and permits to estimate the influences changes in its environmental conditions on the behavior of the system; that is to say, the control and optimization of the system for future is allowed to execute. As the further extension and future recommendations of the current development models, additional realistic features of game theory and evolutionary dynamics within the proposed model would be addressed. It can be said, the mathematical model used in the chapter 4 was the asymmetric 2×2 game, PV (photovoltaic) and CF (coal-fuel) system, under the evolutionary game settings. We calculate different analysis; theoretical analysis, numerical simulation to show various stability conditions with parameter variations. In real world scenario, such models are not perfectly captured by the all. As future work, experimental survey can be considered to validate the mathematical model more realistic based on real world scenario.

Appendix

Appendix

(Chapter 4)

Evolutionary game analysis between two power generation systems to protect the environment

Game 1

Payoff matrix of game 1

$$\begin{array}{cc} & \begin{array}{cc} \boldsymbol{CF}\ (\boldsymbol{C}) & \boldsymbol{CF}\ (\boldsymbol{D}) \end{array} \\ \begin{array}{c} \boldsymbol{PV}\ (\boldsymbol{C}) \\ \boldsymbol{PV}\ (\boldsymbol{D}) \end{array} & \begin{pmatrix} B_p - C_p,\ B_c - C_c & \frac{B_p}{2} - C_p, \frac{B_c}{2} \\ \frac{B_p}{2}, \frac{B_c}{2} - C_c & 0, 0 \end{pmatrix} \end{array}$$

The benefit for a PV in choosing cooperation strategy is-

$$\Pi_{pc} = x(B_p - C_p) + (1-x)\left(\frac{B_p}{2} - C_p\right) = xB_p - xC_p + \frac{B_p}{2} - \mathrm{C_p} - x\frac{B_p}{2} + xC_p$$

$$= x\frac{B_p}{2} + \frac{B_p}{2} - \mathrm{C_p} \qquad (A1)$$

The benefit for a PV in choosing non-cooperation strategy is-

$$\pi_{pd} = \frac{xB_p}{2} \qquad (A2)$$

The average benefits for a PV in choosing mixed strategies can be derived as

$$\Pi_{pm} = y * \Pi_{pc} + (1-y) * \pi_{pd} = y\left(x\frac{B_p}{2} + \frac{B_p}{2} - C_p\right) + (1-y) * x\frac{B_p}{2}$$

$$= xy\frac{B_p}{2} + y\frac{B_p}{2} - yC_p + \frac{xB_p}{2} - \frac{xyB_p}{2}$$

$$= \frac{B_p}{2}(x+y) - yC_p \qquad (A3)$$

Similarly,

The benefits for coal in choosing cooperation strategy are

$$\Pi_{cc} = y(B_c - C_c) + (1-y)\left(\frac{B_c}{2} - C_c\right) = yB_c - yC_c + \frac{B_c}{2} - C_c - \frac{yB_c}{2} + yC_c$$

$$= \frac{yB_c}{2} + \frac{B_c}{2} - C_c \qquad (A4)$$

The benefits for coal in choosing non-cooperation strategy are

$$\pi_{cD} = \frac{yB_c}{2} \qquad (A5)$$

The average benefits for a coal in choosing mixed strategies can be derived as

$$\Pi_{cm} = x * \Pi_{cc} + (1-x) * \pi_{cD} = x\left(\frac{yB_c}{2} + \frac{B_c}{2} - C_2\right) + (1-x) * \left(\frac{yB_c}{2}\right)$$

$$= \frac{xyB_c}{2} + \frac{xB_c}{2} - xC_c + \frac{yB_c}{2} - \frac{xyB_c}{2} = \frac{B_c}{2} * (x+y) - xC_c \qquad (A6)$$

Based on these, if PV and coal both choose cooperation strategy, the replicator dynamics differential equation (variant with time) is

$$\frac{dy}{dt} = y\left(\Pi_{pc} - \Pi_{pm}\right) = y(x\frac{B_p}{2} + \frac{B_p}{2} - C_p - (\frac{B_p}{2}(\mathrm{x}+\mathrm{y}) - yC_p))$$

$$= y\left(\frac{xB_p}{2} + \frac{B_p}{2} - C_p - \frac{xB_p}{2} - \frac{yB_p}{2} + yC_p\right) = y\left(\frac{B_p}{2} - C_p - \frac{yB_p}{2} + yC_p\right)$$

