The Paradox of Corruption in Civil Society

مفارقة الفساد في المجتمع المدني

By

Rasha Sayed Abdelhamid Ibrahim

Student ID 90106

Dissertation submitted in partial fulfilment of the requirements for the degree of MSc Informatics (Knowledge and Data Management)

Faculty of Engineering & Information Technology

Dissertation Supervisor
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Abstract

Cooperation is one key aspect of human social behavior. Principally, punishment drives the evolution of cooperation in societies. The issue of how to promote and maintain cooperation is one of the main topics of the game theory. Punishment is an effective and successful mechanism in promoting the cooperation in public good interactions. Although peer punishment is a key mechanism for sanctioning free-riders to promote cooperation, it is unstable because of the second-order free-riders, such as cooperators who refuse to punish defectors. Centralized sanctioning institutions punish defectors and eliminate second-order free-rides by sanctioning cooperators. Centralized institutions have complete dominance over the population including peer punishment, which results into a stable regime. However, this behavior raises some questions; is this centralized institution really stable? If so, then why does strong centralized punishment sometimes fail to maintain cooperation? Does cooperation in societies require decentralized enforcement in addition to the centralized authority? Why some countries tolerate a form of peer punishment as legitimate? This thesis introduces corruption in the model to study the stability of the strong centralized institutions and the evolving of peer punishment together with the centralized authority. This thesis PGG (Public Good Game) model shows that the effectiveness of this strong centralized authority is compromised when corruptors bribe pool-punishers. With strong centralized institution sanctioning, this institution is considered as a single point of failure and is susceptible to corruption, which prevents peer punishment from maintaining cooperation while the social welfare is worsened. On the contrary, with weaker centralized institution sanctioning, the peer punishment is given a room to restore the cooperation and relatively the social welfare. This thesis results prove that in the presence of corruption, the stability of strong centralized authority collapses and social welfare deteriorates. This strong centralized institution can promote cooperation and restore social welfare, if and only if, it allows a legitimate form of citizen-driven peer punishment form.

الخلاصة

التعاون جانب رئيسي من السلوك الاجتماعي البشري. في الأساس يدفع العقاب تطور التعاون في المجتمعات . مسألة كيفية تعزيز ومواصلة التعاون هي واحدة من المواضيع الرئيسية لنظرية اللعبة. العقاب هو آلية فعالة وناجحة في تعزيز التعاون في تفاعلات الصالح العام. على الرغم من أن عقاب الأقران هو آلية أساسية لفرض عقوبات على الدراجين الأحرار من أجل تعزيز التعاون، إلا أنها آلية غير مستقرة بسبب الدراجين الأحرار من الدرجة الثانية، مثل المتعاونين الذين يرفضون معاقبة المنشقين . مؤسسات العقاب المركزية تعاقب المنشقين وتقضي على الدراجين الأحرار من الدرجة الثانية من خلال فرض عقوبات على المتعاونين . المؤسسات المركزية لديها هيمنة كاملة على السكان بما في من يقوم بعقاب الأقران، مما يؤدي إلى نظام مستقر. ومع ذلك، يثير هذا السلوك بعض الأسئلة؛ هل هذه المؤسسة المركزية مستقرة حقا؟ إذا كان الأمر كذلك، فلماذا يفشل العقاب المركزي القوي أحيانا في الحفاظ على التعاون؟ هل يتطلب التعاون في المجتمعات الإنفاذ اللامركزي بالإضافة إلى السلطة المركزية؟ لماذا تتسامح بعض الدول في شكل من أشكال عقاب الأقران باعتباره شرعي؟ تقدم هذه الأطروحة الفساد إلى النموذج لدراسة استقرار المؤسسات المركزية القوية و تطورة عقاب الأقران معا مع السلطة المركزية. ويبين نموذج نظرية لعبة الصالح العام لهذا البحث أن فعالية هذه السلطة المركزية القوية تتدهور عندما يقوم المفسدون برشوة من يقوم بعقاب المجموعة. مع فرض عقوبات قوية من المؤسسة المركزية، تعتبر هذه المؤسسة بمثابة نقطة محتملة للفشل و عرضة للفساد، الأمر الذي يمنع عقاب الأقران من الحفاظ على التعاون بينما يسوء الرفاه الاجتماعي. على العكس من ذلك، مع عقاب أضعف من المؤسسة المركزية، يتم إعطاء عقاب الأقران مساحة لاستعادة التعاون و نسبيا الرفاه الاجتماعي. تثبت نتائج هذه الأطروحة أنه في وجود الفساد، ينهار استقرار السلطة المركزية القوية و يتدهور الرفاه الاجتماعي. يمكن لهذه المؤسسة المركزية القوية أن تعزز التعاون و أن تستعيد الرفاه الاجتماعي، إذا وفقط إذا، سمحت بشكل مشروع من أشكال عقاب الأقران التي يحركها المواطن.

Acknowledgements

I would like to express my thanks to all whom supported me in this thesis. First and foremost, I dedicate special thanks to my mentor and supervisor, Professor Doctor Sherief Abdalla. Had it not been for his guidance, advices, and consistent support, I would not have been here discussing my thesis nor its results that are currently under review by the Journal of the Royal Society Interface as part of the research paper titled “Corruption Drives the Emergence of Civil Society.”

I would also like to thank my family; my husband, my mother and my children for their relentless support, patience, and understanding.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(Rasha Sayed Abdelhamid Ibrahim)

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Chapter 1

1 Overview

1.1 Introduction

Cooperation is a fundamental aspect of human social behavior. Social sanctioning is an effective strategy for promoting and maintaining cooperation among selfish individuals. Peer punishment is a key mechanism for sanctioning free-riders to promote cooperation in public good provisions. Nevertheless, it is still considered unstable because of the second-order free-riders such as cooperators who refuse to punish defectors. Experimental evidences from PGG show that centralized sanctioning institutions punish defectors and eliminate second-order free-rides by sanctioning cooperators, thus leading to greater levels of cooperation. Centralized institutions, pool-punishers, prevail, replace all populations including peer punishment and establish a stable regime.

The dominance and the stability of the pool punishment create some issues; is this centralized institution really stable? If the centralized institution is stable, why does strong centralized punishment sometimes fail to maintain cooperation? If the centralized institution is dominant, why cooperation in some societies requires decentralized enforcement in addition to the centralized authority? Why some countries tolerate a form of peer punishment as legitimate?

This thesis introduces the strategy of corruption in the model to explain why centralized institution sometimes fail, why societies want to limit the severity of centralized punishment, and why peer punishment evolves together with the centralized authority. This thesis PGG model shows that the effectiveness of this strong centralized authority gets compromised when corruptors bribe pool-punishers. This thesis also introduces the strategy of hybrid-punishers in the PGG model to explain why peer punishment is more effective in increasing the cooperation level in the presence of corruption.

This thesis results shows that with strong centralized institution sanctioning, this institution is considered as a single point of failure and is prone to corruption, which prevents peer punishment from maintaining cooperation while the social welfare deteriorates. In contrast, with weaker centralized institution sanctioning, the peer punishment is given a chance to restore the cooperation and relatively the social welfare. This thesis results also prove that in the presence of corruption, the stability of strong centralized authority completely collapses and social welfare is worsened. This strong centralized institution can promote cooperation and relatively restore social welfare, if and only if, it allows a form of citizen-driven peer punishment in policing the commons.

1.2 Problem Statement

Since long time ago, to best govern a society and promote collaborative efforts is one of the main topics of the game theory (Hardin 1968; Hobbes 1960). Punishment is an effective mechanism in promoting the cooperation in public good interactions (Gächter, Renner & Sefton 2008; Henrich et al. 2006; Herrmann, Thoeni & Gächter 2008).

Although the importance of punishment for promoting cooperation is confirmed, the best way to maintain cooperative behavior in a society is debatable. Is it well-maintained by a centralized sanctioning authority via sanctioning institutions (Hardin 1968; Hobbes 1960) or is it best preserved by more decentralized enforcement via peer-punishers (Dietz, Ostrom & Stern 2003; Kropotkin 1907).

Decentralized enforcement is a key mechanism to ensure cooperation in societies (Nowak 2006). Different forms of peer punishment have been extensively studied and assessed using evolutionary models and behavioral experiments (Axelrod 2006; Boyd & Richerson 1992; Egas & Riedl 2008; Fehr & Gächter 1999; Ohtsuki et al. 2006; Santos, Pacheco & Lenaerts 2006), however, this costly punishment evolution and stability is still a debatable question (Fehr & Gächter 2002). Alternatively, individuals' punishment for free-riders can be done by adopting social-ties for avoiding free-riders interaction (Santos, Pacheco & Lenaerts 2006).

Although the vital role of peer punishment in promoting cooperation is highly respected, it suffers from the presence of counter-punishment (Fehr & Gächter 1999; Nikiforakis 2008). It also suffers from second-order free-riders (Dreber et al. 2008; Fowler 2005b; Panchanathan & Boyd 2004). Solving this second-order free-riders problem by punishment mechanism leads to unlimited revert (Fowler 2005b). Moreover, costly peer punishment positively affects the cooperation level but has a negative effect on the average payoff of the group (Dreber et al. 2008). Various peer punishment mechanisms in PGG models impose fines on free-riders after the PGG (Yamagishi 1986).

Recently, several researches show that the centralized authority, pool-punishers, is proven to be performing better punishment than decentralized authority, peer-punishers, despite of being costly as it eliminates second-order free-riders (Ostrom 1990; Sigmund et al. 2010; Traulsen, Röhl & Milinski 2012). Sigmund et al. (2010) presents a pool punishment model where individuals contribute to centralized authority which sanctions free-riders. This pool punishment model avoids second-order free-riders as the central authority punishes whoever does not contribute to common pool punishment. Though, human societies prefer delegating punishment to centralized sanctioning and legitimate authority regardless of being costly (Baldassarri & Grossman 2011; Sigmund et al. 2010; Traulsen, Röhl & Milinski 2012;).

Although Sigmund et al. (2010) model shows that the centralized pool punishment prevails, replaces all populations including peer punishment and establishes a stable regime; this kind of pool punishment dominance creates three riddles.

First; Sigmund et al. (2010) results imply that the centralized and legitimate authority ultimately establishes a very stable regime and thus increases cooperation in societies. However, low levels of participation in public goods are observed in several authoritarian states that have the tendency to increase the level of individuals' punishment (Acemoglu

& Robinson 2012; Deacon 2009; Lake & Baum 2001). Second; Sigmund et al. (2010) results also imply that centralized authority, pool-punishers, promptly prevail, replacing other population including peer-punishers and establishing a stable regime. On the other hands, most of human societies demonstrate combination of centralized and decentralized forms of punishment (Harcourt 2011; Moghadam 2012; Morsi 2013). Third; Sigmund et al. (2010) results also imply that the pool-punishers punish peer-punishers as they do not contribute to the common pool punishment, however, in human societies, several forms of political participation, such as jury duty are considered as social peer punishment (Fowler & Kam 2007; Grechenig, Nicklisch & Thöni 2010; Smirnov et al. 2010).

1.3 Questions the Research Addresses

This thesis aims to answer the following research questions?

1. Can the evolutionary game model explain why strong centralized punishment sometimes fails to maintain cooperation in societies? Could it be because of corruption? Does cooperation in societies require decentralized enforcement in addition to the centralized authority?

2. Can the evolutionary game model explain why some countries tolerate a form of peer punishment as legitimate?

3. Can the evolutionary game model explain the correlation of social welfare to strong stability of centralized authority? to corruption? and to legitimate pool-peer-punishers?

1.4 Contributions

In this section, thesis main contributions are outlined. The following illustration shows how the thesis work answers the research questions in details.

1. Can the evolutionary game model explain why strong centralized punishment sometimes fails to maintain cooperation in societies? Could it be because of corruption? Does cooperation in societies require decentralized enforcement in addition to the centralized authority?
   This thesis results imply that using the Sigmund et al. (2010) PGG model, as the second-order punishment severity increases, the pool-punishers have a complete dominance over the population and totally replaces peer-punishment, thus, cooperation increases. A new corruption strategy is applied to Sigmund et al. (2010) PGG model. This thesis results also prove that the effectiveness of this centralized authority is compromised when corruptors bribe pool-punishers. Moreover, the increase in second-order punishment severity increases corruption

and decreases cooperation. Furthermore, in the presence of corruption, peer punishment becomes more effective in increasing the cooperation level

2. Can the evolutionary game model explain why some countries tolerate a form of peer punishment as legitimate?
   The hybrid punishment is introduced as a form of legitimate peer punishment and is applied to Sigmund et al. (2010) PGG model in the presence of corruption. The thesis results prove that centralized authorities should legalize certain forms of social peer punishment to maintain cooperation in the presence of corruption. The results imply that in the presence of corruption, the hybrid punishment is more effective in maintaining cooperation even if with severe second-order punishment. As the second-order punishment severity increases, the hybrid-punishers have almost complete dominance over the population and the cooperation increases

3. Can the evolutionary game model explain the correlation of social welfare to strong stability of centralized authority? to corruption? and to legitimate pool-peer-punishers?
   This thesis results imply that in general, as the second-order punishment severity increases, the cooperation increases and the social welfare is worsened. The results also imply that as the second-order punishment severity increases, corruptors eventually result in the collapse of the centralized authority and the diminishing of the social welfare. This collapse of central authority can be mitigated by hybrid-punishers, who re-emerge to maintain cooperation and relatively restore social welfare.

Briefly, the contributions of this thesis are:

1. Develop a simulator of Sigmund et al. (2010) PGG model to replicate the results of studying the competition between the peer punishment and pool punishment along time evolution
2. Apply different levels of second-order institutional punishment severity to the developed simulator, then study and evaluate its effect on the centralized authority stability and social welfare
3. Apply corruption strategy to the developed simulator with different levels of second-order institutional punishment severity, then study and evaluate its effect on the centralized authority stability and social welfare
4. Apply both corruption and hybrid punishment strategy to the developed simulator with different levels of second-order institutional punishment severity, then study and evaluate its effect on the centralized authority stability and social welfare. Hybrid-punisher is also studied as a legitimate form of peer-punishers.

1.5 Scope

The simulator is based on Sigmund et al. (2010) evolutionary game dynamics for fixed populations' model. It follows the same settings including the population strategies, the parameters settings, and the payoff calculations. Moreover, this PGG is not obligatory; each player can choose not to participate to the PGG. Furthermore, the individuals are allowed to imitate the successful models and to explore new strategies. The simulation runs has been tuned to various levels of second-order punishment severity while other levels have not been tested. The corruption strategy introduced in this thesis is limited to the corruptors who participate but do not contribute to the PGG, and also bribe the central authority to avoid being punished. This corruption strategy is minimalistic but it helps to test the centralized authority stability and the need for decentralized authority in addition to the centralized one. The hybrid-punishers strategy introduced in this thesis is limited to the one who is acting as peer-pool-punishers and who can punish as peer-punishers and pool-punishers without being punished by the centralized authority. This limited hybrid-punishers strategy explains why many centralized institutions tolerate such kind of peer-punishers. Thus, this thesis deals with a certain type of evolutionary game settings applying two new limited strategies and studies the centralized authority stability and the social welfare.

1.6 Thesis Outlines

The remaining of this thesis is organized as follows: Chapter 2 discusses the related work to this thesis. Chapter 3 represents Sigmund et al. (2010) model developed by previous researches and discusses the results. Chapter 4 explains the developed simulator, presents and evaluates the results, and compares it to Sigmund et al. (2010) model. Chapter 5 presents the results of running the simulator with various second-order punishment severity levels; it also presents the corruption strategy, applies the corruption strategy to the simulator with various second-order punishment severity levels, presents and evaluates the results, compares the results of the two cases and discusses the stability of the centralized authority. Chapter 6 presents the hybrid-punishers strategy, applies both corruption and hybrid-punishers strategy to the simulator with various second-order punishment severity levels, presents and evaluates the results. Chapter 7 discusses the overall social welfare, presents the social welfare when applying various second-order punishment severity levels in the case of Sigmund et al. (2010) model, in the case of corruption presence, and in the case of both corruption and hybrid-punishers presence, it also presents, compares and evaluates the results. Chapter 8 concludes and summarizes this thesis; discusses the results and presents the future work.

Chapter 2

2 Literature Survey

Since almost the beginning of the twentieth century, researchers' attention was drawn to how to best govern the society and promote collaborative efforts. The issue of how to promote and maintain cooperation among selfish individuals is the main topic of game theory (Hardin 1968; Hobbes 1960).

Numerous hypothetical and experimental researches discuss and emphasize on the essential role of punishment, or sanctioning free-riders (also known as defectors or non-cooperators), to ensure cooperation in society. Principally, punishment is an effective and successful mechanism in promoting the cooperation in public good interactions (Gächter, Renner & Sefton 2008; Henrich et al. 2006; Herrmann, Thoeni & Gächter 2008).

Although researches emphasize on the importance of the punishment for promoting cooperation and policing the commons, the debate still exists around whether the cooperative behavior in a society can be best maintained by a centralized sanctioning authority via sanctioning institutions (Hardin 1968; Hobbes 1960) or it is best preserved by more decentralized enforcement via peer-punishers (Dietz, Ostrom & Stern 2003; Kropotkin 1907)

Decentralized enforcement, Peer punishment, or also called individual sanctioning of free-riders, is a key mechanism to ensure cooperation in societies (Nowak 2006). Peer Punishment is a form of direct reciprocity. Different forms of peer punishment have been extensively studied and assessed using evolutionary models and behavioral experiments (Axelrod 2006; Boyd & Richerson 1992; Egas & Riedl 2008; Fehr & Gächter 1999; Ohtsuki et al. 2006; Santos, Pacheco & Lenaerts 2006). Individuals' punishment for free-riders can be done implicitly via simple behavioral reciprocity, as in the case of simple, effective and successful tit for tat strategy in game theory, where the agent who is using this strategy will cooperate first, then the agent imitates his opponent's earlier action, if his opponent earlier was cooperating, then he is cooperating, if he was defecting, then he will defect (Axelrod 2006). On the other hand, Individuals' punishment for free-riders can be done explicitly via costly punishment, where individuals are acting altruistically, incurs cost for themselves to punish defectors with no material gain, to flourish and maintain cooperation in societies. Punishers are seen as altruistic because other players can get benefits from the punisher's costly punishment. However, even this costly punishment evolution and stability is still a debatable question (Fehr & Gächter 2002). Alternatively, Individuals' punishment for free-riders can be done by adopting social-ties for avoiding free-riders interaction, where each individual adjusts his strategy and his social ties based on his own interest through evolution, This individual strategy and social structure evolution is a key mechanism for maintaining cooperation behavior in societies (Santos, Pacheco & Lenaerts 2006).

Although the vital role of peer punishment in promoting cooperation is highly respected, it suffers from many problematic issues. One of these issues, under the presence of counter-punishment, is that the individuals become less or un-willing to punish or that it results in a sequence of revengeful punishment .This results into a reasonably payoff loss compared to applying no punishment strategy (Fehr & Gächter 1999; Nikiforakis 2008). Second issue, cooperation yield as a result of peer punishment is a public game by itself. This generated cooperation can collapse by second-order free-riders, players who cooperate with others but do not punish free-riders, which ultimately results into free-riders re-emergence (Dreber et al. 2008; Fowler 2005b; Panchanathan & Boyd 2004). Besides, if the second-order free-riders problem is solved by punishment mechanism, third-order free-riders should be spread which ultimately results into free-riders re-emergence and so on, leading to unlimited revert. This unlimited sequence of free-riding challenges the peer punishment mechanism to promote and maintain cooperation (Fowler 2005b). Third issue; peer costly punishment affects positively on the cooperation level but negatively at the average payoff of the group. The player who earns the highest payoff does not have tendency to punish others in the group (Dreber et al. 2008).

A various sanctioning systems has been investigated and assessed. Many public good games experiments have modeled peer punishment mechanism as imposing fines on free-riders after the PGG (Yamagish 1986). Other experiments have applied the institutional sanctioning mechanism for punishing free-riders (Ostrom 1990).

Recently, several researches show that the centralized authority, pool-punishers, have been proved to be doing better punishment than decentralized authority, peer-punishers, despite of being costly as it eliminates second-order free-riders (Sigmund et al. 2010; Traulsen, Röhl & Milinski 2012). Sigmund et al. (2010) presents a pool punishment model where individuals contribute to centralized authority that sanctions free-riders. This pool punishment model avoids second-order free-riders as the central authority punishes who do not contribute to common pool punishment, in other words, the central authority punishes whoever do not want to punish free-riders even if he contributes to the joint effort. This facilitates pool-punishers to prevail, replacing all other population and establishing a stable regime (Sigmund et al. 2010). Over time and due to these advantages, human societies prefer delegating punishment to centralized sanctioning and legitimate authority regardless of being costly (Baldassarri & Grossman 2011; Sigmund et al. 2010; Traulsen, Röhl & Milinski 2012), and also centralized institutions continue to gain unilateral and undisputed power for legitimate punishment over different forms of peer-punishers by stigmatizing (Rosenbaum 2011) and criminalizing (Hallam 1821).

However, Sigmund et al. (2010) model shows that the centralized pool punishment prevails, replaces all populations including peer punishment and establishes a stable regime. This kind of pool punishment dominance creates three dilemmas.

First; Sigmund et al. (2010) results imply that the centralized and legitimate authority eventually establishes very stable regime and thus increases cooperation in societies. However, low levels of participation and public goods are observed in several authoritarian states that already have the ability to increase the level of individuals' punishment (Acemoglu & Robinson 2012). Alternatively, western democracies (Acemoglu & Robinson 2012; Deacon 2009; Lake & Baum 2001) and other states with well-participation in public goods tend to limit the centralized punishment of individuals and give more room for different forms of peer-punishers.

Second; Sigmund et al. (2010) results also imply that centralized authority, pool-punishers, promptly prevail, replacing other population including peer-punishers and establishing a stable regime, although most of human societies demonstrate combination of centralized and decentralized forms of punishment. Even in societies in which centralized punishment is applied, where individuals pay taxes to a centralized police, individuals participate in costly actions to stand against other individuals who apply any kind of harm to public goods. As a recent example, the Occupy protests to the Arab Spring demonstrate that even if the centralized authority punishes protestors, they still stand against who harm the public goods at their own cost (Harcourt 2011; Morsi 2013; Moghadam 2012).

Third; Sigmund et al. (2010) results also imply that the pool-punishers punish peer-punishers as they do not contribute to the common pool punishment. In Sigmund et al. (2010) model, the peer-punishers are considered illegitimate. Although in human societies, several forms of political participation, such as civil litigation, jury duty and anti-incumbent voting are considered as altruistic and social peer punishment (Fowler & Kam 2007; Grechenig, Nicklisch & Thöni 2010; Smirnov et al. 2010).

Chapter 3

3 The PGG Model with Punishment

Sigmund et al. (2010) proposed a model of centralized sanctioning institution, and pool-punishers; in which pool-punishers contribute to common punishment pool before joining the collaborative effort as willing to punish free-riders. Pool punishment enables the second-order free-riders punishment. As it is well known in societies, sanctioning institutions forbid individuals to apply the society law by their own hands, Sigmund et al. (2010) investigated the prevalent model and the competition between pool punishment and peer punishment through social learning. As a result of his investigation, it is found out that in the absence of second-order punishment, peer-punishers dominate most of the time and do better than pool punishment. On the other hand, in the presence of second-order punishment, pool-punishers prevail and take over and they become the dominant population dispatching free-riders and all other forms of punishment including peer-punishers (Sigmund et al. 2010).

In this section, the Sigmund et al. (2010) PGG model will be described in details. Further, the five strategies will be listed and their corresponding payoff computation will be illustrated. Moreover, different punishment strategies will be compared. At the end, the results will be illustrated and discussed.

3.1 PGG Model Definition

Sigmund et al. (2010) PGG Model is based on the original evolutionary game dynamics for fixed populations. The model baseline is a PGG with five different strategies including two different punishment strategies. PGG is a simple model for studying contributions to a common pool before the collaborative effort as a guarantee for a social sanctioning system to promote and maintain cooperation in the society.

In this PGG model, let M symbolizes the total population and let N symbolizes the players count that are arbitrarily picked to play a round of game, where $N < M$. As the game is not obligatory, each player has the right to decide whether to participate or not to the PGG (Sigmund et al. 2010; Fowler 2005a; Hauert 2002a, 2002b). Each player has also has the right to decide whether to contribute or not to the PGG with fixed amount c where $c > 0$.

The population includes cooperators; X, who participate and contribute c, defectors (free-rides); Y, who participate and do not contribute, loners; Z, who choose not to participate and not to contribute, peer-punishers; W, who participate and contribute c but also impose fines at defectors at cost on themselves, and pool-punishers; V, who contribute a fixed amount to a common punishment pool before contributing c to the PGG and impose fines on any player who does not contribute to the common punishment pool.

Once each player chooses his own strategy, each player gets a payoff based on arbitrarily selection of the interacted groups, each player will gain an amount equal to $rc\frac{N_c}{N}$ whether or not they contribute, where the contribution amount, *c*, is magnified by a factor, r > 1, and both are multiplied by a ratio of the number of contributors, N_c, to the number of participants. If all players contribute that means $\frac{N_c}{N} = 1$, then each player will obtain the maximum welfare that can ever be obtained, *rc* (Sigmund et al. 2010).

Briefly, this PGG model is a simple model for studying contributions to a common pool before the collaborative effort as a guarantee for a social sanctioning system to promote and maintain cooperation in the society. Each player follows one of five different strategies. Arbitrarily selection for the interacted groups from the population is done.

3.2 PGG Population

In this PGG, five different strategies are included and can be explained as follows (Sigmund et al. 2010):

- **Cooperators (X):** Cooperators participate, and contribute *c* to the PGG but do not impose any fines on free-riders.
- **Defectors (Y):** Defectors are free-riders who participate but do not contribute to the PGG. Defectors also by definition do not contribute to the common pool.
- **Loners (Z):** This game is not obligatory, each player has the right to decide whether to participate or not to the PGG (Hauert 2002a, 2002b; Sigmund et al. 2010; Fowler 2005a). Loners neither participate nor contribute to the PGG. Although, these loners prefer doing other stuff instead of participating in the PGG, they still get a fixed small payoff, σ. Loners are also called non-participants. If all players are free-riders, then loner payoff, $\sigma = 0$. On the contrary, if all players contribute to the PGG and the common punishment pool, then loner payoff, $\sigma = (r-1)c-G$. so σ lies between 0 and $(r-1)c-G$.
- **Peer-punishers (W):** Peer punishment is a key mechanism for direct reciprocity that facilitates the free-riders elimination. Peer-punishers participate and contribute *c* to the PGG but after the game, they impose fine, β, on each free-rider (defector) at cost, γ exists in their group (Nowak 2006).
  If the peer-punishers in the group is N_w and the free-riders at the same group is N_y, then each free-rider pays βN_w as a total fine and each peer-punisher incurs γN_y.
- **Pool-punishers (V):** As an alternative to peer-punishers' direct punishment strategy, pool-punishers do not directly punish free-riders. Otherwise, pool-punishers pay a fixed amount, *G*, to a common punishment pool before participating and contributing *c* to the PGG. Any player, such as free-riders and peer-punishers, who does not contribute to the common punishment pool, pays fine, BN_v, where N_v is the number of pool-punishers and B > 0. This strategy eliminates the second-order free-riders problem (Sigmund et al. 2010) as it punishes any player who does not contribute to the common punishment pool.

Briefly, in this PGG model, five different strategies; cooperators, defectors, loners, peer-punishers and pool-punishers, are followed. Each player payoff is computed according to its strategy and based on arbitrarily selection of the interacted groups.

3.3 Social Learning

Social learning is a perception about the individuals' learning attitude within a society; the individual social behavior is principally learned by exploring, observing and imitating others' successful actions. Several models for social learning have been investigated. In this model, it is assumed that individuals prefer to imitate successful strategies.

In this PGG social learning model, two players *i* and *j* are selected arbitrarily where the players' payoff, P_i and P_j, were previously calculated according to their strategy (*X, Y, Z, W,* or *V*). Each player imitates and adopts other player's strategy with a probability which increases as the difference between their payoff increases and as s increases (Sigmund et al. 2010).

$$\frac{1}{1 + \exp[-s(P_j - P_i)]}$$

Equation 3.1: Imitation Probability

Where $s > 0$, s is the imitation strength. There are three different cases for imitation:

- If s = 0 or $P_i = P_j$, then toss a coin to decide on whether to imitate or not
- If s = small values, weak imitation regime is followed when a more successful player is more often imitated by other players
- If s tends to infinity, strong imitation regime is followed when the most successful player is always imitated by other players

The imitating regime can reach a limit when imitation cannot yield any situation change so that an exploration regime has been also embedded in this PGG. A very small exploration rate; μ, is considered in this PGG model where each player can change its strategy randomly without any imitation to other players (Sigmund et al. 2010).

Briefly, in this PGG model, Social learning by imitation and exploration are applied to players that are arbitrarily picked and directly influences their current strategy.

3.4 No Punishment Strategies

To have clearer explanation of the payoff calculations, it is better to illustrate the payoff computation starting from its baseline where there is no punishment (Sigmund et al. 2010).

In a population; *M*, which consists of cooperators; *X*, and defectors; *Y*, where $Y = M - X$ and *N* players are arbitrarily picked to play the PGG. Then, the cooperators payoff is calculated as follows (Sigmund et al. 2010):

$$P_x = rc\frac{X-1}{M-1} - c$$

Equation 3.2: Cooperators payoff in a population of X and Y

While, the defector payoff is calculated as follows:

$$P_y = rc\frac{X}{M-1}$$

Equation 3.3: Defectors payoff in a population of *X* and *Y*

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, and loners; *Z*, *X* = *M* – *Z* – *Y*, and *N* players are arbitrarily picked to play the PGG. Then, the probability that (N-1) players are not intending to participate in the PGG as follows:

$$P_\sigma = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}$$

Equation 3.4: Loners probability in a population of *X*, *Y* and *Z*

Substituting with the loners' probability and the added strategy, then, the cooperators payoff is calculated as follows:

$$P_x = P_\sigma \sigma + (1 - P_\sigma)c(r\frac{M-Z-Y-1}{M-Z-1} - 1)$$

$$P_x = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\,\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})c(r\frac{M-Z-Y-1}{M-Z-1} - 1)$$

Equation 3.5: Cooperators payoff in a population of *X*, *Y* and *Z*

While, the defectors payoff is calculated as follows:

$$P_y = P_\sigma \sigma + (1 - P_\sigma)rc\frac{M-Z-Y}{M-Z-1}$$

$$P_y = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\,\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})rc\frac{M-Z-Y}{M-Z-1}$$

Equation 3.6: Defectors payoff in a population of *X*, *Y* and *Z*

While, the loners payoff is calculated as follows:

$$P_z = \sigma$$

Equation 3.7: Loners payoff in a population of *X*, *Y* and *Z*

Analyzing the *X*, *Y* and *Z* parameters in equations 3.6 and 3.7, it is found out that (Sigmund et al. 2010):

- If there is no loners, $Z = 0$, the defectors perform better than cooperators, $P_y > P_x$
- If there is no defectors, $Y = 0$, the cooperators perform better than loners, $P_x > P_z$
- If there is no cooperators, $X = 0$, the loners perform better than defectors, P_z

Briefly, in a population; *M*, which consists of cooperators; *X*, defectors; *Y*, and loners; *Z*, the model behavior is analyzed and the payoff for each strategy is illustrated.

3.5 Pool Punishment Strategy

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, and pool-punishers; *V*, where $M = X + Y + Z + V$ and *N* players are arbitrarily picked to play the PGG. Pool-punishers pay a fixed amount *G* to a common punishment pool before participating and contributing *c* to the PGG. Free-riders will be punished by the pool-punishers and their fine will be proportional to their number BN_v, where N_v is the number of pool-punishers and $B > 0$. The pool-punishers payoff is calculated as follows (Sigmund et al. 2010):

$$P_v = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})[c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - G]$$

Equation 3.8: Pool-punishers payoff in a population of *X, Y, Z* and *V*

Two cases were studied for pool-punishers (Sigmund et al. 2010):

- With no second-order punishment: the average payoff of cooperators and loners remains the same as equations 3.5 and 3.7. The defectors payoff is calculated as follows:

$$P_y = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})rc\frac{M-Z-Y}{M-Z-1} - \frac{B(N-1)V}{M-1}$$

Equation 3.9: Defectors payoff in a population of *X, Y, Z* and *V*

- With second-order punishment: the average payoff for loners remains the same as equations 3.7. The cooperators must also be punished as they do not pay the fixed amount, *G*, to the common punishment pool. The cooperators payoff is calculated as follows:

$$P_x = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - \frac{B(N-1)V}{M-1}$$

Equation 3.10: Cooperators payoff in a population of *X, Y, Z* and *V*

Briefly, applying pool punishment strategy, *V*, to a population; *M*, which consists of cooperators; *X*, defectors; *Y*, and loners; *Z*, with and without second-order punishment. The model behavior is analyzed and the payoff for each strategy is illustrated.

3.6 Peer Punishment Strategy

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, and peer-punishers; *W*, where $M = X + Y + Z + W$ and *N* players are arbitrarily picked to play the PGG. Peer-punishers participate and contribute c to the PGG but after the game. They impose fine; β, on each free-rider (defector) at cost; γ exists in their group. If the peer-punishers in the group is N_w and the free-riders at the same group is N_y, then each free-rider pays βN_w as a total fine and each peer-punisher incurs γN_y. The peer-punishers payoff is calculated as follows (Sigmund et al. 2010):

$$P_w = P_x - \frac{(N-1)Y}{M-1}\gamma$$

$$P_w = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - \frac{(N-1)Y}{M-1}\gamma$$

Equation 3.11: Peer-punishers payoff in a population of *X*, *Y*, *Z* and *W*

Two cases were studied for peer-punishers (Sigmund et al. 2010):

- With no second-order punishment: the payoff of cooperators and loners remain unchanged. The defectors payoff is calculated as follows:

$$P_y = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})rc\frac{M-Z-Y}{M-Z-1} - \frac{(N-1)W}{M-1}\beta$$

Equation 3.12: Defectors payoff in a population of *X*, *Y*, *Z* and *W*

- With second-order punishment: The cooperators must also be punished by peer-punishers since they do not punish free-riders. The peer-punishers consider that cooperators fail to punish defectors so that they impose fine β on cooperators at cost γ at themselves.

$$P_w = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - \frac{(N-1)Y}{M-1}\gamma - \frac{(N-1)X}{M-1}\gamma(1 - \frac{\binom{M-Y-2}{N-2}}{\binom{M-Y-2}{N-2}})$$

Equation 3.13: Peer-punishers payoff in a population of *X*, *Y*, *Z* and *W*

The cooperators payoff is calculated as follows:

$$P_X = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - \frac{(N-1)W}{M-1}\beta(1 - \frac{\binom{M-Y-2}{N-2}}{\binom{M-Y-2}{N-2}})$$

Equation 3.14: Cooperators payoff in a population of *X, Y, Z* and *W*

3.7 Pool-Punishers and Peer-Punishers Competition

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; *W*, where $M = X + Y + Z + V + W$ and *N* players are arbitrarily picked to join the PGG. Two cases were studied in this PGG model. First; without second-order punishment, peer-punishers dominate most of time in long run although sometimes second-order free-riders try to invade. Second; with second-order punishment, pool-punishers ultimately prevail and set up a very stable regime, as pool-punishers punish peer-punishers for not paying in the common punishment pool. The peer-punishers payoff is calculated as follows (Sigmund et al. 2010):

$$P_W = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}\sigma + (1 - \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}})c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - \frac{B(N-1)V}{M-1} - \frac{(N-1)Y}{M-1}\gamma - \frac{(N-1)X}{M-1}\gamma(1 - \frac{\binom{M-Y-2}{N-2}}{\binom{M-Y-2}{N-2}})$$

Equation 3.15: Peer-punishers payoff in a population of *X, Y, Z, V,* and *W*

Briefly, in Sigmund et al. (2010) model, pool punishment punishes peer-punishers as they do not contribute to the common pool punishment; peer-punishers are considered illegitimates.

3.8 PGG Model Results

Sigmund et al. (2010) model is based on evolutionary game theory in a population of fixed size; *M,* including five different strategies; *X, Y, Z, V,* and *W*. Random samples of *N* players who have the chance to join the game. Each player payoff is calculated according to his strategy. The players are allowed to imitate each other strategy through social learning according to a defined probability that is counted on the difference between the players' payoffs. Moreover, the players can change arbitrarily to another strategy according to a defined exploration rate. Additionally, participating in the game is optional rather than obligatory. Eventually, the prevalent model of pool-punishment and peer-punishment was compared.

The results will be clearly mentioned as follows (Sigmund et al. 2010), as shown in Figure 3.1:

- The competition between the pool-punishers and the peer-punishers are determined by the presence or the absence of the second-order punishment
- In the absence of second-order punishment, peer-punishers dominate most of time but sometimes second-order free-rider tries to conquer the population. Occasionally, the defectors invade then loners take over but peer-punishers remerge again to stabilize for quite a long time. In general, peer-punishers perform better than pool-punishers in this case
- In the presence of second-order punishment, pool-punishers apply sanctioning to the second-order free-riders even though they all contribute to the collaborative effort. Pool-punishers consider any player who doesn't contribute to the common punishment pool, even if he contributes to the common good, as a free-rider including defectors, cooperators and even peer-punishers. Pool-punishers emerge and eventually lead to a very stable regime. In general, pool-punishers perform better than pool-punishers in this case
- Both pool-punishment and peer-punishment are costly mechanisms to impose penalties on free-riders. Pool-punishment is considered more expensive within society than peer-punishment since a fixed cost has to be paid to the common punishment pool. On the other hand, pool-punishment is more stable regime than peer-punishment. Moreover, peer-punishment is absolutely not suitable for second-order punishment

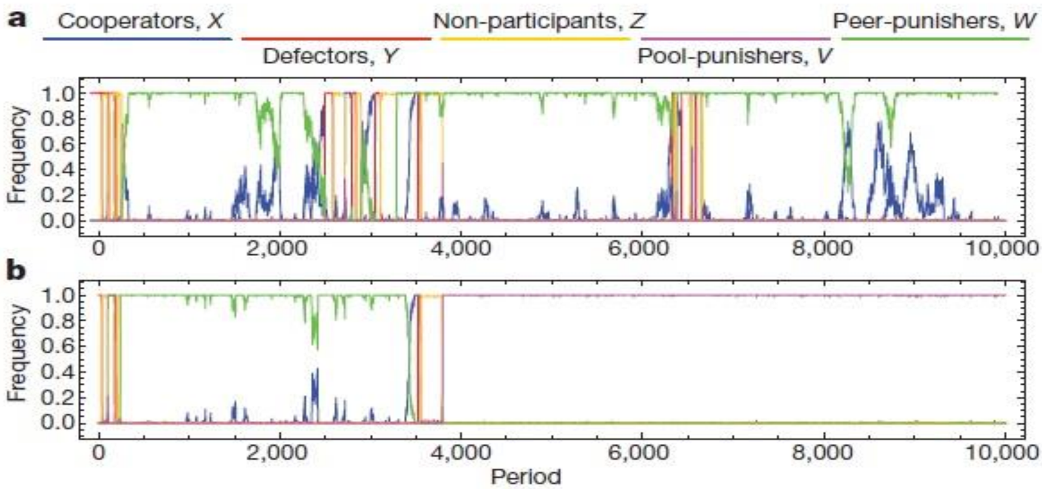

Figure 3.1: Pool-punishment and peer-punishment time evolution competition, (a) without second-order punishment, (b) with (Sigmund et al. 2010)

Briefly, In the presence of second-order punishment, pool-punishers emerge and ultimately lead to a very stable regime. Pool-punishers perform better than peer-punishers. In the absence of second-order punishment, peer-punishers dominate most of time. Peer-punishers perform better than pool-punishers.

Chapter 4

4 Replicating Previous PGG Model Results

In this section, the Sigmund et al. (2010) PGG model and his results have been replicated. The simulation model is reviewed briefly, and the simulation implementation is illustrated in details. Consequently, simulation without and with second-order punishment are described, and finally, the results are presented and discussed

4.1 Simulation Model

This simulator uses the same Sigmund et al. (2010) PGG model including the same population strategies, social learning regime, and payoff calculations described in Chapter 3. Briefly, evolutionary game is applied to population of fixed size M. Let M symbolizes the total population and let N symbolizes the players count that are arbitrarily picked to play a round of the game, where $N < M$. As the game is not obligatory, each player has the right to decide whether to participate or not to the PGG. Each player has the right to decide whether to contribute or not to the PGG with fixed amount c where $c > 0$.

The population includes:

- Cooperators; X: who participate and contribute c to the PGG
- Defectors (free-rides); Y: who participate and do not contribute to the PGG
- Loners; Z: who choose neither participate nor contribute to the PGG
- Peer-punishers; W: who participate and contribute c to the PGG but also impose fines at defectors at cost on themselves
- Pool-punishers; V: who contribute a fixed amount to a common punishment pool before contributing c to the PGG and impose fines on any player who does not contribute to the common punishment pool.

Once each player chooses his own strategy, he gets a payoff based on arbitrarily selection of the interacted groups. Each player imitates and adopts other player's strategy with a probability which increases as the difference between their payoff increases, and as s increases, where $s > 0$, and s is the imitation strength. Each player can change its strategy arbitrarily without any imitation to other players; the players' exploration is directly proportional to a very small exploration rate; μ, where $\mu>0$.

4.2 Simulation Implementation

The Sigmund et al. (2010) PGG model has been developed and tested to replicate the same results as his research. The following is a detailed explanation of the software used, the user interface, simulator parameters, the simulator algorithm, pseudo code and the pay-off calculations

4.2.1 Software Used

Two different Software packages have been used for developing the simulator:

- Eclipse which is a multi-language software development environment comprising an Integrated Development Environment (IDE) and an extensible plug-in system. It is used to develop applications in Java. It was used to implement all parts of the simulator[1]
- EpsGraphics2D library which is a perfect choice for creating high quality EPS Graphics. It is used in the simulator implantation to obtain high quality graphics result[2]

4.2.2 User Interface and Outputs

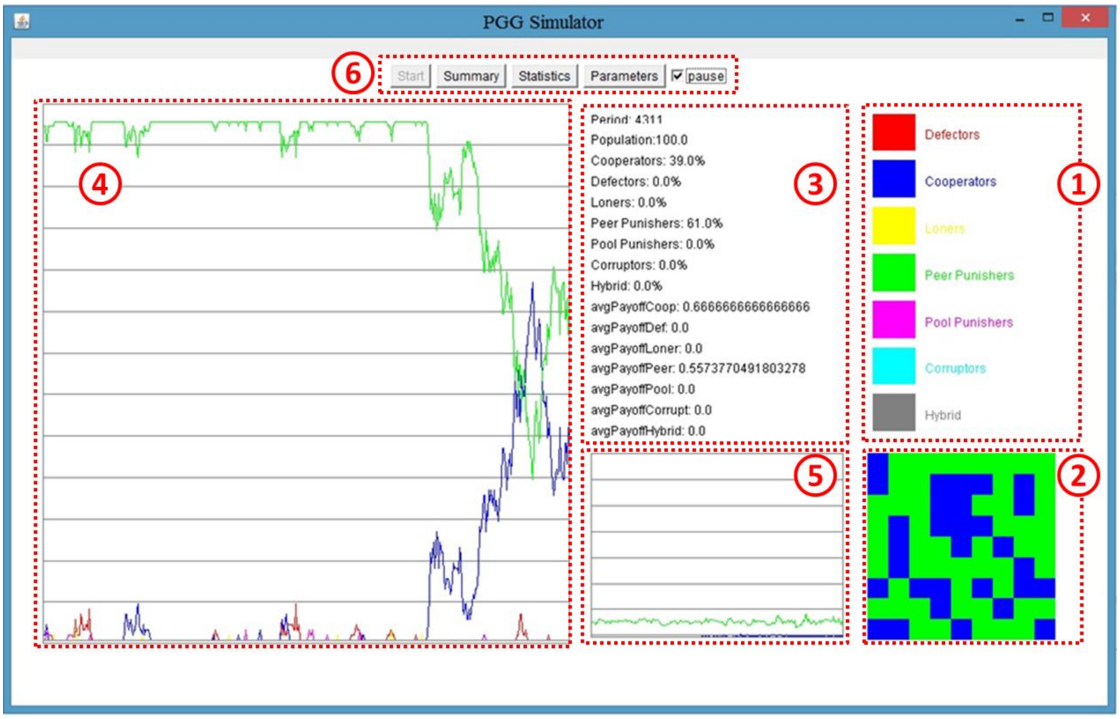

Figure 4.1: PGG Simulator user interface

As shown in Figure 4.1, the simulator user interface has six main components:

1. **Legend**: A color key to indicate each strategy. These colors are used in other components where each color represents its population strategy.
2. **Strategy Map**: At each period step, this map shows the strategy of each individual in the overall population. The map is a grid of 100 squares which equals to M population. Each square represents an individual in the population and is colored to reflect the strategy of that individual at the very instant period step. In other words, the Strategy Map takes presents a snapshot of the overall population at each period step showing the strategies of all the individuals.