$$= y\left\{\frac{B_p}{2}(1-y) - C_p(1-y)\right\}$$

$$= y(1-y)\left(\frac{B_p}{2} - C_p\right) \qquad (A7)$$

$$\frac{dx}{dt} = x(\Pi_{cc} - \Pi_{cm}) = x\left(\mathrm{y}\frac{B_c}{2} + \frac{B_c}{2} - C_c - \left(\frac{B_c}{2} * (x+y) - \mathrm{x}C_c\right)\right)$$

$$= x\left(\frac{yB_c}{2} + \frac{B_c}{2} - C_c - \frac{B_c}{2}x - \frac{B_c}{2}y + \mathrm{x}C_c\right) = x\left(\frac{B_c}{2}(1-x) - C_c(1-x)\right)$$

$$= x(1-x)\left(\frac{B_c}{2} - C_c\right) \qquad (A8)$$

The Jacobian matrix is as

$$J=\begin{bmatrix}(1-2y)\left(\frac{B_p}{2}-\ C_p\right) & 0 \\ 0 & (1-2x)(\frac{B_c}{2}\ -\ C_c\ )\end{bmatrix} \quad (A9)$$

Eigenvalue consider:

$$det(J)\ =\begin{bmatrix}(1-2y)\left(\frac{B_p}{2}-\ C_p\right) - \lambda & 0 \\ 0 & (1-2x)\left(\frac{B_c}{2}-\ C_c\ \right)-\lambda\end{bmatrix}$$

According to Eigenvalue condition,

$$det(J)\ =\ 0$$

⇨ $\begin{bmatrix}(1-2y)\left(\frac{B_p}{2}-\ C_p\right)\ -\ \lambda & 0 \\ 0 & (1-2x)\left(\frac{B_c}{2}-\ C_c\ \right)-\lambda\end{bmatrix}=0$

⇨ $\{(1-2y)\left(\frac{B_p}{2}-\ C_p\right)\ -\ \lambda\ \}\{(1-2x)\left(\frac{B_c}{2}-\ C_c\ \right)-\lambda\ \}=0$

Let, $a\ =\ (1-2y), b\ =\ \left(\frac{B_p}{2}-\ C_p\right), c\ =\ (1-2x), d\ =\ \left(\frac{B_c}{2}-\ C_c\ \right)$

⇨ $(ab\ -\ \lambda)(cd-\ \lambda)\ =\ 0$

⇨ $abcd - ab\,\lambda\ - cd\,\lambda\ -\ \lambda^2\ = 0$

⇨ $\lambda^2 -\ \lambda(ab+cd)+abcd=0$

⇨ $\lambda^2 -\ \lambda\{(1-2y)\left(\frac{B_p}{2}-\ C_p\right)+\left((1-2x)\left(\frac{B_c}{2}-\ C_c\ \right)\right\}+\ (1-2y)\left(\frac{B_p}{2}-\ C_p\right)(1-2x)\left(\frac{B_c}{2}-\right.$

$\left.C_c\ \right)=0$

$\Rightarrow\ \lambda^2 - \lambda\{ (\frac{B_p}{2} - C_p - 2y\frac{B_p}{2} + 2yC_p) + \mathbf{(}\ \frac{B_c}{2} - C_c - 2x\frac{B_c}{2} + 2xC_c\mathbf{)\}}\ + (1-2y)(1-2x)\left(\frac{B_p}{2} - C_p\right)\left(\frac{B_c}{2} - C_c\right) = 0$

$\Rightarrow\ \lambda^2 - \lambda(\frac{B_p}{2} - C_p - 2y\frac{B_p}{2} + 2yC_p + \frac{B_c}{2} - C_c - 2x\frac{B_c}{2} + 2xC_c) + (1-2x-2y+4xy)(\frac{B_pB_c}{4} - \frac{B_p}{2} * C_c - C_p * \frac{B_c}{2} + C_pC_c) = 0$

$$=> \lambda_1(\lambda_2) = \frac{(\frac{B_p}{2} - C_p - \mathbf{2y}\frac{B_p}{2} + 2yC_p + \frac{B_c}{2} - C_c - 2x\frac{B_c}{2} + 2xC_c) \pm \sqrt{(\frac{B_p}{2} - C_p - 2y\frac{\mathrm{B}}{2} + 2yC_p + \frac{B_c}{2} - C_c - 2x\frac{\mathrm{B}}{2} + 2xC_c)^2 - 4.1.(1-2x-2y+4xy)(\frac{B_p}{2}\frac{B_c}{2} - \frac{B_p}{2} * C_c - C_p * \frac{B_c}{2} + C_pC_c)}}{2}$$

(A10)