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[1] Eclipse IDE for Java Developers, accessed June 12th, 2013, available for download from http://www.eclipse.org/

[2] EpsGraphics2D, accessed January 1st, 2013, available for download from http://www.jibble.org/epsgraphics/

3. **Statistics**: This component shows a set of statistics at each period step. It shows the period step counter, the percentage for each strategy within the overall population, and the average payoff for each strategy from the beginning of the simulation run up to the very instant step period.
4. **Strategy Population Graph**: This graph component has two axes; the x-axis represents period steps during the simulation run, and the y-axis represents the population. Up to seven graphs are shown, each representing the population of a specific strategy. Each graph is denoted by its strategy color key as defined in the Legend. As opposed to the Strategy Map, which shows a snapshot at the very instant period step, the Strategy Population Graph shows the population of each strategy at the very instant period step in addition to the historic period steps as well. For instance, let us assume that the simulation starts at t_0, then at t_0 period step, the Strategy Population Graph will plot up to seven points in seven colors each represents the population of that specific strategy. When the simulation advances to t_1, this graph component will shift the points plotted at t_0 to the left on step on the x-axis, and plot new seven points that represent the population per strategy at t_1.As a result of that, at t_1 we shall see seven graphs plotted, each shows the population per its strategy at t_0 and t_1. As the simulation goes on, each of the seven graphs will always show the population value of its strategy at t_n and all of the values of t_{n-1}, t_{n-2}, t_{n-3}, and so on. At any given t_n, the sum of the values of the seven graphs equals the overall population, which is 100 in our simulation.
5. **Strategy Payoff Graph**: This graph component has two axes; the x-axis represents period steps during the simulation run, and the y-axis represents the average payoff. Up to seven graphs are shown, each representing the average payoff for specific strategy. Each graph is denoted by its strategy color key as defined in the Legend. Similar to the Strategy Population Graph, this Strategy Payoff Graph shows the average payoff for each strategy at the very instant period step in addition to the historic period steps as well. For instance, let us assume that the simulation starts at t_0, then at t_0 period step, the Strategy Payoff Graph will plot up to seven points in seven colors each represents the average payoff for that specific strategy. When the simulation advances to t_1, this graph component will shift the points plotted at t_0 to the left on step on the x-axis, and plot new seven points that represent the average payoff per strategy at t_1.As a result of that, at t_1 we shall see seven graphs plotted, each shows the average payoff per its strategy calculated at t_0 and t_1. As the simulation goes on, each of the seven graphs will always show the average payoff value for its strategy calculated at t_n and all of the previously calculated values at t_{n-1}, t_{n-2}, t_{n-3}, and so on.
6. **Control Panel**: is a group of buttons and controls that allow the user to:
   - Start Button: To start the simulation run
   - Summary Button: To display the Strategy Population Graph in a separate window showing covering the entire simulation run as shown in Figure 4.2

- Statistics Button: To open a separate window that shows the Statistics for the entire simulation run as shown in Figure 4.3
- Parameters Button: To open a separate window with all the model parameters and their values. The user can use this window to alter the simulation parameters as shown in Figure 4.4
- Pause Check Box: Where the user can pause and resume the simulation

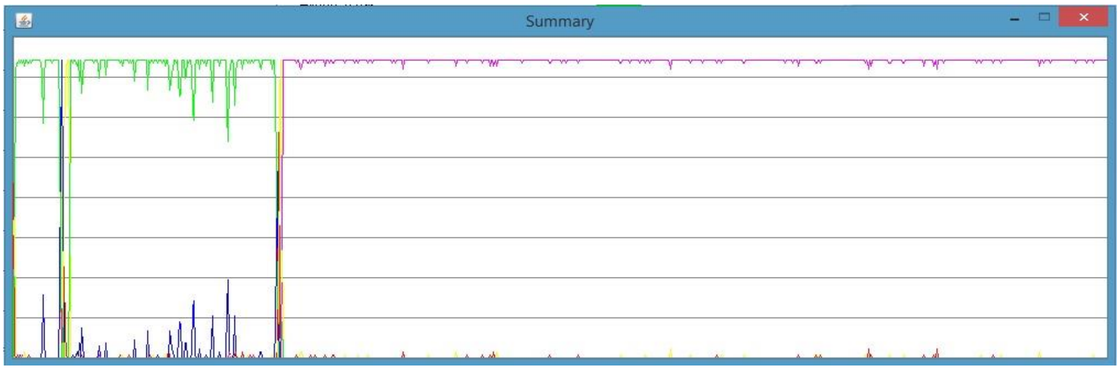

Figure 4.2: Summary report

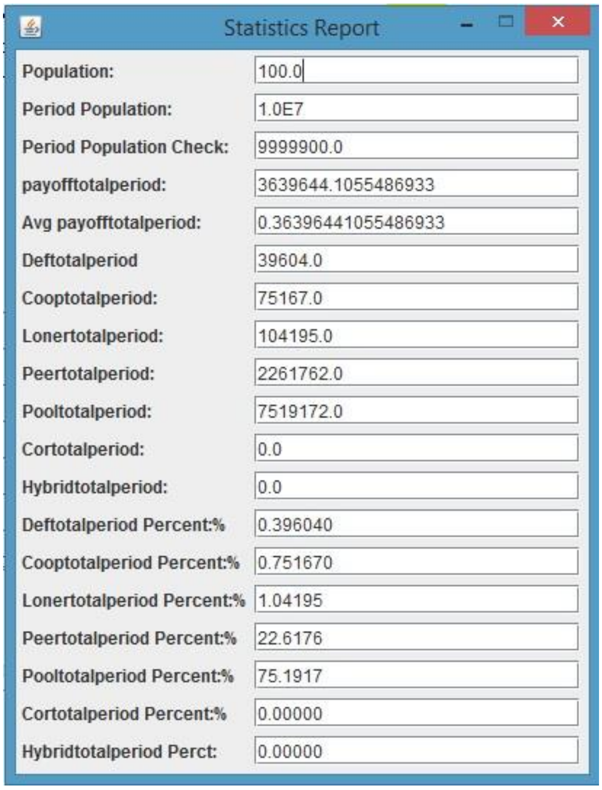

Figure 4.3: Statistics report

Figure 4.4: Parameters and values

4.2.3 Simulator Parameters

As shown in Table 4.1 below, the parameters and their corresponding values have been used in simulating this PGG model.

Population size	M	100
Random sample size	N	5
PGG contribution	c	1.0
PGG multiplier	r	3.0
Exploration rate	μ	0.001
Imitation Strength	s	100000
Loner payoff	σ	1.0
Pool punishment fine factor	B	0.7
Pool punishment cost	G	0.7
Peer punishment fine factor	β	0.7
Peer punishment cost	γ	0.7

Table 4.1: Simulator parameters and corresponding values

4.2.4 Payoff Calculations

Once each player chooses his own strategy, each player gets a payoff based on arbitrarily selection of the interacted groups. Each player will gain an amount equal to $rc\frac{Nc}{N}$ whether or not he contributes, where the contribution amount; *c*, is multiplied by a factor; *r* > 1, and both are multiplied by a ratio of the number of contributors, *Nc*, to the number of participants. If all players contribute, this means $\frac{Nc}{N} = 1$, then each player will obtain the maximum welfare that can ever be obtained; *rc*. Each player imitates and adopts other player's strategy with a probability which increases as the difference between their payoff increases and as *s* increases, where *s* > 0, and *s* is the imitation strength. Each player can change its strategy arbitrarily without any imitation to other players; the players' exploration is directly proportional to a very small exploration rate, μ.

Cooperators participate and contribute; *c* to the PGG but do not impose any fines on free-riders. Defectors participate but do not contribute to the PGG. Defectors also, by model definition, do not contribute to the common pool. Although loners neither participate nor contribute to the PGG, they still get a fixed small payoff; *σ*. Loners are also called non-participants. If all players are free-riders, then loner payoff; *σ* = 0. On the contrary, if all players contribute to the PGG and the common punishment pool, then loner payoff; *σ* = *(r-1)c-G*. So *σ* lies between 0 and *(r-1)c-G*. Peer-punishers participate and contribute; c to the PGG but after the game, they impose fine; *β*, on each free-rider at cost; *γ* exists in their group. If the peer-punishers in the group is *Nw* and the free-riders at the same group is *Ny*, then each free-rider pays; *βNw* as a total fine and each peer-punisher incurs *γNy*. Pool-punishers pay a fixed amount; *G* to a common punishment pool before participating and contributing; *c* to the PGG. Pool-punishers punish any player who does not contribute to the common punishment pool by imposing fine; *BNv*, where *Nv* is the number of pool-punishers and *B* > 0.

The average payoff of each individual is calculated according to its strategy. Each time the individual is selected in the arbitrarily selection of the interacted groups; *N* after the PGG, the individual payoff is added to his accumulated payoff and the individual accumulated count of his instances is increased by one, then the individual average payoff is calculated by dividing the accumulated payoff by the accumulated number of instances. The accumulated payoff and the accumulated number of instances for any individual are reset if and only if this individual changes his strategy by imitation or exploration routine.

4.2.5 Simulator Algorithm

In this section, the existing Sigmund et al. (2010) model has been simulated and all its processes have been summarized in the following algorithms. The main process of the simulator that is responsible for the PGG modeling is summarized as algorithm 4.1.

Algorithm 4.1: PGG modeling

Input: Five strategies and M population
Output: one complete run of PGG
foreach *period step i in 100,000 period steps (one complete run)* **do**
  Get *N samples from M population randomly;*
  Calculate *the average payoff per each player in N;*
  foreach *f iteration in M do*
    Generate *a random value r;*
    if *random value r < exploration rate* **then**
      Pick *a random player from population M and change its strategy arbitrarily to one of the rest four strategies;*
    else
      Choose *randomly any two players from M population;*
      Calculate *the imitation probability according to the two players' payoff;*
      if *imitation probabilities == 0.5* **then**
        Toss *a coin*
        if *coin probability > 0.5* **then**
          Update *the strategy of one player by the strategy of the other;*
          Reset *the accumulated count and payoff of the player who updated his strategy;*
        end
      else
        if *imitation probability < 0.5* **then**
          Do *nothing;*
        else
          Update *the strategy of one player by the strategy of the other;*
          Reset *the accumulated count and payoff of the player who updated his strategy;*
        end
    end
  end
end

Algorithm 4.1 shows the simulator main process which works as follows: Each complete run considered as 100,000 period steps, each period step contains 100 iterations of social learning either by imitation or exploration. *M* symbolizes the total population, where *M*=100, and *N* symbolizes the players count, where *N* =5. For this PGG model, five strategies; cooperators, defectors, loners, peer-punishers and pool-punishers, are applied to the *M* population. Initially, all the individuals are assigned to defectors strategy. For each period step *i* in 100,000 period steps, choose *N* players arbitrarily to play a game round. After playing the game round, the average payoff for each player in *N* samples is calculated. For each iteration *f* in 100 iterations, a random value *r* is picked. If this random value *r* is less than the exploration rate μ, where μ=0.001, then the exploration routine is executed. The exploration is implemented so that a random player is picked from *M* population and changes its strategy arbitrarily to one of the other four strategies. If this random value *r* is more than the exploration rate, then the imitation routine is executed. The imitation routine is implemented that two players *i* and *j* are selected randomly from *M* population where the players' payoff are P_i and P_j, the imitation probability is calculated as a function of the two players, *i* and *j*, payoffs difference (P_j-P_i) and the imitation strength *s*, where *s*=100,000. If the imitation probability is 0.5 then toss a coin to decide on whether to imitate or not, if the coin probability is more than 0.5, then update the strategy of player *i* by the strategy of player *j* and reset the accumulated count and payoff of player *i*. If the imitation probability is less than 0.5 then do nothing. If the imitation probability is more than 0.5 then update the strategy of player *i* by the strategy of player *j* and reset the accumulated count and payoff of player *i*. This process shows briefly one complete run of the modeled PGG.

Algorithm 4.2: Average payoff calculations

Input: Five strategies, N samples, M population, and one period step
Output: Average payoff of each player in N is calculated at one period step
foreach *player i in N samples* **do**
    Calculate *the payoff for player i according to its current strategy;*
    Increment *the accumulated count of player i by one;*
    Add *the payoff to the accumulated payoff of player i;*
    Calculate *the average payoff for player i using its accumulated count and payoff;*
end

Algorithm 4.2 shows the simulator average payoff calculator routine which works as follows: Given the five strategies; cooperators, defectors, loners, peer-punishers and pool-punishers, *M* population and *N* samples. For each player *i* in *N* samples, the player *i* payoff is calculated according to its strategy with the option of second-order punishment model. The accumulated count is the number of times player *i* has been chosen in *N* samples and to be in the PGG. It started to count up since the last time player *i* changed his strategy; this accumulated count for any player was reset at the last time this player changed his strategy. This accumulated count for player *i* is incremented by one. The accumulated payoff for player *i* sum up the payoffs of this player each time he is chosen in *N* samples and to be in the PGG; this accumulated payoff for any player was reset the last time this player changed his strategy. Thus, the player *i* payoff is added to his accumulated payoff. The average payoff of player *i* is calculated by dividing the accumulated payoff by the accumulated count.

Algorithm 4.3: Calculate the average payoff for each population per strategy at one period step and the total welfare of all populations at one period step

Input: Five strategies, M population, individuals payoff, and one period step
Output: The count and the average payoff of each population per strategy in M is calculated at one period step
foreach *individual i in M population* **do**
    Add *the average payoff for individual i to the accumulated pay off of the population of his strategy;*
    Increment *the accumulated count of of the individual population i strategy by one;*
    Add *the average payoff for individual i to the total payoff for all populations; e.g accumulate the welfare for all populations;*
end
Calculate *the average payoff for each population per strategy;*

Algorithm 4.3 shows the simulator average payoff for each population per strategy and total welfare for all populations at one period step calculator routine which works as follows: Given the five strategies; cooperators, defectors, loners, peer-punishers and pool-punishers, *M* population, individuals payoff and one period step. For each individual *i* in *M* population, the individual *i* average payoff is added to the accumulated payoff of the population of his strategy. Then, the accumulated count of the population of individual *i* is incremented by one. The individual *i* average payoff is also added to the accumulated payoff of all individuals at *M* population at this period step. After summing up all the average payoffs of all individuals that follow same strategy, the average payoff for each population per strategy is calculated by dividing the accumulated payoff by the accumulated count for each population per strategy at this period step .Thus, at each period step, the total average payoff for all individuals that follows the same strategy is calculated and the social welfare of all individuals in *M* population is summed up.

Algorithm 4.4: Calculate the average welfare of all populations for one complete run

Input: M population, and welfare for all populations at one period step
Output: The average welfare of all populations is calculated for one complete run
foreach *period step p in one complete run* **do**
    Add *the welfare in M population at period step p to the accumulated welfare;*
end
Calculate *the average welfare for all populations for one complete run;*

Algorithm 4.4 shows the average welfare for all populations at one complete run calculator routine which works as follows: Given *M* population and welfare at one period step, for each period step *p* in one complete run, equals to 100,000 period while each period step includes 100 iterations of imitation and exploration, the welfare in *M* population is added up to the accumulated welfare. After executing one complete run, the average welfare for all population is calculated.

4.3 Simulation without Second-order Punishment

The Simulator has been executed for massive number of runs to test the PGG model described in Chapter 3 and to study the competition between pool punishment and peer punishment. This section illustrates the simulation runs without second-order punishment. In the absence of second-order punishment, peer-punishers impose fines on only free-riders, defectors, at their own cost. Similarly, Pool-punishers impose fines on only free-riders, defectors, by paying a fixed amount to common punishment pool. As continuity to the payoff calculations in Chapter 3, this section illustrates the payoff calculation for each player according to his strategy without applying second-order punishment.

Following Sigmund et al. (2010); in a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; *W*, where $M = X + Y + Z + V + W$. *N* players are arbitrarily picked to join the PGG. Then, the probability that (N-1) players are not intending to participate in the PGG is calculated as follows:

$$P_\sigma = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}$$

Equation 4.1: Loners probability in *M* population

The cooperator under the absence of second-order punishment is not punished by the peer-punisher or pool-punishers; the cooperators payoff is calculated as follows:

$$P_x = P_\sigma \sigma + (1 - P_\sigma) c (r \frac{M - Z - Y - 1}{M - Z - 1} - 1)$$

Equation 4.2: Cooperators payoff without second-order punishment

The defector is punished by the pool-punishers and peer-punishers; the defectors payoff is calculated as follows:

$$P_y = P_\sigma \sigma + (1 - P_\sigma) rc \frac{M - Z - Y}{M - Z - 1} - \frac{B(N-1)V}{M-1} - \frac{(N-1)W}{M-1} \beta$$

Equation 4.3: Defectors payoff without second-order punishment

While, the loners payoff is calculated as follows:

$$P_z = \sigma$$

Equation 4.4: Loners payoff without second-order punishment

The pool-punishers payoff is calculated as follows:

$$P_v = P_\sigma \sigma + (1 - P_\sigma) [c (r \frac{M - Z - Y - 1}{M - Z - 1} - 1) - G]$$

Equation 4.5: Pool-punishers payoff without second-order punishment

The peer-punishers payoff is calculated as follows:

$$P_W = P_\sigma \sigma + (1 - P_\sigma)c(r\frac{M - Z - Y - 1}{M - Z - 1} - 1) - \frac{(N-1)Y}{M-1}\gamma$$

Equation 4.6: Peer-punishers payoff without second-order punishment

4.4 Simulation with Second-order Punishment

The Simulator has been executed for massive number of runs to test the PGG model described in Chapter 3 and to study the competition between pool punishment and peer punishment. This section illustrates the simulation runs applying second-order punishment. Peer-punishers apply second-order punishment by imposing fines on cooperators at their own cost. The cooperators are punished by peer-punishers as they do not punish free-riders. Similarly, Pool-punishers impose fines on cooperators and peer-punishers, by paying a fixed amount to common punishment pool. Pool-punishers punish peer-punishers and cooperators as they do not contribute to the common pool punishment; they are considered illegitimates. As continuity to the payoff calculations in Chapter 3, this section illustrates the payoff calculation for each player according to his strategy with applying second-order punishment.

Following Sigmund et al. (2010) PGG model ; in a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; *W*, where $M = X + Y + Z + V + W$. *N* players are arbitrarily picked to join the PGG. Then, the probability that (N-1) players are not intending to participate in the PGG is calculated as follows:

$$P_\sigma = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}$$

Equation 4.7: Loners probability with second-order punishment

$$P_{second} = \frac{\binom{M-Y-2}{N-2}}{\binom{M-2}{N-2}}$$

Equation 4.8: Peer-punishers second-order probability

With second-order punishment, the cooperator is punished by the peer-punishers because he does not punish free-riders, and the cooperator is also punished by the pool-punishers as he does not contribute to the common pool punishment; the cooperators payoff is calculated as follows:

$$P_X = P_\sigma \sigma + (1 - P_\sigma)c(r\frac{M - Z - Y - 1}{M - Z - 1} - 1) - \frac{B(N-1)V}{M-1} - \frac{(N-1)W}{M-1}\beta\,(1 - P_{second})$$

Equation 4.9: Cooperators payoff with second-order punishment

The defector is punished by the pool-punishers and peer-punishers; the defectors payoff is calculated as follows:

$$P_y = P_\sigma\sigma + (1 - P_\sigma)rc\frac{M-Z-Y}{M-Z-1} - \frac{B(N-1)V}{M-1} - \frac{(N-1)W}{M-1}\beta$$

Equation 4.10: Defectors payoff with second-order punishment

While, the loners payoff is calculated as follows:

$$P_z = \sigma$$

Equation 4.11: Loners payoff with second-order punishment

The pool-punishers payoff is calculated as follows:

$$P_v = P_\sigma\,\sigma + (1 - P_\sigma)[c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - G]$$

Equation 4.12: Pool-punishers payoff with second-order punishment

With second-order punishment, the peer-punisher is also punished by the pool-punishers as he does not contribute to the common pool punishment; he is considered as illegitimates. The peer-punishers payoff is calculated as follows:

$$P_w = P_\sigma\sigma + (1 - P_\sigma)c(r\frac{M-Z-Y-1}{M-Z-1} - 1) - \frac{B(N-1)V}{M-1} - \frac{(N-1)Y}{M-1}\gamma - \frac{(N-1)X}{M-1}\gamma(1 - P_{second})$$

Equation 4.13: Peer-punishers payoff with second-order punishment

4.5 Results and Discussion

The results of the numerous simulation runs were averaged to end up with one result set. It was found that this result set is comparable to the existing results in Sigmund et al. (2010) research paper:

- Without second-order punishment:
  As shown in Figure 4.5, the competition between pool-punishers and peer-punishers over period steps obtained from the simulator is to a large extent similar to Sigmund at al. (2010) results shown in Figure 3.1. Peer-punishers dominate most of time but sometimes second-order free-rider try to conquer the population. Occasionally, the defectors invade then loners take over but peer-punishers remerge again to stabilize for a quiet long time. In general, peer-punishers perform better than pool-punishers in this case

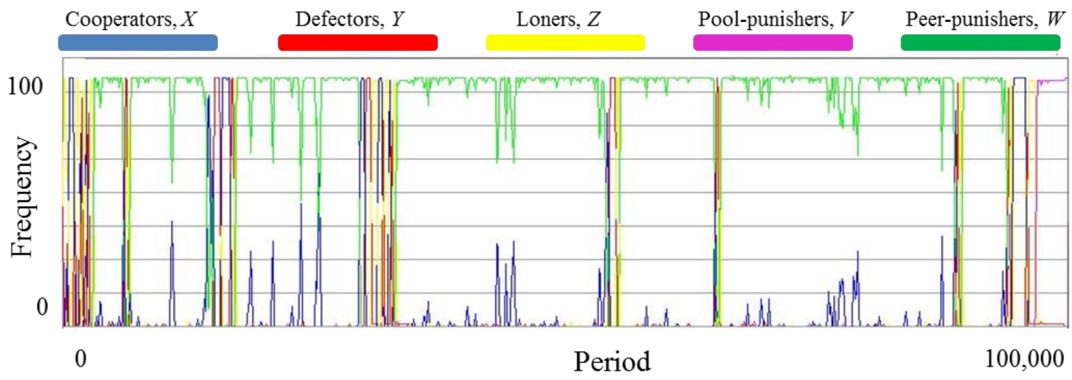

Figure 4.5: Simulator result without second-order punishment

- With second-order punishment
  As shown in Figure 4.6, the competition between pool-punishers and peer-punishers over period steps obtained from the simulator is to a large extent similar to the Sigmund et al. (2010) results shown in 3.1. The slight difference between this simulator and Sigmund et al. (2010) results is the fact that some of this simulation runs showed pool-punishers prevailing very early even without competing with peer-punisher as shown in Figure 4.7. Pool-punishers apply sanctioning to the second-order free-riders even though they all contribute to the collaborative effort. Pool-punishers consider any player who doesn't contribute to the common punishment pool even if he contributes to the common good as an outlaw including also cooperators and peer-punishers. Pool-punishers emerge and ultimately lead to a very stable regime. In general, pool-punishers perform better than pool-punishers in this case

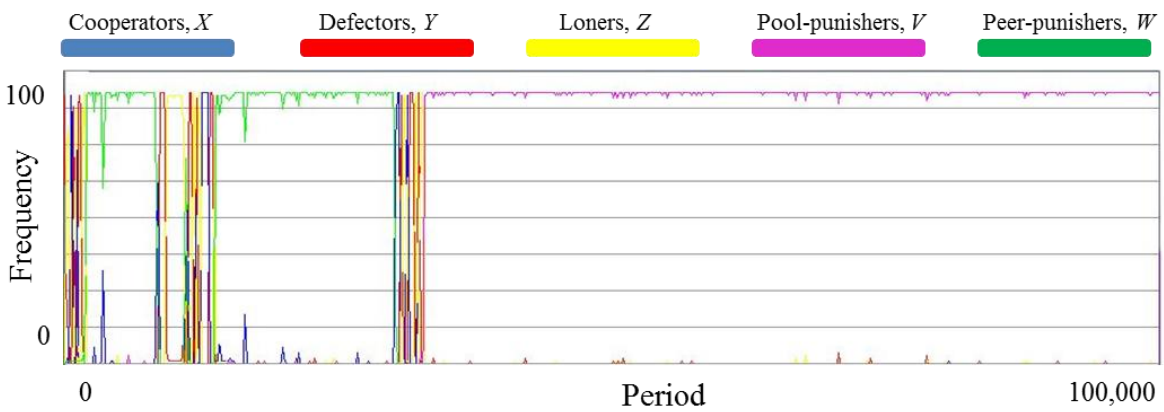

Figure 4.6: Simulator first set of result with second-order punishment

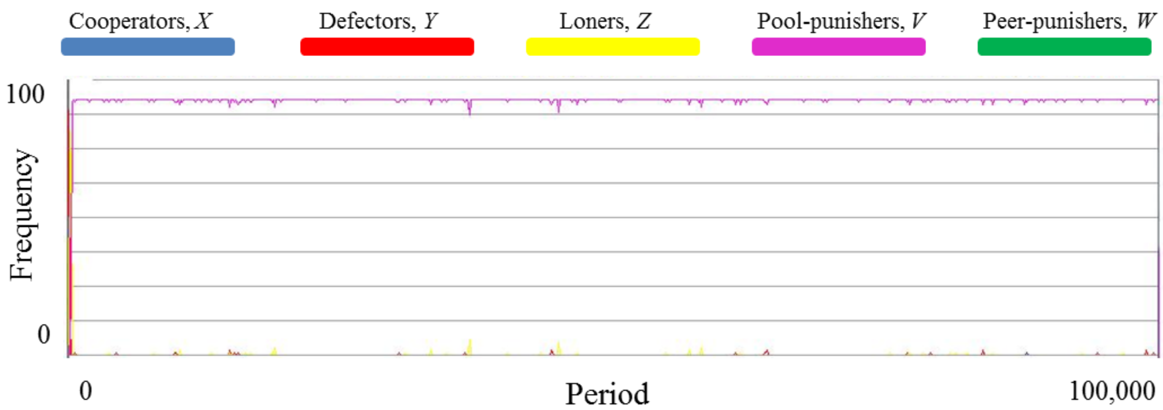

Figure 4.7: Simulator second set of results with second-order punishment

The simulator replicates to a large extend the Sigmund et al. (2010) results. This thesis is focusing on studying this model with second-order punishment. Three problematic debates popped up from analyzing these result:

- It ensures that centralized institutions continue to gain unilateral and undisputed power for legitimate punishment over peer-punishers. The centralized pool punishment prevails, replaces peer punishment and establishes a stable regime. The results also imply that increasing the severity of the centralized and legitimate authority increases cooperation in societies.
  This point leads to these questions: Is strong centralized authority stable? why strong centralized punishment sometimes fails to maintain cooperation in societies? Could it be because of corruption? Does cooperation in societies require decentralized enforcement in addition to the centralized authority?
- The results also imply that the pool punishment punishes peer-punishers as they do not contribute to the common pool punishment. In Sigmund et al. (2010) model, the peer-punishers are considered illegitimates.
  This point leads to the question: why some countries tolerate a form of peer punishment as legitimate?

Chapter 5

5 The Study of the Centralized Institutions Stability

Sigmund el al. (2010) showed that centralized institutions gain unilateral and undisputed power for legitimate punishment over peer-punishers. The centralized pool punishment prevails, replaces all population including peer-punishers and establishes a stable regime. The centralized pool punishment model eliminates second-order free-riders problem as it applies sanctioning to the second-order free-riders even though they all contribute to the collaborative effort. Pool-punishers consider any player who doesn't contribute to the common punishment pool as second-order free-rider including peer-punisher, even if he contributes to the common goods (Sigmund et al. 2010).

Pool-punishers in Sigmund et al. (2010) model pay a fixed amount; *G* to a common punishment pool before participating and contributing; *c* to the PGG. Applying second-order punishment, any player, such as free-riders and peer-punishers, who does not contribute to the common punishment pool, pays fine; BN_v, where N_v is the number of pool-punishers and B > 0, where B is the severity of second-order punishment. As illustrated in Chapter 3 payoff calculations, the pool punishment fine is represented by $\frac{B(N-1)V}{M-1}$, where *B* is the severity of second-order punishment, *N* is the players count that are arbitrarily picked to play a round of game, *M* is the overall population and *V* is the pool-punishers population that knows that the game is not obligatory.

In this chapter, the first set of research questions to be answered includes: Is strong centralized authority stable? Can the evolutionary game model explain why strong centralized punishment sometimes fails to maintain cooperation in societies? Could it be because of corruption? Does cooperation in societies require decentralized enforcement in addition to the centralized authority?

The answers to these research questions will be obtained by:

- Investigating the effect of manipulating the second-order punishment severity parameter; *B,* when it is applied to the simulator PGG model on the centralized authority stability
- Modeling the corruption strategy
- Applying the corruption strategy to the simulator PGG model investigating the effect of manipulating of second-order punishment severity parameter on the centralized authority stability
- Comparing the PGG model behavior for the simulation runs with and without applying the corruption strategy while tuning the *B* parameter

5.1 The Effect of Centralized Punishment Severity on the PGG Model

For the Sigmund et al. (2010) PGG model described in Chapter 3, in a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; *W*, and *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values vary along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8, where B = 0.7 is the default value that was used by Sigmund et al. (2010) model. The results have been collected (Appendix A.1) and analyzed as follows:

As shown in Figure 5.1 and Table 5.1 when B = 0.0001 (weaker pool punishment), peer-punishers are more stable and perform better than pool-punishers. Occasionally, the defectors and pool-punishers try to take over but peer-punishers remerge and stabilize again.

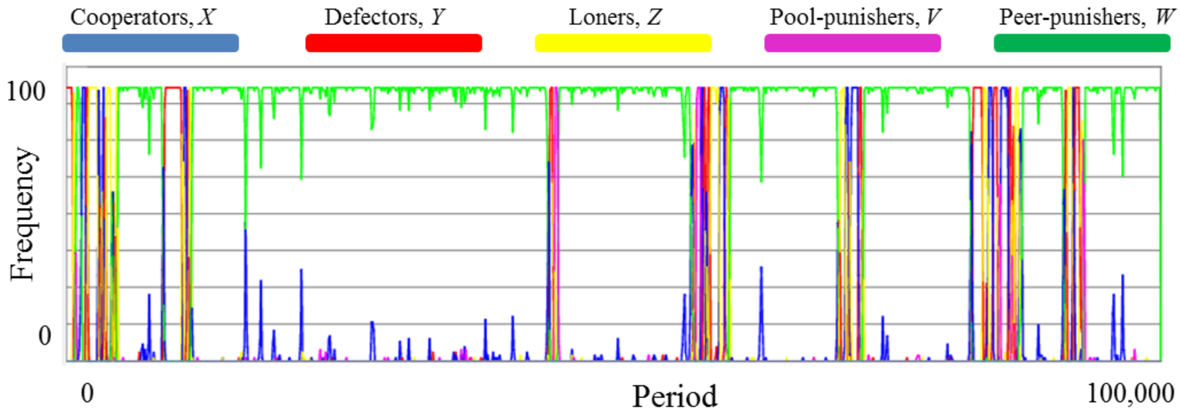

Figure 5.1: Simulation result of population percentage of five strategies when B=0.0001

Pop	*X*	*Y*	*Z*	*W*	*V*
%	5.65	4.50	5.38	83.5	0.85

Table 5.1: Population average of five strategies when B=0.0001

As shown in Figure 5.2 and Table 5.2 when B = 0.06 (weak pool punishment), peer-punishers are still more stable and perform better than pool-punishers, but frequently, the defectors and pool-punishers try to take over as the second-order punishment severity slightly increases but peer-punishers remerge and stabilize again.

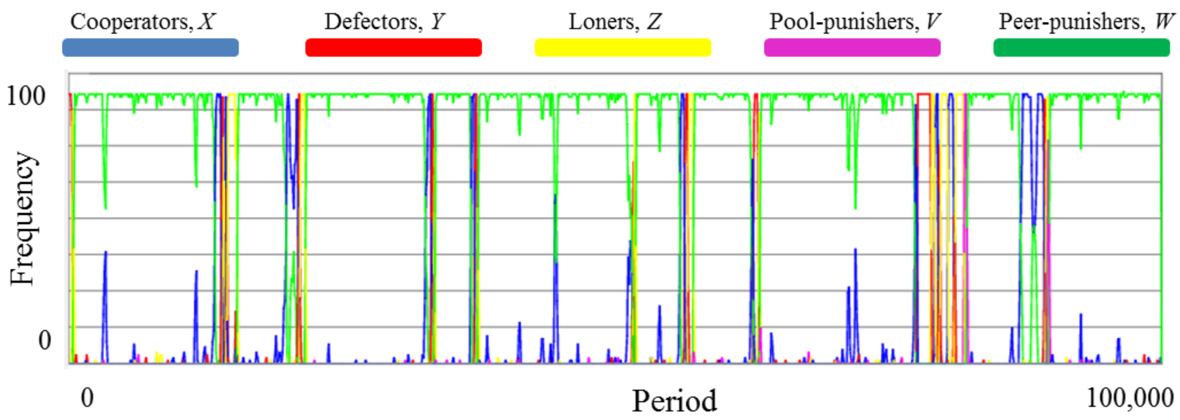

Figure 5.2: Simulation result of population percentage of five strategies when B=0.06

Pop	*X*	*Y*	*Z*	*W*	*V*
%	6.30	4.98	5.64	82.2	0.78

Table 5.2: Population average of five strategies when B=0.06

As shown in Figure 5.3 and Table 5.3 when B = 0.7 (intermediate pool punishment), although there are real competition between pool-punishers and peer-punishers, pool-punishers perform better than pool-punishers, it eventually succeed to invade the peer-punishers and ultimately lead to a very stable regime.

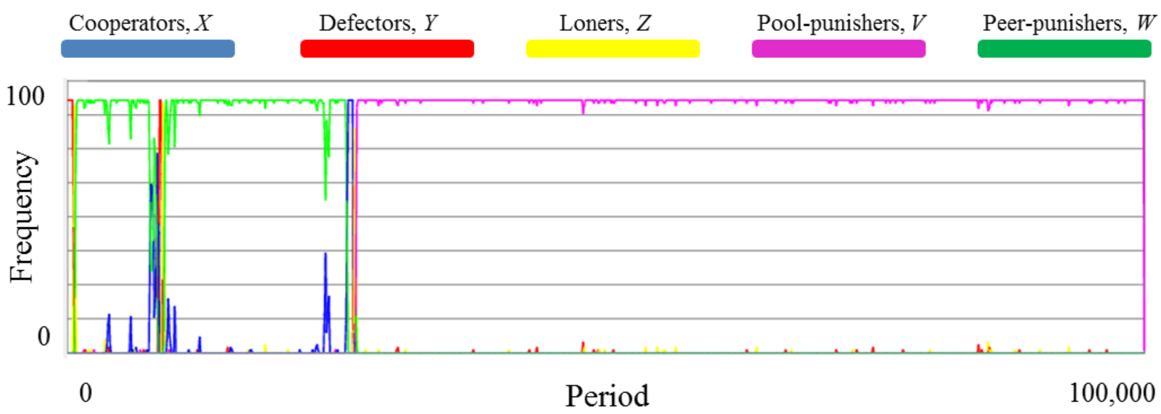

Figure 5.3: Simulation result of population percentage of five strategies when B=0.7

Pop	*X*	*Y*	*Z*	*W*	*V*
%	1.58	1.30	1.56	20.8	74.6

Table 5.3: Population average of five strategies when B=0.7

As shown in Figure 5.4 and Table 5.4 when B = 2.1 (intermediate pool punishment), although the competition between pool-punishers and peer-punishers is very weak, pool-punishers perform better than pool-punishers, it succeed to invade the peer-punishers and ultimately lead to a very stable regime.

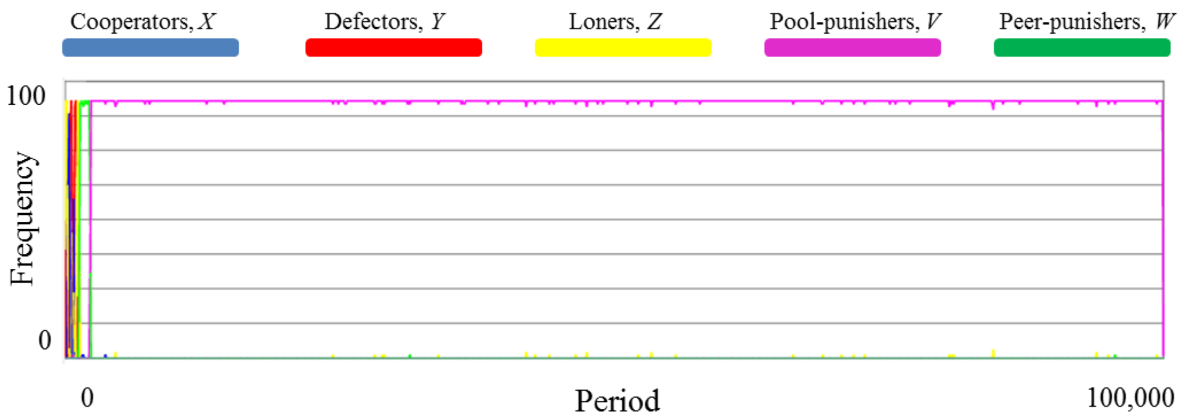

Figure 5.4: Simulation result of population percentage of five strategies when *B*=2.1

Pop	***X***	***Y***	***Z***	***W***	***V***
%	0.41	0.63	0.58	4.28	94.0

Table 5.4: Population average of five strategies when *B*=2.1

As shown in Figure 5.5, 5.6, 5.7 and 5.8, also in Table 5.5, 5.6, 5.7 and 5.8 when *B* = 6.3, *B* = 7.0, *B* = 18.6, *B* = 55.8 (strong pool punishment), pool-punishers are more stable and perform much better than peer-punishers. As the second-order punishment severity becomes stronger, the pool punishment has approximately complete dominance of the system and entirely replaces peer-punishment.

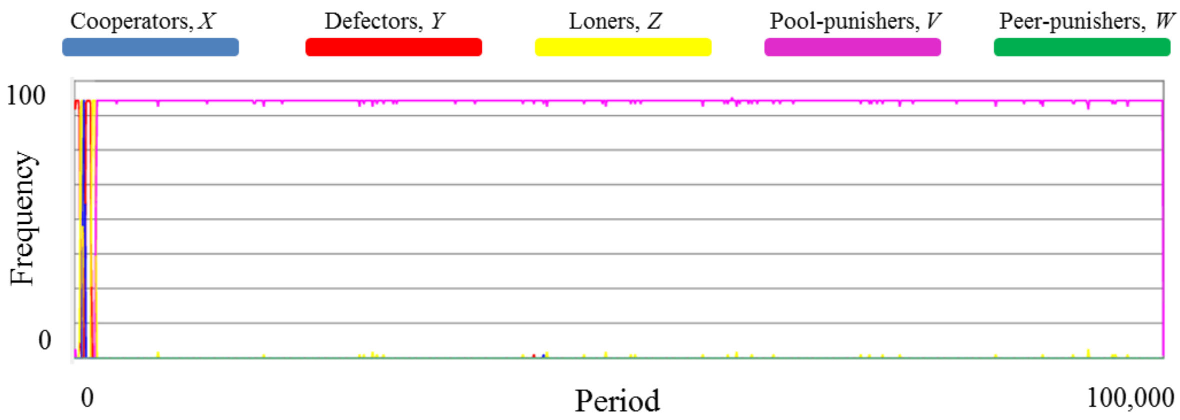

Figure 5.5: Simulation result of population percentage of five strategies when *B*=6.3

Pop	***X***	***Y***	***Z***	***W***	***V***
%	0.14	0.26	0.45	0.51	98.6

Table 5.5: Population average of five strategies when *B*=6.3

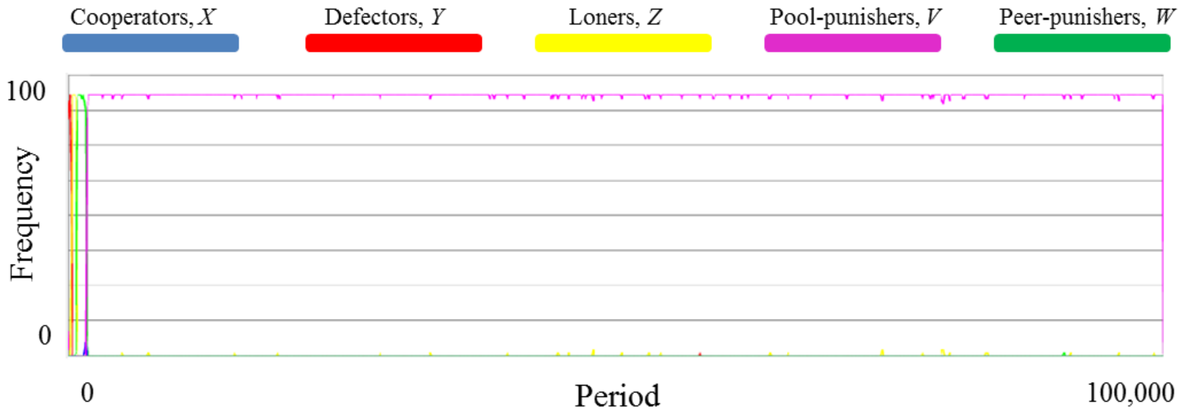

Figure 5.6: Simulation result of population percentage of five strategies when *B*=7.0

Pop	***X***	***Y***	***Z***	***W***	***V***
%	0.08	0.22	0.39	0.43	98.8

Table 5.6: Population average of five strategies when *B*=7.0

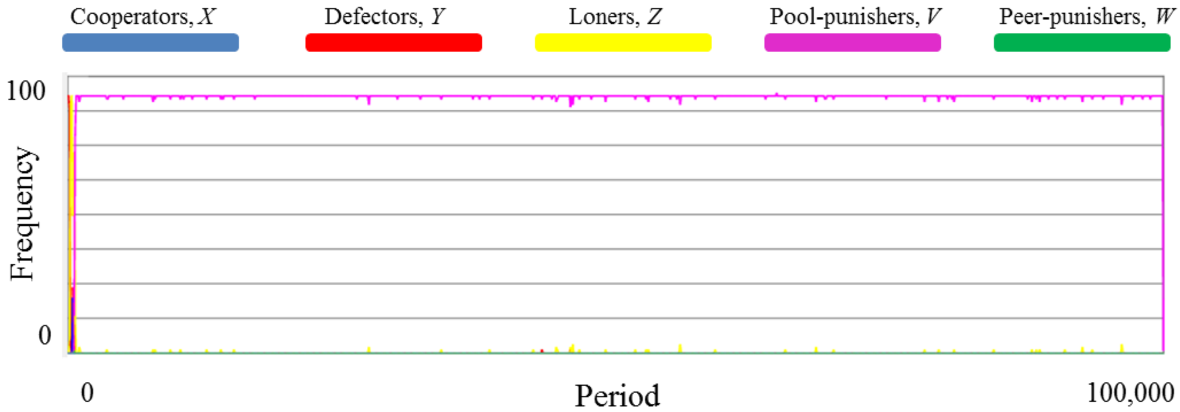

Figure 5.7: Simulation result of population percentage of five strategies when *B*=18.6

Pop	***X***	***Y***	***Z***	***W***	***V***
%	0.21	0.37	0.49	0.24	98.6

Table 5.7: Population average of five strategies when *B*=18.6

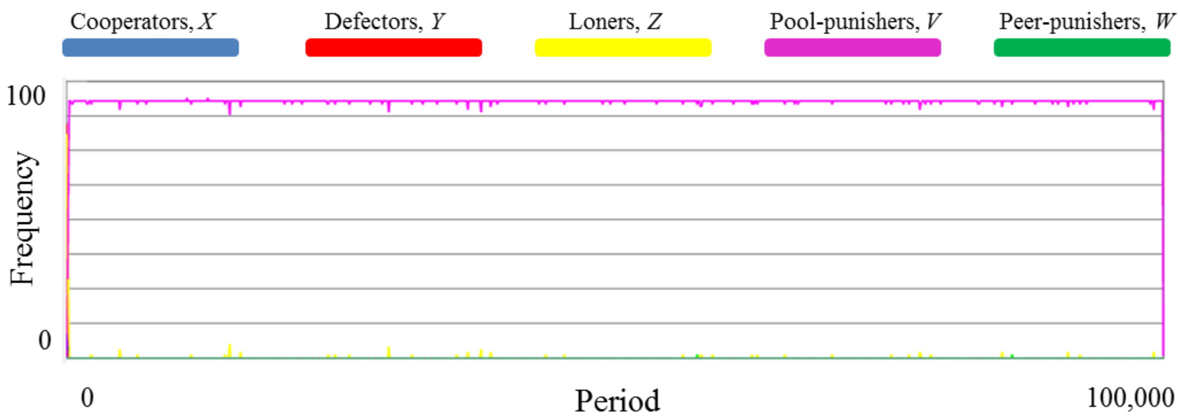

Figure 5.8: Simulation result of population percentage of five strategies when *B*=55.8

Pop	*X*	*Y*	*Z*	*W*	*V*
%	0.16	0.22	0.52	0.19	98.8

Table 5.8: Population average of five strategies when *B*=55.8

As predicted, Table 5.9 and Figure 5.9 ensured that as the sanctioning severity of the institutional authority escalates, the stability of the system increases, since the institutional authority becomes more dominant and diminishes the peer-punishment. Table 5.9 and Figure 5.9 can be analyzed as follows:

- With weak second-order punishment severity (low *B*, approximately when *B*<0.7), peer-punishers are more stable and perform better than pool-punishers. Occasionally, the defectors invade then loners take over but peer-punishers remerge and stabilize again. As the second-order punishment severity becomes weaker, the peer punishment emerges more easily.
- With intermediate second-order punishment severity (intermediate *B*, approximately when 0.7<*B*<2.1) , although there is real competition between pool-punishers and peer-punishers, the pool -punishers emerge and ultimately lead to a very stable regime
- With strong second-order punishment severity (high *B*, approximately when *B*>2.1), pool-punishers are more stable and perform much better than peer-punishers. As the second-order punishment severity becomes stronger, the pool punishment has approximately complete dominance of the system and entirely replaces peer-punishment. Pool-punishers are ultimately preventing peer-punishers from gaining ground.