Game 2

Payoff matrix of game 2

$$\begin{array}{ccc} & \boldsymbol{CF\ (C)} & \boldsymbol{CF\ (D)} \\ \boldsymbol{PV\ (C)} & \frac{B_p}{2} + \frac{S}{2}, \frac{B_c}{2} + \frac{S}{2} & 0, B_c + S \\ \boldsymbol{PV\ (D)} & B_p + S, 0 & \frac{B_p}{2} - C_p, \frac{B_c}{2} - C_c \end{array}$$

We could get the expected benefit for PV chosen cooperation strategy is:

$$\Pi_{pc} = x\left(\frac{B_p}{2} + \frac{S}{2}\right) = x\frac{B_p}{2} + x\frac{S}{2} \qquad (A11)$$

The expected benefit for a PV in choosing non-cooperation strategy is:

$$\Pi_{pD} = x(B_p + S) + (1-x)\left(\frac{B_p}{2} - C_p\right)$$

$$= xB_p + xS + \frac{B_p}{2} - C_p - \frac{xB_p}{2} + xC_p = \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p \qquad (A12)$$

So, the average expected benefits for a PV in choosing mixed strategies can be derived as $\Pi_{pm} = y * \Pi_{pc} + (1-y) * \Pi_{pd}$

$$= y\left(x\frac{B_p}{2} + x\frac{S}{2}\right) + (1-y) * \left(\frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p\right)$$

$$= xy\frac{E_p}{2} + xy\frac{S}{2} + \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p - \frac{yxE_p}{2} - yxS - \frac{yE_p}{2} + y\,C_p - xyC_p$$

$$= -xy\frac{S}{2} + \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p - \frac{yB_p}{2} + y\,C_p - xyC_p \qquad (A13)$$

Similarly,

The expected benefit for coal chosen cooperation strategy is:

$$\Pi_{CC} = y\left(\frac{B_c}{2} + \frac{S}{2}\right) = \frac{yB_c}{2} + \frac{yS}{2} \qquad (A14)$$

The expected benefit for coal chosen non-cooperation strategy is:

$$\pi_{CD} = y\,(B_c + S) + (1-y)\left(\frac{B_c}{2} - C_c\right) = yB_c + yS + \frac{B_c}{2} - C_c - y\frac{B_c}{2} + y\,C_c$$

$$= y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c \qquad (A15)$$

Then, the average expected benefits for a coal chosen mixed strategies can be derived as

$$\Pi_{cm} = x * \Pi_{CC} + (1-x) * \pi_{CD}$$

$$= x\left(\frac{yB_c}{2} + \frac{yS}{2}\right) + (1-x) * \left(y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c\right)$$

$$= x\frac{yB_c}{2} + x\frac{yS}{2} + y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c - xy\frac{B_c}{2} - x\,yS - \frac{xB_c}{2} + xC_c - xy\,C_c$$

$$= -x\frac{yS}{2} + y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c - \frac{xB_c}{2} + xC_c - xy\,C_c \qquad (A16)$$

Based on these, if PV and coal both choose cooperation strategy, the replicator dynamics differential equation (variant with time) is

$$\frac{dy}{dt} = y(\Pi_{pc} - \Pi_{pm})$$

$$= y\left(x\frac{B_p}{2} + x\frac{S}{2} - \left(-xy\frac{S}{2} + \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p - \frac{yB_p}{2} + y\,C_p - xyC_p\right)\right)$$

$$= y\left(x\frac{B_p}{2} + x\frac{S}{2} + xy\frac{S}{2} - \frac{xB_p}{2} - xS - \frac{B_p}{2} + C_p - xC_p + \frac{yB_p}{2} - y\,C_p + xyC_p\right)$$

$$= y\left(-x\frac{S}{2} + xy\frac{S}{2} - \frac{B_p}{2} + C_p - xC_p + \frac{yB_p}{2} - y\,C_p + xyC_p\right)$$

$$= y\left(x\frac{S}{2}(y-1) + \frac{B_p}{2}(y-1) - C_p(y-1) + xC_p(y-1)\right)$$

$$= y(y-1)\left(x\left(\frac{S}{2} + C_p\right) + \frac{B_p}{2} - C_p\right) \qquad (A17)$$