B	0.0001	0.06	0.7	2.1	6.3	7	18.9	55.8
X	5.657	6.305	1.588	0.409	0.144	0.087	0.218	0.164
Y	4.509	4.984	1.302	0.629	0.269	0.219	0.374	0.224
Z	5.381	5.646	1.561	0.587	0.451	0.392	0.495	0.523
W	83.58	82.27	20.89	4.282	0.510	0.432	0.245	0.199
V	0.857	0.783	74.65	94.08	98.62	98.86	98.66	98.88

Table 5.9: Simulation result showing average population percentage of five strategies for various *B* values, second-order punishment severity

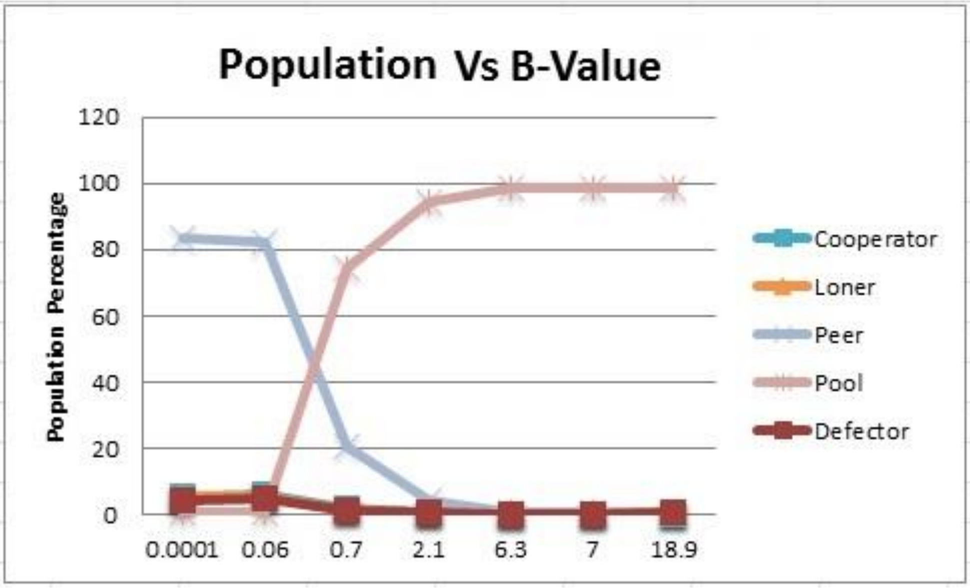

Figure 5.9: Simulation result showing average population percentage of five strategies for various *B* values, second-order punishment severity

These results imply that the dominance of strong centralized institutional punishment and the demise of the peer punishment ensure the stability of the cooperation. However, this stability by definition opposes the concept of protestors and revolution against central authorities. That leads us to the rest of the thesis questions: Can the evolutionary game model explain why strong centralized punishment sometimes fails to maintain cooperation in societies? Could it be because of corruption? Does cooperation in societies require decentralized enforcement in addition to the centralized authority?

5.2 Corruption Strategy

Centralized authority that has monopoly, unilateral and undisputed power for legitimate punishment over peer-punishment, is considered a single point of failure and will be susceptible to corruption.

Corruptors are a certain form of defectors, a corruptor pays the central authority a fixed fee; *KG*, when $KG < G+c$, to avoid punishment for not contributing to the PGG. Corruptors participate but do not contribute to the PGG. The fixed fee *KG* must be less than $G+c$, the total contribution of the pool-punishers. Corruptors by definition do not contribute to the common pool but bribe the centralized authority. Parameter $K \in [0,1]$, this parameter controls the bribe amount as a percentage of *G*, when *G* is the fixed amount paid by the pool-punishers to the common punishment pool. Corruptors are not punished by the pool-punishers as they bribe them but they do not bribe peer-punisher so they are punished by peer-punisher.

Adding corruptor strategy to the PGG model (Sigmund et al. 2010) in chapter 3, in a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers, *W*, and Corruptors *C*, where $M = X + Y + Z + V + W + C$ and *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. The Corruptors payoff is calculated as follows, when $K \in [0,1]$ and $KG < G+c$:

$$P_C = P_\sigma \sigma + (1 - P_\sigma)(rc\frac{M - Z - Y - C}{M - Z - 1} - KG) - \frac{(N-1)W}{M-1}\beta$$

Equation 5.1: Corruptors payoff in a population of *X*, *Y*, *Z*, *V*, *W* and *C*

The simulated PGG model payoff equations have been updated after applying the corruption strategy. Corruptors are manipulated at the payoff equations similar to defector except corruptors are not punished by the centralized authority as they do bribe them. Corruptors are punished only by peer-punishers. The payoff equations are illustrated as follows:

$$P_\sigma = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}$$

Equation 5.2: Loners probability in the presence of corruption

$$P_{second} = \frac{\binom{M-Y-C-2}{N-2}}{\binom{M-2}{N-2}}$$

Equation 5.3: Peer-punishers second-order probability in the presence of corruption

$$P_x = P_\sigma \sigma + (1 - P_\sigma)c(r\frac{M - Z - Y - C - 1}{M - Z - 1} - 1) - \frac{B(N-1)V}{M-1} - \frac{(N-1)W}{M-1}\beta\ (1 - P_{second})$$

Equation 5.4: Cooperators payoff in the presence of corruption

$$P_y = P_\sigma \sigma + (1 - P_\sigma) rc \frac{M - Z - Y - C}{M - Z - 1} - \frac{B(N-1)V}{M-1} - \frac{(N-1)W}{M-1} \beta$$

Equation 5.5: Defectors payoff in the presence of corruption

$$P_z = \sigma$$

Equation 5.6: Loners payoff in the presence of corruption

$$P_v = P_\sigma \sigma + (1 - P_\sigma)[c(r \frac{M - Z - Y - C - 1}{M - Z - 1} - 1) - G]$$

Equation 5.7: Pool-punishers payoff in the presence of corruption

$$P_w = P_\sigma \sigma + (1 - P_\sigma) c(r \frac{M - Z - Y - C - 1}{M - Z - 1} - 1) - \frac{B(N-1)V}{M-1} - \frac{(N-1)(Y+C)}{M-1} \gamma - \frac{(N-1)X}{M-1} \gamma (1 - P_{second})$$

Equation 5.8: Peer-punishers payoff in the presence of corruption

The corruption strategy is introduced in this thesis to investigate both why strong centralized punishment sometimes fails to maintain cooperation in societies, and also why the strong centralized authority should tolerate the peer punishment as legitimate.

5.3 Applying Corruption Strategy to the PGG Model

Corruption strategy is applied to the Sigmund et al. (2010) PGG model described in chapter 3. In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, and corruptors, *C*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. The corruptor parameter $K = 0.5$. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8, where $B = 0.7$ is the default value that was used by Sigmund et al. (2010) model. The results have been collected (Appendix A.2) and analyzed as follows:

As shown in Figure 5.10 and Table 5.10 when $B = 0.0001$ (weaker pool punishment), peer-punishers dominate and prevent corruptor to gain ground. Peer-punishers are more stable and perform better than pool-punishers. Occasionally, the defectors and corruptors try to take over but peer-punishers prevent them to gain ground. Peer-punishers remerge and stabilize again.

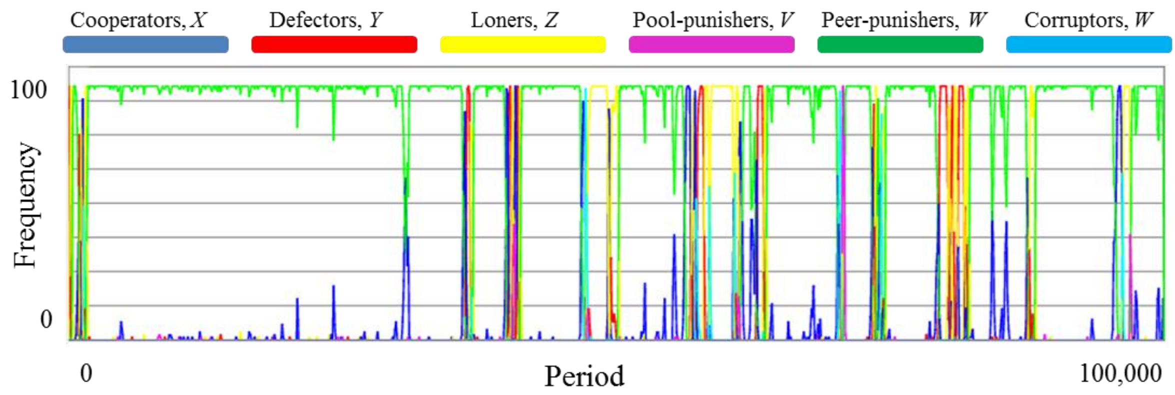

Figure 5.10: Simulation result of population percentage of six strategies when *B*=0.0001

Pop	X	Y	Z	W	V	C
%	4.48	3.99	6.82	82.7	0.78	1.18

Table 5.10: Population average of six strategies when *B*=0.0001

As shown in Figure 5.11 and Table 5.11 when B = 0.06 (weak pool punishment), peer-punishers become less dominate but still prevent corruptors to gain ground. Peer-punishers are still stable and perform better than pool-punishers. Occasionally, the defectors and corruptors try to take over but peer-punishers prevent them to gain ground. Peer-punishers remerge and stabilize again.

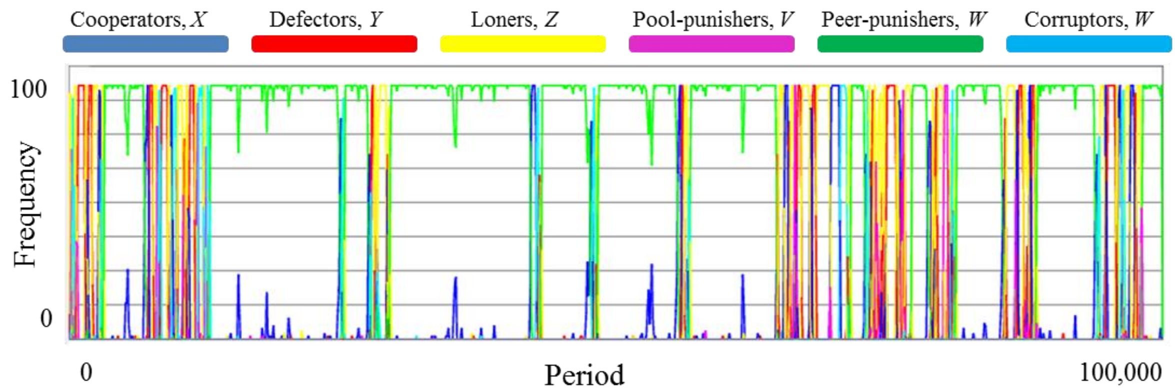

Figure 5.11: Simulation result of population percentage of six strategies when *B*=0.06

Pop	X	Y	Z	W	V	C
%	4.87	4.25	7.42	81.3	0.74	1.35

Table 5.11: Population average of six strategies when *B*=0.06

As shown in Figure 5.12 and Table 5.12 when B = 0.7 (intermediate pool punishment), peer-punishers become less dominate but still prevent corruptors to gain ground. Peer-punishers are still stable and perform better than pool-punishers. Occasionally, the defectors and corruptors try to take over but peer-punishers prevent them to gain ground. Peer-punishers remerge and stabilize again. Interestingly, Loners starts to gain ground.

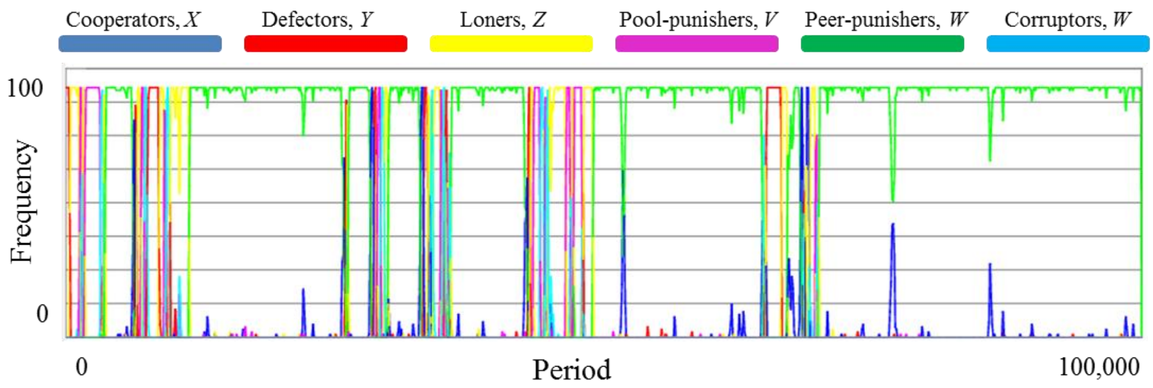

Figure 5.12: Simulation result of population percentage of six strategies when *B*=0.7

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***
%	4.68	5.21	9.56	75.2	3.05	2.33

Table 5.12: Population average of six strategies when *B*=0.7

As shown in Figure 5.13 and Table 5.13 when *B* = 2.1 (intermediate pool punishment), peer-punishers become less dominate but still prevent corruptors to gain ground. Peer-punishers are still stable and perform better than pool-punishers. Occasionally, the defectors, pool-punishers and corruptors try to take over but peer-punishers prevent them to gain ground. Peer-punishers remerge and stabilize again. Interestingly, Loners gain more ground.

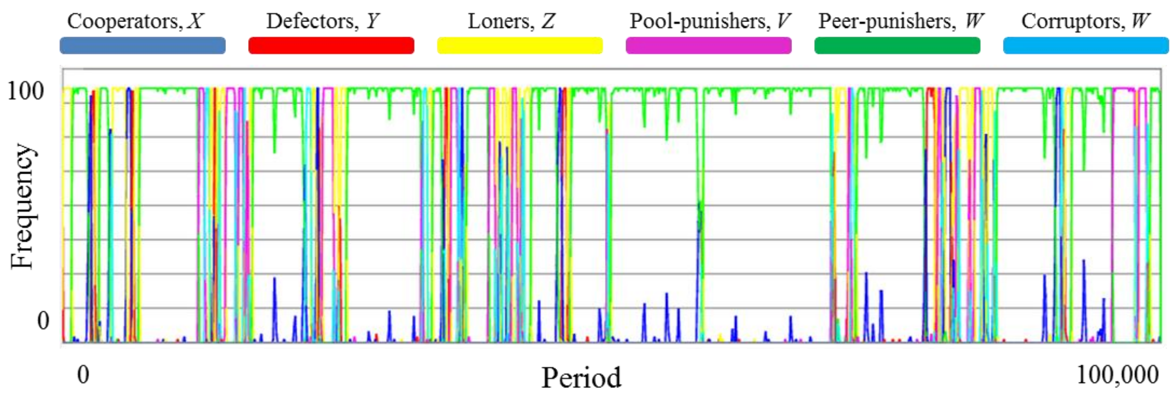

Figure 5.13: Simulation result of population percentage of six strategies when *B*=2.1

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***
%	5.00	3.86	10.8	71.0	5.80	3.39

Table 5.13: Population average of six strategies when *B*=2.1

As shown in Figures 5.14, 5.15, 5.16, and 5.17, also in Tables 5.14, 5.15, 5.16, and 5.17, when B = 6.3, B = 7.0, B = 18.6, and B = 55.8 (Strong pool punishment), peer-punishers diminish, corruptors increase, pool-punishers gain some ground, and interestingly loners become the most adopted strategy. As B increases, the strong centralized authority loses its unilateral and undisputed power in the presence of corruption and the cooperation decreases as loners, which are the majority of the population, do not participate in the PGG.

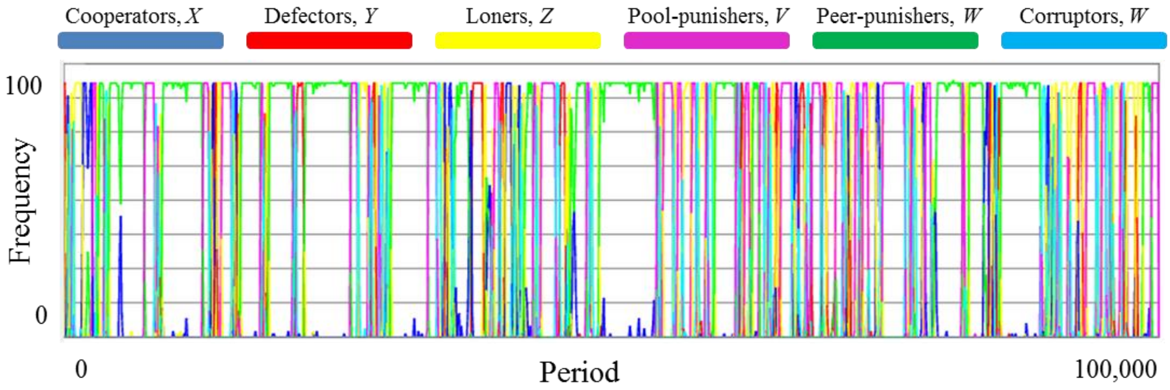

Figure 5.14: Simulation result of population percentage of six strategies when B=6.3

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***
%	5.43	6.37	23.4	36.4	19.5	8.74

Table 5.14: Population average of six strategies when B=6.3

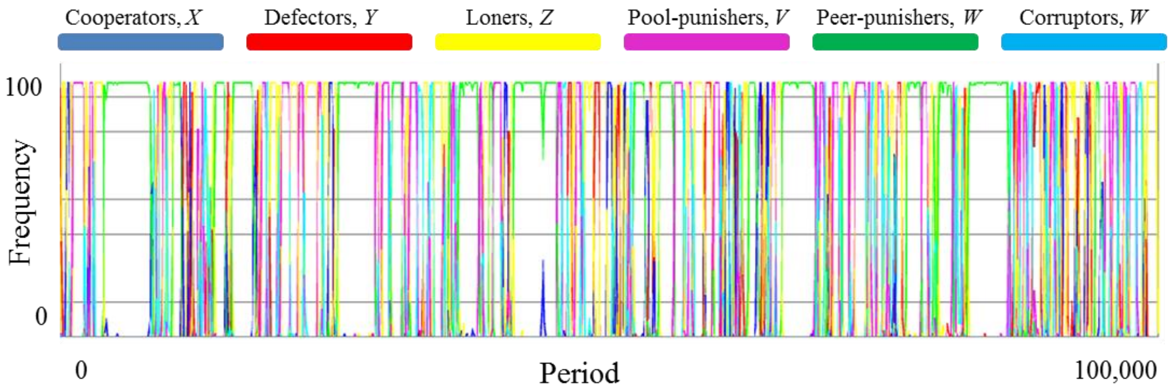

Figure 5.15: Simulation result of population percentage of six strategies when B=7.0

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***
%	4.93	6.34	22.7	36.5	20.0	9.36

Table 5.15: Population average of six strategies when B=7.0

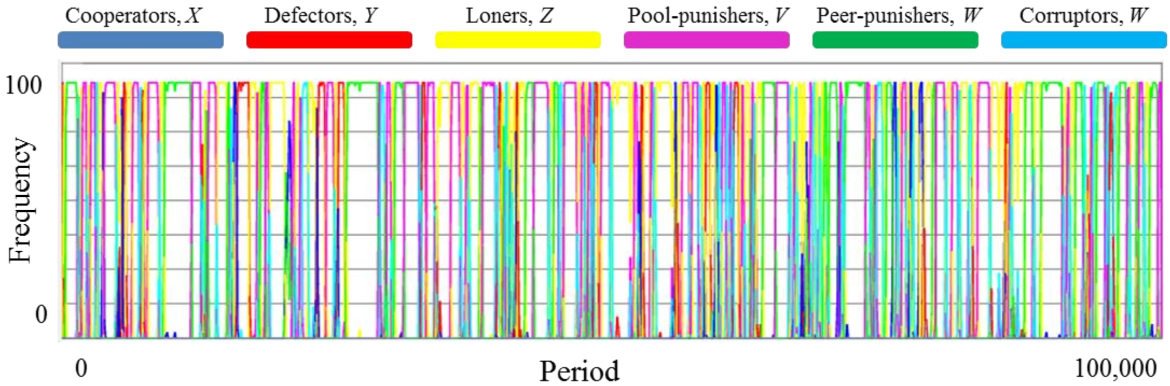

Figure 5.16: Simulation result of population percentage of six strategies when *B*=18.6

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***
%	5.35	7.71	31.7	17.3	25.5	12.3

Table 5.16: Population average of six strategies when *B*=18.6

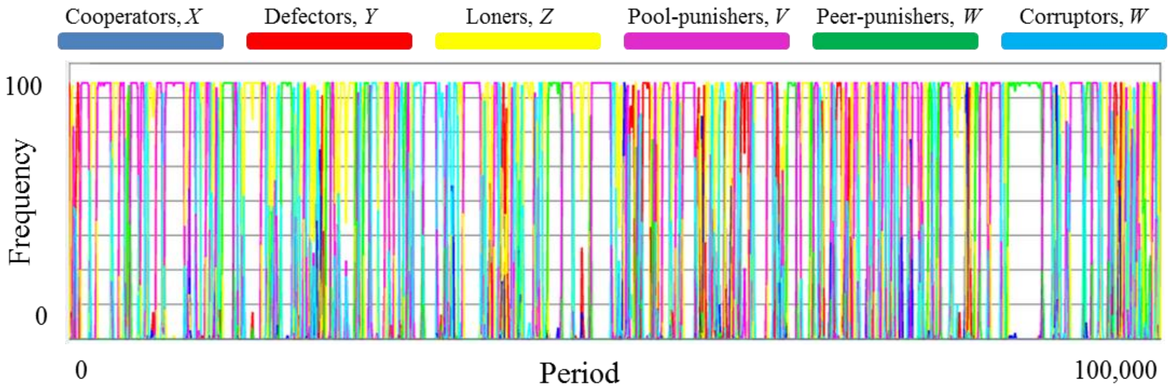

Figure 5.17: Simulation result of population percentage of six strategies when *B*=55.8

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***
%	4.11	6.76	32.9	13.2	29.1	13.7