Again,

$$\frac{dx}{dt} = x(\Pi_{CC} - \Pi_{Cm})$$

$$= x\left(\frac{yB_c}{2} + \frac{yS}{2} - \left(-x\frac{yS}{2} + y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c - \frac{xB_c}{2} + xC_c - xy\,C_c\right)\right)$$

$$= x(\frac{yB_c}{2} + \frac{yS}{2} + x\frac{yS}{2} - y\frac{B_c}{2} - yS - \frac{B_c}{2} + C_c - y\,C_c + \frac{xB_c}{2} - xC_c + xy\,C_c)$$

$$= x(\frac{yS}{2} + x\frac{yS}{2} - yS - \frac{B_c}{2} + C_c - y\,C_c + \frac{xB_c}{2} - xC_c + xy\,C_c)$$

$$= x(\frac{yS}{2} + x\frac{yS}{2} - yS - \frac{B_c}{2} + C_c - y\,C_c + \frac{xB_c}{2} - xC_c + xy\,C_c)$$

$$= x(\frac{yS}{2}(x-1) + \frac{B_c}{2}(x-1) - C_c(x-1) + y\,C_c(x-1))$$

$$= x(x-1)(\frac{yS}{2} + \frac{B_c}{2} - C_c + y\,C_c)$$

$$= x(x-1)\left(y\left(\frac{S}{2} + C_c\right) + \frac{B_c}{2} - C_c\right) \qquad (A18)$$

The Jacobian matrix is as

$$J = \begin{bmatrix} (2y-1)(x\left(\frac{S}{2}+C_p\right)+\frac{B_p}{2}-C_p) & y(y-1)(\frac{S}{2}+C_p) \\ x(x-1)(\frac{S}{2}+C_c) & (2x-1)(y\left(\frac{S}{2}+\ C_c\right)+\frac{B_c}{2}-\ C_c) \end{bmatrix} \quad (A19)$$

Eigen value consider as:

$$det(J) = \begin{bmatrix} (2y-1)(x\left(\frac{S}{2}+C_p\right)+\frac{B_p}{2}-C_p) - \lambda & y(y-1)(\frac{S}{2}+C_p) \\ x(x-1)(\frac{S}{2}+C_c) & (2x-1)(y\left(\frac{S}{2}+\ C_c\right)+\frac{B_c}{2}-\ C_c)-\lambda \end{bmatrix}$$

According to Eigen value condition,

$$det(J) \ = \ 0$$

$$\Rightarrow \begin{bmatrix} (2y-1)(x\left(\frac{S}{2}+C_p\right)+\frac{B_p}{2}-C_p) - \lambda & y(y-1)(\frac{S}{2}+C_p) \\ x(x-1)(\frac{S}{2}+C_c) & (2x-1)(y\left(\frac{S}{2}+\ C_c\right)+\frac{B_c}{2}-\ C_c)-\lambda \end{bmatrix} = 0$$

$$\Rightarrow ((2y-1)(x\left(\frac{S}{2}+C_p\right)+\frac{B_p}{2}-C_p) - \lambda)((2x-1)(y\left(\frac{S}{2}+\ C_c\right)+\frac{B_c}{2}-\ C_c)-\lambda)-\ (\,x(x-1)(\frac{S}{2}+ C_c))(\,y(y-1)(\frac{S}{2}+C_p)) = 0$$

$$\lambda_1 = \frac{1}{4}(-B_c - \ B_p + 2C_c + 2C_p + 2B_c x - 4C_c x - 2C_p x - Sx + 2B_p y \ - 2C_c y - 4C_p y - Sy + 4C_c xy + 4C_p xy + 4Sxy - \sqrt{\left(B_c + B_p - 2C_c - 2C_p - 2B_c x + 4C_c x + 2\,C_p x + Sx - 2B_p y + 2C_c y + 4C_p y + Sy - 4C_c xy - 4C_p xy - \ 4Sxy\right)^2 - 4\left(4C_c C_p - 12C_c C_p x - 2C_c Sx + 8C_c C_p x^2 + 4\,C_c S x^2 - 12\,C_c C_p y - 2C_p Sy + 32C_c C_p xy + 4C_c Sxy + 4C_p Sxy - 20C_c C_p x^2 y - 10C_c S x^2 y - 2C_p S x^2 y - S^2 x^2 y + 8C_c C_p y^2 + 4C_p S y^2 - 20C_c C_p x y^2 - 2C_c S x y^2 - 10C_p S x y^2 - S^2 x y^2 + 12C_c C_p x^2 y^2 + 6C_c S x^2 y^2 + 6C_p S x^2 y^2 + 3S^2 x^2 y^2 + \ B_c\,(-1+2x)\left(B_p + 2C_p(-1+x) + Sx\right)(-1+2y) + B_p(-1+2x)(-1+2y)(2C_c(-1+y)+Sy)\right)}\Big)$$