Table 5.17: Population average of six strategies when *B*=55.8

As Predicted, Table 5.18 and Figure 5.18 can be analyzed as follows:

- With weak second-order punishment severity (low *B*, approximately when *B*<0.7), peer-punishers dominate and prevent corruptors to gain ground. Peer-punishers are more stable and perform better than pool-punishers. Occasionally, the defectors and corruptors try to take over but peer-punishers prevent them to gain ground, peer-punishers remerge and stabilize again. Weak centralized punishment allows the peer-punishers to evolve together with the centralized institution. As per this corruption model , only peer-punishers are capable of imposing fines on corruptors

- With intermediate second-order punishment severity (intermediate *B*, approximately when 0.7<*B*<2.1), peer-punishers become less dominate but still prevent corruptors to gain ground. Peer-punishers are still stable and perform better than pool-punishers. Occasionally, the defectors and corruptors try to take over but peer-punishers prevent them to gain ground, peer-punishers remerge and stabilize again. Interestingly, Loners starts to gain ground.
- With strong second-order punishment severity (high *B*, approximately when *B*>2.1), As *B* increases, peer-punishers diminish as they are severely punished by pool-punishers, corruptors increase as they bribe pool-punishers to avoid punishment and no fines imposed by peer-punishers , pool-punishers gain some ground, and interestingly loners becomes the most adopted strategy. As *B* increases, the strong centralized authority loses its unilateral and undisputed power in the presence of corruption and fails to maintain cooperation evolution as loners, which are the majority of the population, do not participate in the PGG

B	0.0001	0.06	0.7	2.1	6.3	7	18.9	55.8
X	4.488	4.872	4.630	5.001	5.432	4.929	5.350	4.106
Y	3.989	4.254	5.209	3.863	6.371	6.346	7.712	6.758
Z	6.823	7.422	9.567	10.89	23.46	22.75	31.72	32.94
W	82.72	81.34	75.20	71.04	36.47	36.59	17.32	13.24
V	0.786	0.741	3.050	5.801	19.50	20.00	25.54	29.19
C	1.180	1.358	2.338	3.394	8.742	9.366	12.34	13.75

Table 5.18: Simulation result showing average population percentage of six strategies for various *B* values, second-order punishment severity

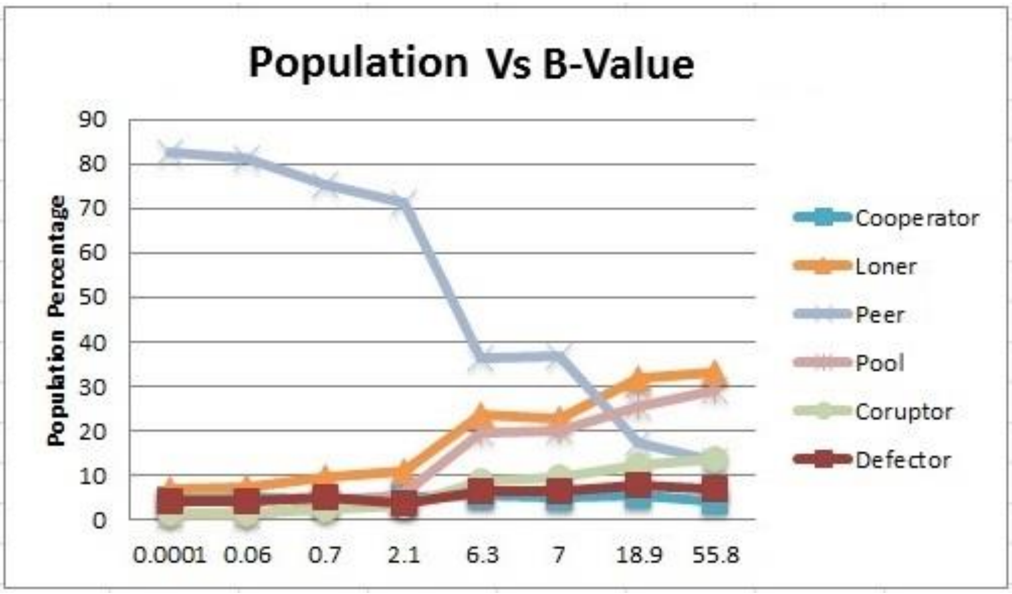

Figure 5.18: Simulation result showing average population percentage of six strategies for various *B* values, second-order punishment severity

These results imply that in the presence of corruption, as the sanctioning severity of the institutional authority escalates, the system becomes unstable as the institutional authority loses its unilateral and undisputed power while the peer-punishment is diminished, and the centralized authority is no longer capable of maintaining the cooperation. Meanwhile, weaker centralized authority allows the peer-punishers to evolve together with the centralized institution punishment, prevent the corruptors and defectors to gain ground and maintain the cooperation evolution.

Using this PGG model, the results imply that strong centralized punishment sometimes fails to maintain cooperation in the presence of the corruption and that cooperation evolution requires decentralized enforcement in addition to the centralized authority.

5.4 Results and Discussion

The strong centralized authority stability is investigated by manipulating the severity of second-order punishment parameter, *B,* at the simulator PGG model. Corruption strategy is introduced and applied to the PGG model with various levels of second-order punishment severity to re-investigate the strong centralized authority stability. The PGG model behavior with and without applying the corruption strategy are compared while tuning second-order punishment severity.

Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8, where *B* = 0.7 is the default value that was used by Sigmund et al. (2010) model. The results have been collected and analyzed for two different cases:

- In the absence of corruption as shown in Figure 5.9 and Table 5.9, for weak second-order punishment severity, peer-punishers are more stable and perform better than pool-punishers. Occasionally, the defectors invade then loners take over but peer-punishers remerge and stabilize again. As the second-order punishment severity becomes weaker, the peer punishment emerges more easily. As the second-order punishment severity increases, pool-punishers are more stable and perform much better than peer-punishers. As the second-order punishment severity becomes stronger, the pool punishment has approximately complete dominance of the system and entirely replaces peer-punishment. Pool-punishers ultimately prevent peer-punishers from gaining ground
- In the presence of corruption as shown in Figure 5.18 and Table 5.18, weak centralized authority allows the peer-punishers to evolve together with the centralized institution punishment, prevent the corruptors and defectors to gain ground and maintain the cooperation evolution; peer-punishers perform better than pool-punisher as they can impose fines on the corruptors. Meanwhile, as the sanctioning severity of the institutional authority escalates, the system becomes

unstable as the institutional authority loses its unilateral and undisputed power while the peer-punishment is diminished, corruptors increase as they bribe pool-punishers to avoid punishment and no fines are imposed by peer-punishers as peer-punisher diminished, and the centralized authority is no longer capable of maintaining the cooperation as loners, which are the majority of the population, do not participate in the PGG

The corruption model helps in explaining if strong centralized authority is stable? And why strong centralized punishment sometimes fails to maintain cooperation? If cooperation evolution requires decentralized enforcement in addition to the centralized authority? The strong centralized authority loses its unilateral power for legitimate punishment and it fails to maintain cooperation in the presence of corruption. Although, peer-punishers prevent the corruptors to gain ground with weak centralized authority, they diminish as well when they are severely punished by pool-punishers. However, societies require decentralized punishment authorities in addition to the centralized one. In this PGG model, peer-punisher is punished by the centralized authority as it is considered as outlaw. Some countries legalize certain form of social peer punishment such as jury duty to maintain cooperation in the presence of corruption (Fowler & Kam 2007; Grechenig, Nicklisch & Thöni 2010; Smirnov et al. 2010). That leads to the rest of the thesis questions; can the evolutionary game model explain why some countries tolerate a form of peer punishment as legitimate?

Chapter 6

6 Hybrid-punishers as Legitimate Form of Peer-Punishers

As the strong centralized authority loses its monopoly, unilateral and undisputed power for legitimate punishment and fails to maintain cooperation in the presence of corruption, a need to legalize a certain form of social peer punishment such as jury duty (Fowler & Kam 2007; Grechenig, Nicklisch & Thöni 2010; Smirnov et al. 2010) arises. Peer-punishers perform better in the face of corruption in maintaining cooperation despite of being punished by the centralized authority as it is considered as outlaw.

In this chapter, the second research question will be answered: Why the strong centralized authority should tolerate the peer punishment as legitimate?

The answer for this research question will be obtained by:

- Modeling the hybrid punishment strategy
- Applying the hybrid punishment strategy to the simulator PGG model investigating the effect of tuning the second-order punishment severity parameter

6.1 Hybrid-punishers Strategy

Hybrid-punishers are a certain form of peer-punishers. A hybrid-punisher pays a fixed amount; *G* to the common punishment pool, same as the pool-punisher, hybrid-punisher participates and contributes; *c* to the PGG but after the game, they impose fine; *β*, on each free-rider (defector) at cost; *γ* exists in their group. Hybrid-punisher is a peer-pool-punisher. Hybrid-punishers are not punished by the pool-punishers as they pay a fixed amount; *G* to the common punishment pool. Hybrid-punishers are not also punished by peer-punishers as they are cooperators and act as peer-punishers in punishing free-riders; in general, hybrid-punishers are not punished.

Adding hybrid-punisher strategy to the PGG model (Sigmund et al. 2010) in chapter 3, in a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers, *W*, Corruptors *C*, and hybrid-punishers, *H*, where *M* = *X* +*Y* + *Z* + *V* + *W* + *C*+ *H* and *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. The hybrid-punishers payoff is calculated as follows:

$$P_h = P_\sigma \sigma + (1 - P_\sigma)[c(r \frac{M - Z - Y - C - 1}{M - Z - 1} - 1) - G] - \frac{(N-1)(Y + C)}{M - 1}\gamma - \frac{(N-1)X}{M-1}\gamma(1 - P_{second})$$

Equation 6.1: Hybrid-punishers payoff in a population of *X, Y, Z, V, W, C,* and *H*

The simulated PGG model payoff equations have been updated after applying the hybrid-punishment strategy; Hybrid-punishers are not punished by any punishment strategy, including the pool-punishers as they pay a fixed amount; *G*, to the common punishment pool and the peer-punishers as they act similar to peer-punishers in punishing free-riders. Hybrid-punisher punishes all other population except the pool-punishers; Hybrid-punisher punishes defectors for not contributing to the PGG and to the common punishment pool, while punishes cooperators for not punishing free-riders and not contributing to the common punishment pool. The payoff equations are illustrated (Sigmund et al. 2010) as follows:

$$P_\sigma = \frac{\binom{Z}{N-1}}{\binom{M-1}{N-1}}$$

Equation 6.2: Loners probability in the presence of hybrid-punishers

$$P_{second} = \frac{\binom{M-Y-C-2}{N-2}}{\binom{M-2}{N-2}}$$

Equation 6.3: Peer-punishers second-order probability in the presence of hybrid-punishers

$$P_x = P_\sigma\sigma + (1 - P_\sigma)c(r\frac{M-Z-Y-C-1}{M-Z-1} - 1) - \frac{B(N-1)(V+H)}{M-1} - \frac{(N-1)(W+H)}{M-1}\beta\,(1 - P_{second})$$

Equation 6.4: Cooperators payoff in the presence of hybrid-punishers

$$P_y = P_\sigma\sigma + (1 - P_\sigma)rc\frac{M-Z-Y-C}{M-Z-1} - \frac{B(N-1)(V+H)}{M-1} - \frac{(N-1)(W+H)}{M-1}\beta$$

Equation 6.5: Defectors payoff in the presence of hybrid-punishers

$$P_z = \sigma$$

Equation 6.6: Loners payoff in the presence of hybrid-punishers

$$P_v = P_\sigma\sigma + (1 - P_\sigma)[c(r\frac{M-Z-Y-C-1}{M-Z-1} - 1) - G]$$

Equation 6.7: Pool-punishers payoff in the presence of hybrid-punishers

$$P_w = P_\sigma\sigma + (1 - P_\sigma)c(r\frac{M-Z-Y-C-1}{M-Z-1} - 1) - \frac{B(N-1)(V+H)}{M-1} - \frac{(N-1)(Y+C)}{M-1}\gamma - \frac{(N-1)X}{M-1}\gamma(1 - P_{second})$$

Equation 6.8: Peer-punishers payoff in the presence of hybrid-punishers

$$P_c = P_\sigma \sigma + (1 - P_\sigma)(rc\frac{M - Z - Y - C}{M - Z - 1} - KG) - \frac{(N-1)(W + H)}{M - 1}\beta$$

Equation 6.9: Corruptors payoff in the presence of hybrid-punishers

Briefly, the hybrid punishment strategy is introduced in this thesis to investigate why the strong centralized authority should tolerate the peer punishment as legitimate.

6.2 Applying both Corruptors and Hybrid-punishers Strategies to the PGG Model

Corruption and hybrid-punishers strategies are applied to the Sigmund et al. (2010) PGG model described in chapter 3, In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, corruptors, *C*, and hybrid-punishers, *H*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6 and 55.8, where *B* = 0.7 is the default value that was used by Sigmund et al. (2010) model. The results have been collected (Appendix B) and analyzed as follows:

As shown in Figure 6.1 and table 6.1 when *B* = 0.0001 (weaker pool punishment), peer-punishers dominate and prevent corruptors to establish a stable regime. Peer-punishers are more stable and perform better than pool-punishers. Peer-punishers promote and maintain the cooperation evolution. Occasionally, the defectors, corruptors, pool-punishers and hybrid-punishers try to take over but peer-punishers prevent them to gain ground. Peer-punishers remerge and stabilize again.

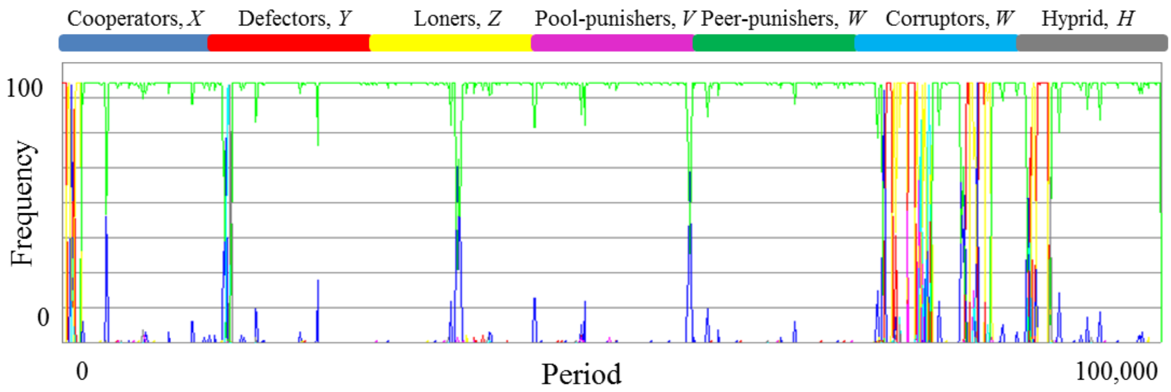

Figure 6.1: Simulation result of population percentage of seven strategies when *B*=0.0001

Pop	*X*	*Y*	*Z*	*W*	*V*	*C*	*H*
%	3.22	3.45	3.86	87.2	0.56	0.98	0.67

Table 6.1: Population average of seven strategies when *B*=0.0001

As shown in Figure 6.2 and Table 6.2 when *B* = 0.1 (weak pool punishment), peer-punishers become less dominant but still prevent corruptors to gain ground. Peer-punishers are still stable and perform better than pool-punishers. Occasionally, the defectors, corruptors, pool-punishers and hybrid-punishers try to take over but peer-punishers prevent them to gain ground. , Peer-punishers re-remerge and re-stabilize, they promote and maintain the cooperation evolution.

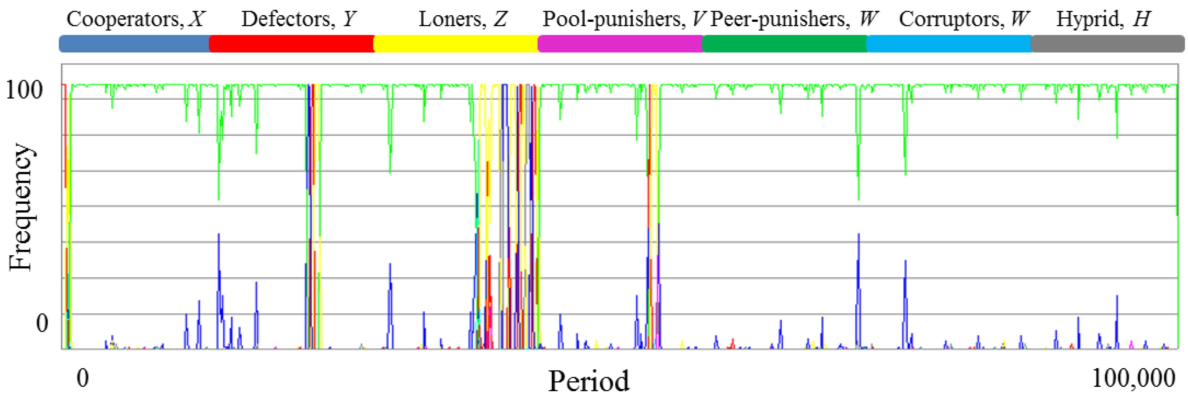

Figure 6.2: Simulation result of population percentage of seven strategies when *B*=0.1

Pop	*X*	*Y*	*Z*	*W*	*V*	*C*	*H*
%	4.59	3.78	4.82	83.8	0.48	1.25	1.18

Table 6.2: Population average of seven strategies when *B*=0.1

As shown in Figure 6.3 and Table 6.3 when *B* = 0.7 (intermediate pool punishment), peer-punishers become less dominant but still prevent corruptors to gain ground. Peer-punishers perform better than pool-punishers. Hybrid-punishers emerge and gain ground. Hybrid-punishers prevent corruptors to gain ground and perform better than pool-punishers. Peer-punishers and hybrid-punishers promote and maintain the cooperation evolution.

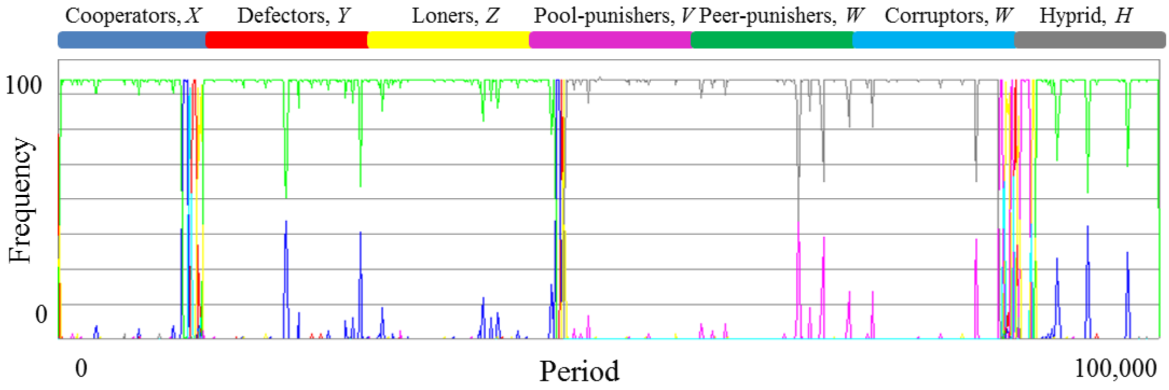

Figure 6.3: Simulation result of population percentage of seven strategies when B=0.7

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***	***H***
%	2.55	2.56	4.89	48.6	3.87	1.77	35.6

Table 6.3: Population average of seven strategies when B=0.7

As shown in Figure 6.4 and Table 6.4 when B = 2.1 (strong pool punishment), peer-punishers starts to diminish. Hybrid-punishers become more stable preventing the corruptors from gaining ground. Hybrid-punishers perform better than pool-punishers and peer-punishers. Pool-punishers start to emerge and gain ground. Peer-punishers and hybrid-punishers promote and maintain the cooperation evolution.

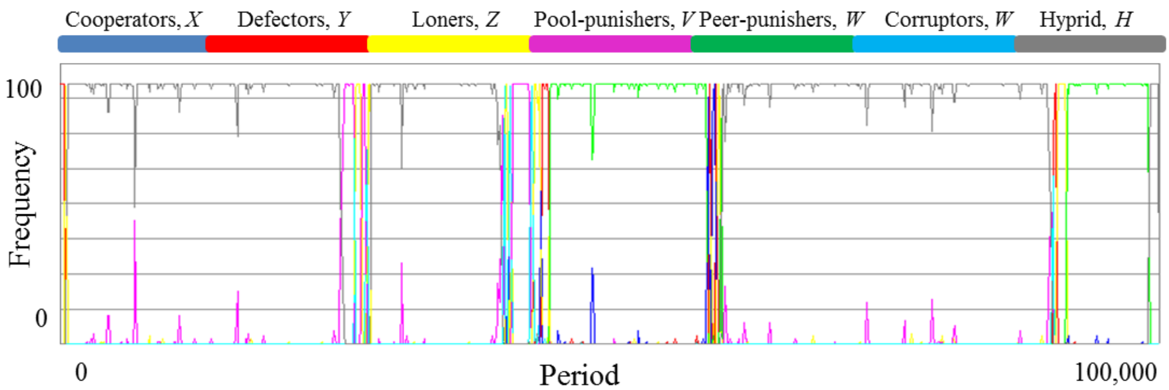

Figure 6.4: Simulation result of population percentage of seven strategies when B=2.1

Pop	***X***	***Y***	***Z***	***W***	***V***	***C***	***H***
%	1.83	1.94	6.27	25.6	6.67	2.60	54.9

Table 6.4: Population average of seven strategies when B=2.1

As shown in Figures 6.5, 6.6, and 6.7, also in Tables 6.5, 6.6, and 6.7, when B = 7.0, B = 18.6, and B = 55.8 (stronger pool punishment), peer-punishers are totally diminished. Hybrid-punishers dominate and prevent corruptors, loners, and peer-punishers to gain ground. Hybrid-punishers are more stable and perform better than pool-punishers. Hybrid-punishers promote and maintain the cooperation evolution. Pool-punishers try to emerge and gain ground.

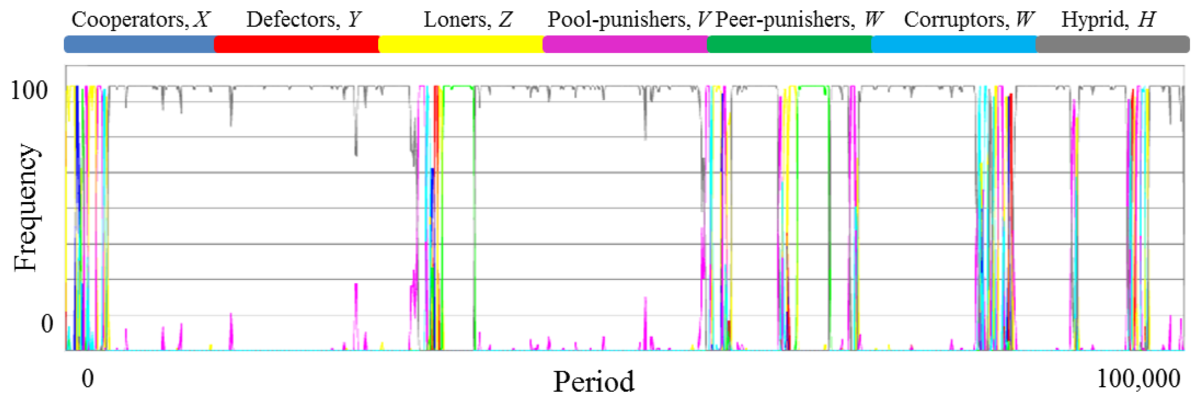

Figure 6.5: Simulation result of population percentage of seven strategies when B=7.0

Pop	*X*	*Y*	*Z*	*W*	*V*	*C*	*H*
%	0.90	1.91	5.21	3.70	6.19	2.70	79.3

Table 6.5: Population average of seven strategies when B=7.0

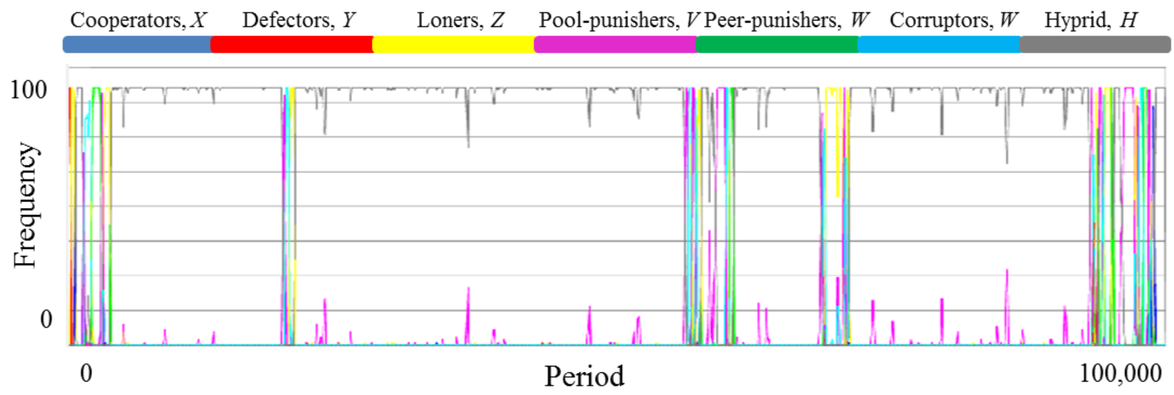

Figure 6.6: Simulation result of population percentage of seven strategies when B=18.6

Pop	*X*	*Y*	*Z*	*W*	*V*	*C*	*H*
%	0.87	1.81	5.95	1.37	7.68	3.23	79.0

Table 6.6: Population average of seven strategies when B=18.6

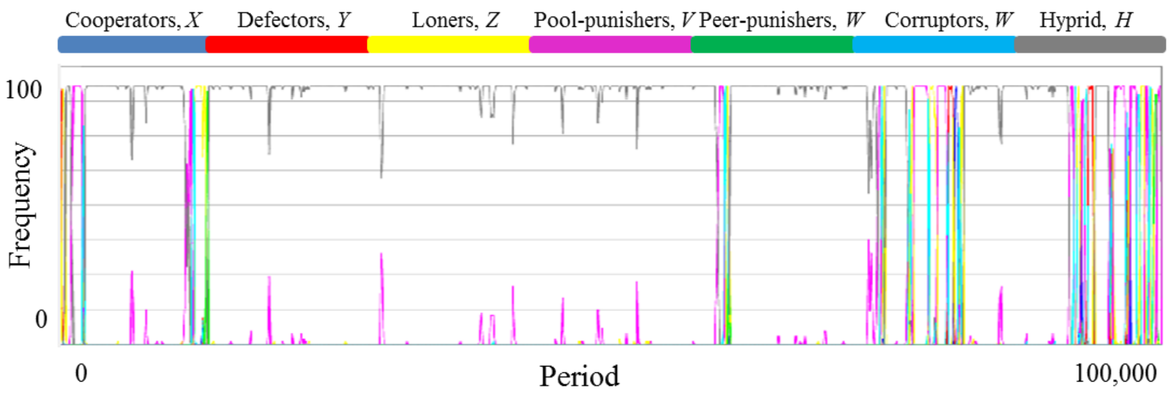

Figure 6.7: Simulation result of population percentage of seven strategies when *B*=55.8

Pop	*X*	*Y*	*Z*	*W*	*V*	*C*	*H*
%	0.52	1.16	5.95	1.22	8.87	2.89	79.3

Table 6.7: Population average of seven strategies when *B*=55.8

6.3 Results and Discussion

While the strong centralized authority loses its unilateral power for legitimate punishment and fails to maintain cooperation in the presence of corruption, peer-punishers perform better in the face of corruption despite of being punished by the centralized authority as they are considered as outlaw. Hybrid punishment strategy is introduced and applied to the PGG model with various levels of second-order punishment to explain why some countries tolerate a form of peer punishment as legitimate?

Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6 and 55.8, where *B* = 0.7 is the default value that was used by Sigmund et al. (2010) model. The results have been collected and analyzed as shown in Figure 6.8 and Table 6.8.

B	0.0001	0.1	0.7	2.1	7	18.9	55.8
X	3.224	4.594	2.554	1.834	0.902	0.871	0.525
Y	3.455	3.785	2.561	1.944	1.913	1.816	1.167
Z	3.868	4.822	4.899	6.275	5.216	5.957	5.949
W	87.22	83.87	48.63	25.69	3.699	1.369	1.225
V	0.564	0.484	3.878	6.678	6.196	7.685	8.879
C	0.984	1.253	1.777	2.604	2.707	3.236	2.892
H	0.677	1.180	35.69	54.96	79.36	79.06	79.35

Table 6.8: Simulation result showing average population percentage of seven strategies for various *B* values, second-order punishment severity

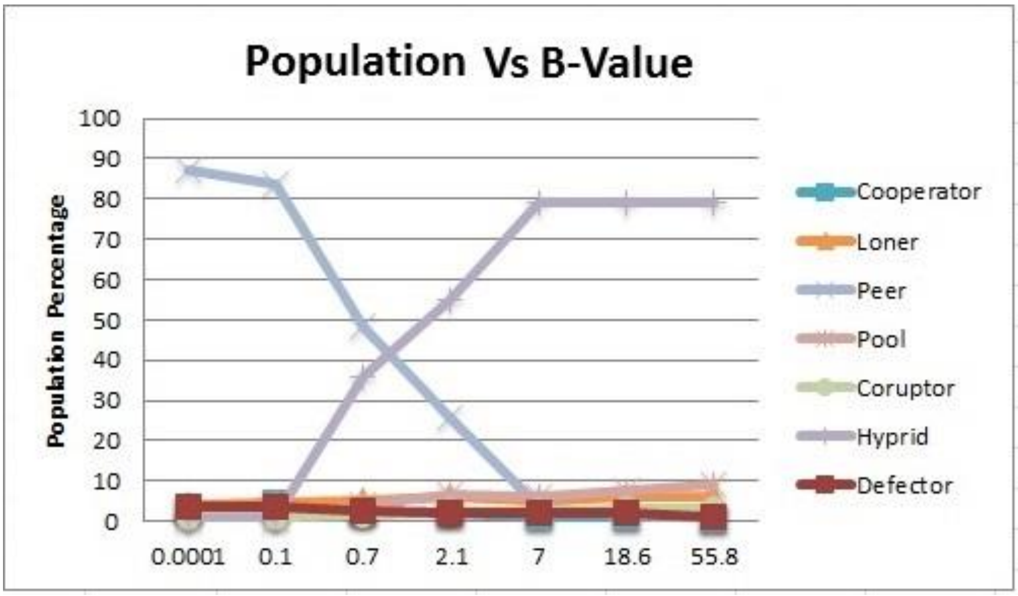

Figure 6.8: Simulation result showing average population percentage of seven strategies for various *B* values, second-order punishment severity

Under weak pool punishment, peer-punishers dominate and prevent corruptor to gain ground. Peer-punishers are more stable and perform better than pool-punishers. Peer-punishers promote and maintain the cooperation evolution. Occasionally, the defectors, corruptors, pool-punishers and hybrid-punishers try to take over but peer-punishers prevent them to gain ground. Peer-punishers remerge and stabilize.

While centralized punishment is severe, peer-punishers are totally diminished. Hybrid-punishers dominate and prevent corruptors, loners, and peer-punishers to gain ground. Hybrid-punishers promote and maintain the cooperation evolution. Hybrid-punishers are more stable and perform better than pool-punishers. Although hybrid-punishers pay more than pool-punishers, hybrid-punishers engage in peer punishment without being sanctioned. Hence, hybrid-punishers have a complete dominance over the population.

Briefly, cooperation rarely flourishes with only strong centralized authority in the presence of corruption. Cooperation needs peer-punishers who act against corruptors without being punished by the centralized authority. This gives a chance for hybrid-punishers who act as peer–punishers and pool-punishers.

Chapter 7

7 Social Welfare

Both pool-punishment and peer-punishment are costly mechanisms to impose penalties on free-riders. Pool-punishment is considered more expensive within society than peer-punishment since a fixed cost has to be paid to the common punishment pool regardless the number of the free-riders. Pool punishment is absolutely uneconomic when the number of free-riders is low. As the number of free-rides increases, pool punishment becomes more economic. Although, second-order free-riders pay fines imposed by both pool-punishers and peer-punishers, peer-punishment is absolutely not suitable for second-order punishment. If all contribute to the PGG, then peer-punishers are considered as second-order free-riders. Thus, pool-punishment is a more stable regime than peer-punishment when second-order punishment is applied. In many experiments, it is found out that cooperation in collaborative effort increases as a result of costly punishment strategies. Thus, the overall all welfare is reduced (Egas & Riedl 2008).

In this chapter, the third research questions set will be answered; can the evolutionary game model explain the correlation of social welfare to strong stability of centralized authority? to corruption? and to legitimate pool-peer-punishers?

The answer for this research question will be obtained by:

- Investigating the effect of manipulating the second-order punishment severity parameter in the Sigmund et al. (2010) model on the social welfare
- Applying the corruption strategy to the simulator PGG model, investigating the effect of manipulating the second-order severity punishment parameter on the social welfare
- Applying the corruption and hybrid punishment strategies to the simulator PGG model, investigating the effect of manipulating the second-order punishment severity parameter on the social welfare

7.1 Case of the PGG Model

For the Sigmund et al. (2010) PGG model described in chapter 3, In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; *W*, and *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8, where $B = 0.7$ is the default value that was used by Sigmund et al. (2010) model. The social welfare has been collected (Appendix C) corresponding to each *B* value and the results are analyzed as follows:

Pop	0.0001	0.06	0.7	2.1	6.3	7.0	18.6	55.8
%	0.465	0.462	0.359	0.331	0.324	0.323	0.329	0.309

Table 7.1: Social welfare average of five strategies for various B values, second-order punishment severity

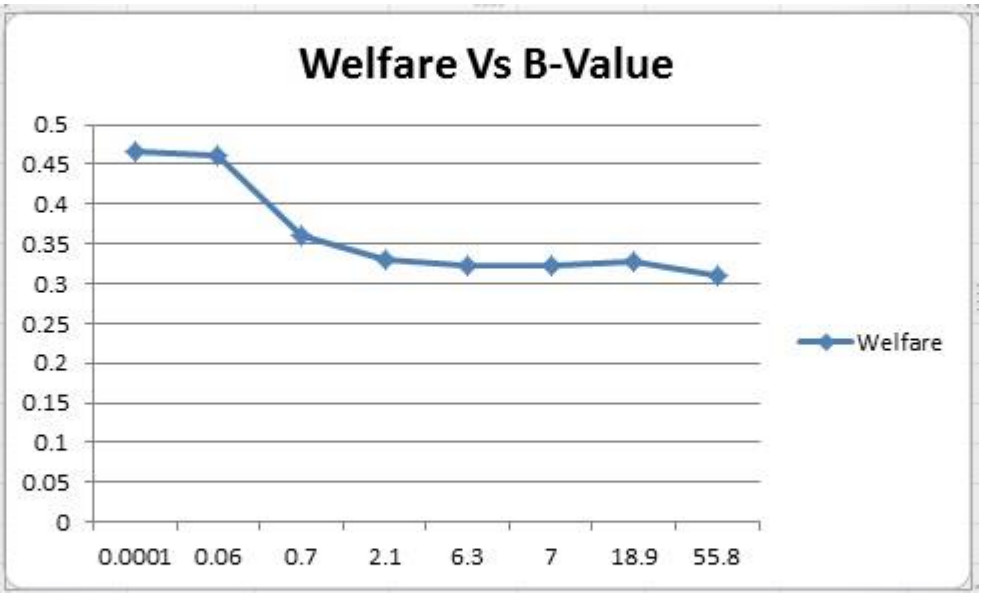

Figure 7.1: Simulation result showing social welfare of five strategies for various *B* values, second-order punishment severity

As shown in Table 7.1 and Figure 7.1, there are three different parts to be analyzed:

- For weak second-order punishment severity (low *B*, approximately when *B*<0.7), where peer-punishers are more stable, perform better than pool-punishers, and maintain cooperation, the social welfare is relatively high when peer-punishers are the dominance population
- For intermediate second-order punishment severity (intermediate *B*, approximately when 0.7<*B*<2.1), where pool-punishers perform better than pool-punishers, as it eventually succeeded to invade the peer-punishers and ultimately lead to a very stable regime, the social welfare decreases. In this transit area, there is a strong competition between pool-punishers and peer-punishers that ends up with the dominance of pool-punisher. This pool-punishers invasion decreases the social welfare as the pool-punishers have to pay a fixed amount to the common pool punishment even in the absence of free-riders
- For strong second-order punishment severity (high *B*, approximately when *B*>2.1), pool-punishers are more stable as they become the dominant population and entirely replace other population. Pool-punishers ultimately prevent peer-punishers from gaining any ground. Although, this is a relatively stable payoff area as the

pool-punishers are the dominant populations, the social welfare decreases relative to the area where the peer-punishers were the dominant population. This is due to the fixed amount which is paid by the pool-punishers to the common pool punishment even in the absence of free-riders

Briefly, as the second-order punishment severity increases, the social welfare decreases. In general, this drop in social welfare resulted from the invasion of pool-punishers who have to pay a fixed amount to the common pool punishment even in the absence of free-riders

7.2 Applying Corruption Strategy to the PGG Model

Corruption strategy is applied to the Sigmund et al. (2010) PGG model described in chapter 3, In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, and corruptors, *C*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. The corruptor parameter $K = 0.5$. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8, where $B = 0.7$ is the default value that was used by Sigmund et al. (2010) model. The social welfare has been collected corresponding to each *B* value and the results are analyzed as follows:

Pop	**0.0001**	**0.06**	**0.7**	**2.1**	**6.3**	**7.0**	**18.6**	**55.8**
%	0.458	0.454	0.435	0.427	0.331	0.329	0.271	0.246

Table 7.2: Social welfare average of six strategies for various *B* values, second-order punishment severity

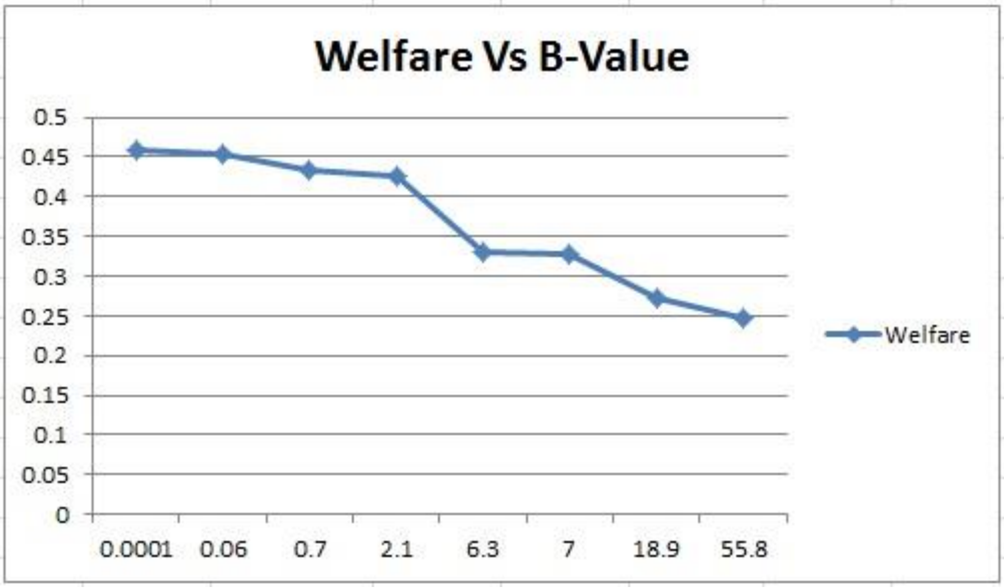

Figure 7.2: Simulation result showing social welfare of six strategies for various *B* values, second-order punishment severity

As shown in Table 7.2 and Figure 7.2, there are three different parts to be analyzed:

- For weak second-order punishment severity (low *B*, approximately when *B*<0.7), peer-punishers dominate, prevent corruptors to gain ground and maintain cooperation. The social welfare is relatively high when peer-punishers are the dominant population
- For intermediate second-order punishment severity (intermediate *B*, approximately when 0.7<*B*<2.1), peer-punishers become less dominant but still prevent corruptors and loners to gain ground. In this transit area, the social welfare relatively decreases as corruptors, loners, and pool-punishers try to gain ground.
- For strong second-order punishment severity (high *B*, approximately when *B*>2.1) As *B* increases, peer-punishers diminish, corruptors increase, pool-punishers gain some ground, interestingly loners becomes the most adopted strategy, the cooperation diminishes. The increase of corruptors is due to the absence of peer-punishers and the bribe paid to the pool-punishers. The increase of corruptors, pool-punishers, and loners lead to the decrease of social welfare

Briefly, as the second-order punishment severity increases, the social welfare decreases. This drop in social welfare resulted from the invasion of corruptors who bribes the pool-punishers who have to pay a fixed amount to the common pool punishment even in the absence of free-riders, and the loners who do not participate in the PGG.

7.3 Applying both Corruptors and Hybrid-punishers Strategies the PGG Model

Corruption and hybrid-punishers strategies are applied to the Sigmund et al. (2010) PGG model described in chapter 3, In a population; *M*; which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, corruptors, *C*, and hybrid-punishers, *H*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6 and 55.8, where *B* = 0.7 is the default value that was used by Sigmund et al. (2010) model. The social welfare has been collected corresponding to each *B* value and the results are analyzed as follows:

Pop	**0.0001**	**0.1**	**0.7**	**2.1**	**7.0**	**18.6**	**55.8**
%	0.468	0.462	0.398	0.354	0.331	0.304	0.299

Table 7.3: Social welfare average of seven strategies for various *B* values, second-order punishment severity

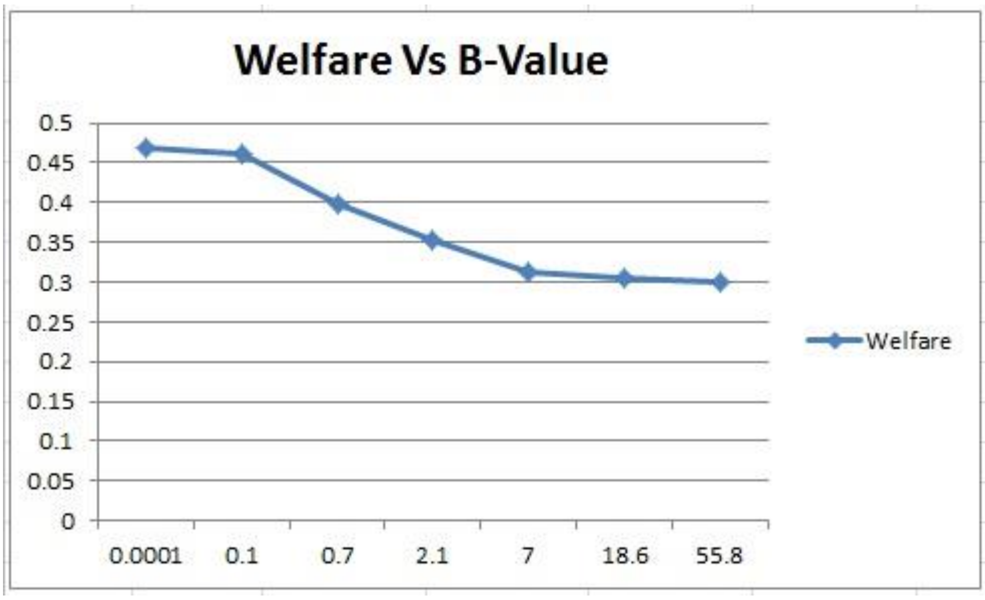

Figure 7.3: Simulation result showing social welfare of seven strategies for various *B* values, second-order punishment severity

As shown in Table 7.3 and Figure 7.3, there are three different parts to be analyzed:

- For weak second-order punishment severity (low *B*, approximately when *B*<0.7), peer-punishers, prevent corruptors to gain ground, and maintain cooperation. The social welfare is relatively high when peer-punishers are the dominant population.
- For intermediate second-order punishment severity (intermediate *B*, approximately when 0.7<*B*<2.1), peer-punishers and hybrid-punishers prevent corruptor to gain ground. Peer-punishers and hybrid-punishers perform better than pool-punishers. In this transit area, the social welfare relatively decreases as hybrid-punishers gain some ground
- For strong second-order punishment severity (high *B*, approximately when *B*>7.0) peer-punishers totally diminish. Hybrid-punishers dominate and prevent corruptors, loners, and peer-punishers to gain ground. The social welfare decreases but is relatively stable as hybrid-punishers are the dominant population. This decrease in social welfare is because of the hybrid-punishers who pays the fixed amount to the common pool punishment even in the absence of free-riders and the cost of punishing the corruptors

Briefly, as the second-order punishment severity increases, the social welfare decreases. In general, this drop in social welfare resulted from the invasion of hybrid-punishers who have to pay a fixed amount to the common pool punishment even in the absence of free-riders and the cost of punishing the corruptors

7.4 Results and Discussion

The above three cases of welfare analysis have been collected together for further investigation; the case of Sigmund et al. (2010) model, the case of applying corruptors strategy to Sigmund et al. model (2010), and the case of applying both corruptors and hybrid-punishers strategy to Sigmund et al. model (2010).