$$(A20)$$

$$\lambda_2 = \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p + 2B_c x - 4C_c x - 2C_p x - Sx + 2B_p y - 2C_c y - 4C_p y - Sy + 4C_c xy + 4C_p xy + 4Sxy + \sqrt{\left(B_c + B_p - 2C_c - 2C_p - 2B_c x + 4C_c x + 2C_p x + Sx - 2B_p y + 2C_c y + 4C_p y + Sy - 4C_c xy - 4C_p xy - 4Sxy\right)^2 - 4\big(4C_c C_p - 12C_c C_p x - 2C_c Sx + 8C_c C_p x^2 + 4C_c Sx^2 - 12C_c C_p y - 2C_p Sy + 32C_c C_p xy + 4C_c Sxy + 4C_p Sxy - 20C_c C_p x^2 y - 10C_c Sx^2 y - 2C_p Sx^2 y - S^2 x^2 y + 8C_c C_p y^2 + 4C_p Sy^2 - 20C_c C_p xy^2 - 2C_c Sxy^2 - 10C_p Sxy^2 - S^2 xy^2 + 12C_c C_p x^2 y^2 + 6C_c Sx^2 y^2 + 6C_p Sx^2 y^2 + 3S^2 x^2 y^2 + B_c(-1+2x)\big(B_p + 2C_p(-1+x) + Sx\big)(-1+2y) + B_p(-1+2x)(-1+2y)(2C_c(-1+y) + Sy)\big)}\Big)$$

$$(A21)$$

$x = 0, y = 0$

$$\lambda_1 = \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p - \sqrt{((B_c + B_p - 2C_c - 2C_p)^2 - 4(-2B_p C_c + B_c(B_p - 2C_p) + 4C_c C_p)}))$$

$$(A22)$$

$$\lambda_2 = \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p + \sqrt{((B_c + B_p - 2C_c - 2C_p)^2 - 4(-2B_p C_c + B_c(B_p - 2C_p) + 4C_c C_p)}))$$

(A23)

$x = 0, y = 1$

$$\lambda_1 = \frac{1}{4}\left(-B_c + B_p - 2C_p - S - \sqrt{\left(B_c - B_p + 2C_p + S\right)^2 - 4(-B_c(B_p - 2C_p) - B_p S + 2C_p S)}\right)$$

$$(A24)$$

$$\lambda_2 = \frac{1}{4}\left(-B_c + B_p - 2C_p - S + \sqrt{\left(B_c - B_p + 2C_p + S\right)^2 - 4(-B_c(B_p - 2C_p) - B_pS + 2C_pS))}\right) \quad (A25)$$

$x = 1\,, y = 0$

$$\lambda_1 = \frac{1}{4}\left(B_c - B_p - 2C_c - S - \sqrt{\left((-B_c + B_p + 2C_c + S\right)^2 - 4(2B_pC_c + 2C_cS - B_c\left(B_p + S\right)))}\right) \quad (A26)$$

$$\lambda_2 = \frac{1}{4}\left(B_c - B_p - 2C_c - S + \sqrt{\left((-B_c + B_p + 2C_c + S\right)^2 - 4(2B_pC_c + 2C_cS - B_c\left(B_p + S\right)))}\right) \quad (A27)$$

$x = 1\,, y = 1$

$$\lambda_1 = \frac{1}{4}\left(B_c + B_p + 2S - \sqrt{(-B_c - B_p - 2s)^2 + 4(B_pS + S^2 + Bc(B_p + S))}\right) \quad (A28)$$

$$\lambda_2 = \frac{1}{4}\left(B_c + B_p + 2S + \sqrt{(-B_c - B_p - 2s)^2 + 4(B_pS + S^2 + Bc(B_p + S))}\right) \quad (A29)$$

$$x = \frac{C_p - \frac{B_p}{2}}{C_p + \frac{S}{2}}, \qquad y = \frac{C_c - \frac{B_c}{2}}{C_c + \frac{S}{2}}$$

$$\lambda_1 = -\frac{1}{2}\sqrt{\frac{(B_c - 2C_c)\left(B_p - 2C_p\right)(B_c + S)\left(B_p + S\right)}{(2C_c + S)\left(2C_p + S\right)}} \quad (A30)$$

$$\lambda_2 = \frac{1}{2}\sqrt{\frac{(B_c - 2C_c)\left(B_p - 2C_p\right)(B_c + S)\left(B_p + S\right)}{(2C_c + S)\left(2C_p + S\right)}} \quad (A31)$$