As shown in Table 7. 4and Figure 7.4, for the three cases, there are three periods to be assessed as follows:

- For weak second-order punishment severity (low *B*, approximately when $B<0.7$), the social welfare is relatively high when peer-punishers are the dominant population. The three cases have approximately the same welfare even in the presence of corruption
- For intermediate to strong second-order punishment severity (low to intermediate *B*, approximately when $0.7<B<7.0$), surprisingly, having corruptors in the population increases the social welfare compared to the other two cases. This phenomenon is due to the fact that in the case of corruption, the competition is between peer-punishers and corruptors; while in the case of hybrid-punishers, the competition is between peer-punishers, hybrid-punishers and corruptors; meanwhile, in the case of pool-punishers, the competition is between peer-punishers and pool-punishers
- For stronger second-order punishment severity (high B, approximately when B>7.0), the pool-punishers case welfare is better than the other two cases. This is due to the fact that pool-punishers are the dominant population and pay only the fixed amount to the common pool punishment. In the corruption case, the loner strategy becomes the most adopted strategy which makes this case the one with the least welfare. The welfare in the case of corruption and hybrid-punishers is intermediate between the corruption case and the pool-punishers case. This is due to the fact that hybrid-punishers are the dominant population and they pay the fixed amount to the common pool punishment and the cost of punishing corruptors.

Briefly, in general, as the second-order punishment severity increases, the social welfare decreases. As the second-order punishment severity increases, corruptors eventually result in the collapse of the centralized authority and the demise of the social welfare. This collapse of central authority can be mitigated by hybrid-punishers, a form of peer-punishers, who re-emerge to maintain cooperation and relatively restore social welfare.

	0.0001	**0.1**	**0.7**	**2.1**	**7**	**18.6**	**55.8**
Without Corruptor & Without Hybrid	0.465	0.461	0.359	0.330	0.323	0.328	0.309
Corruptor	0.457	0.453	0.434	0.427	0.328	0.271	0.246
Corruptor & Hybrid	0.467	0.461	0.397	0.353	0.312	0.304	0.298

Table 7.4: Simulation result showing social welfare of three different settings for various *B* values, second-order punishment severity

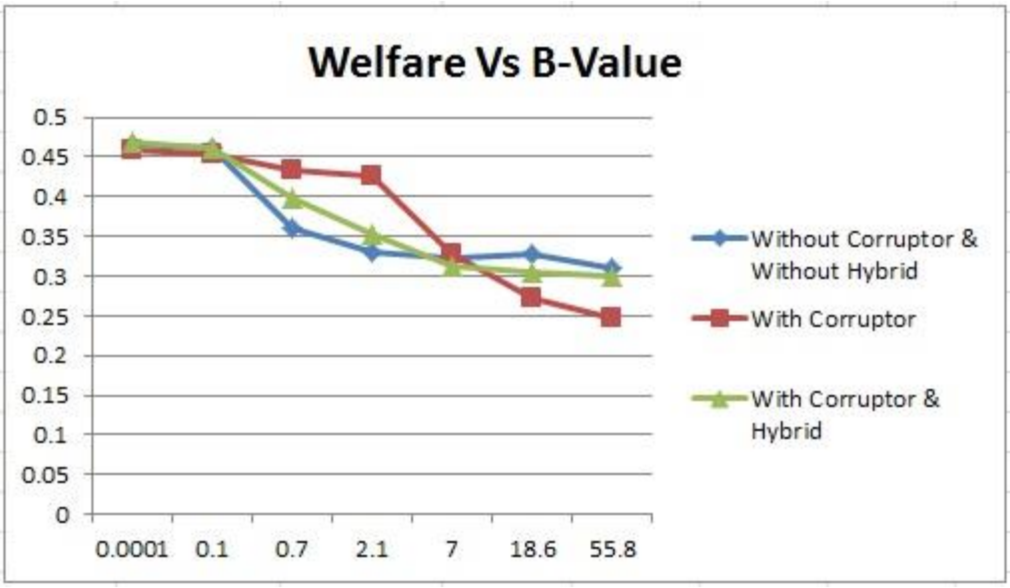

Figure 7.4: Simulation result showing social welfare of three different cases for various B values, second-order punishment severity

Chapter 8

8 Conclusion

8.1 Summary

Cooperation is a key aspect in society. Human society is based to a large extent on punishment mechanisms that promote and maintain cooperation among selfish individuals. The issue of how to promote and maintain cooperation is one of the main topics of the game theory. The essential role of punishment or sanctioning free-riders (also known as defectors or non-cooperators) promotes and maintains cooperation in a society. Although, peer punishment is a key mechanism for sanctioning free-riders to promote cooperation, it is unstable as cooperators refuse to punish defectors. Sigmund et al. (2010) proves that with second-order punishment, the centralized sanctioning institution emerges through social learning and ultimately prevails displacing all other populations including peer punishment, hence leading to a stable regime. Peer-punishers are considered as outlaws in this model as they do not contribute to the common punishment pool.

This thesis introduces a developed simulator that successfully replicates Sigmund et al. (2010) results based on evolutionary game dynamics for fixed populations' model. With tuning the second-order punishment severity of centralized and legitimate authority, it is found out that as this punishment severity increases, the pool-punishers become the dominant population, peer-punishers diminish, cooperation in collaborative effort increases, and the social welfare decreases. Thus, this centralized authority becomes the source of all forms of punishment; hence it becomes a single point of failure.

This thesis introduces and applies corruption model to this stable centralized regime, it destabilizes cooperation and causes peer punishment to evolve as a sustainable strategy. The effectiveness of this centralized authority is compromised when corruptors bribe pool-punishers. Moreover, the increase of second-order punishment severity increases corruption and decreases cooperation and eventually decreases social welfare. Corruptors eventually result in the collapse of the centralized authority, the demise of the peer-punishers; the decrease in welfare and surprisingly, loners become the most adopted strategy. That explains why some countries fail to maintain cooperation in the face of corruption. It also illustrates that decentralized enforcement, peer punishment, is required in societies in addition to the centralized authority. Cooperation rarely flourishes with only strong centralized authority in the presence of corruption.

Peer-punishers perform better in the face of corruption to maintain cooperation despite of being punished by the centralized authority as it is considered as outlaw. This thesis modeled a new form of peer-punishers, hybrid-punisher. This hybrid-punisher is considered a legitimate form of peer-punishers that is not punished by central authority as they contribute to the common punishment pool. It is literally considered as a mix of peer-punishers and pool-punishers strategies. The results imply that in the presence of corruption the hybrid punishment are more effective in maintaining cooperation even if with severe second-order punishment. As the second-order punishment severity increases, the hybrid-punishers become the dominant population, peer-punishers diminish, cooperation in collaborative effort increases, and the social welfare is relatively restored. This explains why some countries tolerate certain forms of peer punishment as legitimate.

This thesis results imply that, in general, as the second-order punishment severity increases, the cooperation increases and the social welfare decreases. These results also imply that as the second-order punishment severity increases, corruptors eventually result in the collapse of the centralized authority and the diminishing of the social welfare. This collapse of central authority can be mitigated by hybrid-punishers, who re-emerge to maintain cooperation and relatively restore social welfare.

8.2 Discussion and Future Work

Sigmund et al. (2010) model presents pool punishment model where individuals contribute to centralized authority which dominates, replaces other populations including peer punishment and establishes a highly stable regime for promoting cooperation. This thesis results imply that increasing the severity of the centralized and legitimate authority increases the level of cooperation in collaborative effort (Sigmund et al. 2010). This means that all forms of punishments are assigned to this strong centralized authority. However, in this thesis, although the dominance of strong centralized authority maintains a stable and cooperative regime, it is considered as its single point of point of failure. Introducing corruption to this stable centralized regime destabilizes cooperation and cause peer punishment to evolve as a sustainable strategy. The effectiveness of this centralized authority is compromised when corruptors bribe pool-punishers. Moreover, the increase in the second-order punishment severity increases corruption and decreases cooperation. These results confirm that corruption is highly destructive in the presence of strong centralized authority as the individuals are severely punished if they try to stand in the face of this corruption (Kopstein 200).

Peer-punishers perform better in the face of corruption to maintain cooperation despite being punished by the centralized authority as they are considered as outlaw. These results explain why some centralized authorities legalize certain forms of social peer punishment to maintain cooperation in the presence of corruption (Fowler & Kam 2007; Grechenig, Nicklisch & Thöni 2010; Smirnov et al. 2010; Egorov, Guriev & Sonin 2009). Aligning with Sigmund et al. (2010) model, this thesis model considers the peer-punishers as outlaw and to be punished by the centralized authority. Alternatively, another form of peer-punishers is introduced in this thesis named as hybrid-punisher. As opposed to Sigmund et al. (2010) model, hybrid-punishers are not penalized by the centralized authority. This hybrid-punisher is considered a legitimate form of peer-punishers that is not punished by central authority but it is literally considered as a mix of peer-punishers and pool-punishers strategies. Hybrid-punisher is also considered legitimate in this model as it contributes to the common pool punishment. The results imply that in the presence of corruption the peer punishment and hybrid punishment are more effective in maintaining cooperation even if with severe second-order punishment. This explains why some countries tolerate a form of peer punishment as legitimate.

As per many experiments, it is found out that cooperation in collaborative effort increases as a result of costly punishment strategies. Thus, the overall all welfare is reduced (Egas & Riedl 2008). Agreeing with this conclusion, this thesis results imply that, in general, as the second-order punishment severity increases, the cooperation increases and the social welfare decreases. These results also imply that as the second-order punishment severity increases, corruptors eventually result in the collapse of the centralized authority and the demise of the social welfare. This collapse of central authority can be mitigated by hybrid-punishers, a form of peer-punishers, who re-emerge to maintain cooperation and relatively restore social welfare.

Future research might relay on this thesis model as follows: in the face of corruption and with severe second-order punishment, the only population that tries to destabilize hybrid-punishers is pure pool-punishers. An investigation should take place to punish pure pool-punishers as they do not engage as hybrid-punishers. The stability of hybrid-punishers in the face of corruption must be investigated; hybrid punishment may be even more stable than peer punishment or pool punishment alone. In the absence of corruption, pool-punishers prevail and establish a stable regime. Applying hybrid-punishers strategy to this stable regime may destabilize pool-punishers; preliminary investigation is done in Appendix A for studying this competition between the pool-punishers and hybrid-punishers in the absence of corruption. Social learning is applied in this model where individuals are allowed to learn by exploring and imitating others' successful actions. Some important issues are not modeled such as individuals' reputation, equity and reciprocity. Another research aspect has to be investigated; the stability of the centralized authority which tolerates a legitimate form of peer punishment in the absence of corruption.

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Appendices

A Collected Data from Studying the Effect of Centralized Punishment Severity

In this appendix, the detailed data for applying different settings to the PGG model is collected and listed.

A.1 Collected Data from Applying the PGG Model

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; *W*, and *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values vary along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8. The results have been collected as follows:

Pop	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
X	9.31	3.96	5.28	6.6	6.25	5.46	3.64	3.94	5.01	6.3	5.49	4.2	3.88	10.3	4.99	5.65
Y	8.18	2.03	3.70	9.10	3.82	4.35	1.75	2.2	2.71	7.4	4.57	3.9	2.87	8.92	1.99	4.50
Z	9.09	2.10	4.47	9.00	5.15	6.46	2.75	4.55	3.18	6.2	5.41	5.39	2.75	10.6	3.43	5.38
W	72.7	91.7	85.8	73.5	83.8	82.8	91.3	87.7	88.3	78.7	83.7	85.7	90.0	68.8	88.9	83.5
V	0.69	0.18	0.65	1.72	0.94	0.85	0.49	1.53	0.70	1.3	0.81	0.7	0.42	1.19	0.59	0.85

Table A.1: Simulation result of population percentage of five strategies when *B*=0.0001

Pop	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
X	6.40	6.31	6.00	6.21	7.48	4.41	6.77	7.30	7.32	6.89	6.37	5.45	5.06	6.17	6.37	6.30
Y	5.81	4.74	2.60	6.50	5.14	5.02	4.90	5.68	3.98	6.80	4.37	6.31	3.54	4.94	4.37	4.98
Z	7.05	5.46	4.06	6.63	7.06	3.14	7.64	5.69	4.91	6.50	6.91	5.57	3.16	3.94	6.91	5.64
W	80.0	82.2	86.9	79.7	79.1	86.4	79.4	81.0	83.1	78.7	81.8	81.5	87.4	84.5	81.8	82.2
V	0.67	1.17	0.41	0.88	1.16	0.94	1.26	0.28	0.60	1.07	0.49	1.07	0.79	0.39	0.49	0.78

Table A.2: Simulation result of population percentage of five strategies when *B*=0.06

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	1.50	5.20	0.93	0.07	3.64	0.51	1.00	0.70	4.77	1.35	0.21	3.42	0.27	0.08	0.08	1.58
Y	0.93	4.08	0.79	0.20	1.86	0.51	0.97	0.71	2.67	1.21	0.90	2.08	1.38	0.60	0.58	1.30
Z	1.36	3.73	0.81	0.23	3.04	1.32	2.94	0.58	2.82	0.72	0.50	3.44	0.56	0.75	0.54	1.56
W	5.65	31.1	29.2	0.07	91.2	0.08	22.8	7.18	89.5	23.9	0.08	12.0	0.10	0.08	0.08	20.8
V	90.5	55.8	68.1	99.4	0.17	97.5	72.2	90.8	0.16	72.7	98.2	79.0	97.6	98.4	98.6	74.6

Table A.3: Simulation result of population percentage of five strategies when *B*=0.7

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	1.00	0.50	0.29	0.17	0.08	0.08	0.08	0.10	1.27	0.99	0.08	0.60	0.13	0.58	0.11	0.41
Y	1.96	0.87	1.24	0.62	0.12	0.67	0.22	0.31	0.66	0.60	0.13	0.32	0.81	0.30	0.54	0.63
Z	0.79	0.68	0.83	0.52	0.31	0.49	0.31	0.34	1.03	0.82	0.29	0.57	0.75	0.50	0.51	0.58
W	1.71	20.8	0.08	0.08	0.08	0.07	0.08	0.07	2.54	16.7	0.08	9.24	0.09	7.03	5.46	4.28
V	94.5	77.1	97.5	98.5	99.3	98.6	99.2	99.1	94.4	80.8	99.4	89.2	98.1	91.5	93.3	94.0

Table A.4: Simulation result of population percentage of five strategies when *B*=2.1

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.11	0.08	0.35	0.08	0.29	0.09	0.08	0.09	0.07	0.17	0.08	0.12	0.08	0.09	0.32	0.14
Y	0.14	0.50	0.35	0.20	0.32	0.15	0.14	0.17	0.12	0.15	0.29	0.25	0.28	0.22	0.67	0.26
Z	0.56	0.41	0.50	0.24	1.03	0.28	0.71	0.54	0.20	0.27	0.27	0.40	0.27	0.31	0.72	0.45
W	0.72	0.07	0.48	0.08	0.09	0.53	0.07	0.08	0.08	0.94	0.08	0.08	1.05	2.18	1.05	0.51
V	98.4	98.9	98.2	99.3	98.2	98.9	98.9	99.1	99.5	98.4	99.2	99.1	98.2	97.1	97.2	98.6

Table A.5: Simulation result of population percentage of five strategies when *B*=6.3

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.08	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.08	0.07	0.08	0.08	0.08	0.13	0.08
Y	0.28	0.20	0.15	0.20	0.17	0.18	0.30	0.27	0.12	0.12	0.26	0.43	0.23	0.13	0.17	0.22
Z	0.21	0.27	0.91	0.33	0.38	0.17	0.40	0.43	0.60	0.32	0.30	0.60	0.16	0.35	0.38	0.39
W	0.08	0.08	0.08	0.07	0.08	0.08	0.08	0.08	2.73	0.55	1.29	0.96	0.08	0.09	0.08	0.43
V	99.3	99.3	98.7	99.2	99.2	99.4	99.1	99.1	96.4	98.9	98.0	97.9	99.4	99.3	99.2	98.8

Table A.6: Simulation result of population percentage of five strategies when *B*=7.0

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.09	0.44	1.37	0.08	0.08	0.08	0.10	0.11	0.08	0.39	0.08	0.08	0.08	0.08	0.08	0.21
Y	0.11	0.58	0.59	0.19	0.18	0.29	0.42	0.89	0.33	0.29	0.16	0.17	0.64	0.14	0.55	0.37
Z	0.28	0.74	0.85	0.23	0.70	0.40	0.52	0.44	0.62	0.42	0.31	0.85	0.41	0.25	0.35	0.49
W	0.07	0.08	0.29	0.08	1.00	0.68	0.08	0.08	0.08	0.08	0.08	0.71	0.08	0.13	0.08	0.24
V	99.4	98.1	96.8	99.3	98.0	98.5	98.8	98.4	98.8	98.7	99.3	98.1	98.7	99.3	98.9	98.6

Table A.7: Simulation result of population percentage of five strategies when *B*=18.6

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.34	0.12	0.08	0.10	0.08	0.07	0.08	0.08	0.09	0.66	0.38	0.08	0.08	0.08	0.08	0.16
Y	0.18	0.56	0.17	0.17	0.21	0.10	0.10	0.17	0.55	0.18	0.11	0.11	0.19	0.23	0.27	0.22
Z	0.56	0.63	0.30	0.31	0.45	0.24	0.41	0.35	0.49	1.50	0.26	0.28	0.33	0.34	1.33	0.52
W	0.09	0.08	0.79	0.08	0.64	0.08	0.52	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.19
V	98.8	98.5	98.6	99.3	98.6	99.4	98.8	99.2	98.7	97.5	99.1	99.4	99.3	99.2	98.2	98.8

Table A.8: Simulation result of population percentage of five strategies when *B*=55.8

A.2 Collected Data from Applying Corruption Strategy to the PGG Model

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, and corruptors, *C*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. The corruptor parameter *K* = 0.5. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8. The results have been collected as follows:

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	4.51	6.47	4.10	2.75	5.49	5.29	7.37	4.28	3.33	3.94	4.85	2.74	2.71	5.22	4.22	4.48
Y	3.25	5.22	5.36	3.91	3.66	4.68	6.89	3.08	3.37	3.64	1.69	2.27	3.29	3.69	5.75	3.99
Z	4.75	8.70	10.5	5.32	5.08	9.89	13.2	4.55	5.15	5.85	4.47	4.10	6.03	7.50	7.06	6.82
W	85.7	75.9	77.7	86.5	83.6	78.6	69.5	86.4	85.1	85.1	87.6	90.2	85.1	82.1	81.1	82.7
V	0.56	1.43	1.52	0.94	0.56	0.52	0.90	0.98	1.44	0.25	0.17	0.20	0.75	0.42	1.06	0.78
C	1.19	2.15	0.73	0.49	1.56	0.99	1.98	0.60	1.50	1.10	1.10	0.46	2.00	1.03	0.74	1.18

Table A.9: Simulation result of population percentage of six strategies when *B*=0.0001

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	9.32	4.48	4.91	2.41	5.51	7.31	3.49	7.15	5.20	3.83	2.99	3.89	4.39	4.22	3.90	4.87
Y	6.24	5.14	3.95	1.42	4.60	8.70	2.80	5.42	3.98	2.27	4.65	2.65	2.85	4.73	4.36	4.25
Z	13.9	7.42	6.41	3.96	7.79	14.3	3.38	9.57	5.86	5.67	6.21	7.23	6.01	8.45	5.04	7.42
W	66.6	81.1	83.6	91.5	80.3	63.8	88.1	74.1	83.6	86.7	85.1	84.8	85.0	79.8	85.2	81.3
V	1.11	1.19	0.44	0.22	0.26	1.86	0.50	1.60	0.48	0.59	0.42	0.25	0.65	1.16	0.33	0.74
C	2.68	0.63	0.66	0.37	1.42	3.89	1.61	2.04	0.80	0.83	0.55	1.17	1.04	1.53	1.08	1.35

Table A.10: Simulation result of population percentage of six strategies when *B*=0.06

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	4.08	2.77	2.46	4.92	5.02	2.96	3.28	6.07	4.33	6.38	7.12	7.10	4.76	4.57	3.56	4.63
Y	5.73	4.74	1.20	5.54	5.64	2.47	3.29	4.21	2.74	10.6	11.1	4.54	6.13	6.60	3.52	5.21
Z	7.69	9.80	4.25	8.10	7.80	5.55	8.98	9.37	7.41	10.0	15.8	12.4	17.1	9.57	9.35	9.56
W	78.8	74.7	90.9	75.5	77.1	85.6	76.1	74.6	81.8	65.5	59.7	70.7	60.8	76.0	79.3	75.2
V	1.55	4.96	0.62	3.53	3.02	1.43	4.71	3.22	1.23	3.41	3.44	2.70	7.16	1.76	2.94	3.05
C	2.05	2.97	0.4	2.33	1.29	1.90	3.59	2.45	2.39	3.91	2.66	2.36	3.91	1.46	1.29	2.33

Table A.11: Simulation result of population percentage of six strategies when *B*=0.7

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	4.21	3.35	5.93	5.80	4.80	6.27	6.14	4.94	4.05	6.24	4.85	3.93	6.56	3.92	3.95	5.00
Y	3.97	3.16	6.68	4.08	3.29	2.99	4.64	3.05	3.86	3.07	3.19	4.14	4.41	3.58	3.77	3.86
Z	8.87	9.32	13.0	8.57	14.3	15.8	15.6	12.4	10.4	3.99	11.4	12.5	11.7	7.27	7.78	10.8
W	75.7	78.1	59.8	81.3	63.0	59.2	57.1	69.9	67.3	86.5	72.6	66.8	69.6	77.8	80.3	71.0
V	4.54	4.36	8.63	0.06	9.93	10.5	11.4	4.88	8.98	0.06	4.50	7.90	4.05	4.65	2.46	5.80
C	2.60	1.64	5.82	0.08	4.60	5.13	4.99	4.64	5.38	0.07	3.40	4.58	3.53	2.75	1.64	3.39

Table A.12: Simulation result of population percentage of six strategies when *B*=2.1

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	6.57	6.27	6.60	5.82	7.43	3.63	5.07	5.93	4.70	2.73	4.43	5.51	5.61	5.93	5.17	5.43
Y	9.04	6.88	6.33	7.02	6.32	5.32	9.02	4.89	5.42	4.85	5.71	4.89	7.53	6.88	5.41	6.37
Z	26.9	18.5	25.5	20.9	28.0	24.7	24.6	19.7	21.9	23.5	26.6	21.0	19.3	25.5	24.8	23.4
W	28.8	38.6	36.5	40.4	33.0	35.2	32.0	46.9	37.1	36.3	30.6	40.7	46.6	32.6	31.2	36.4
V	20.6	20.5	18.3	16.6	14.7	23.7	19.1	15.4	21.0	24.1	22.4	18.3	14.4	19.0	23.6	19.5
C	8.00	9.12	6.67	9.06	10.3	7.24	10.0	6.92	9.71	8.41	10.1	9.50	6.35	9.91	9.66	8.74

Table A.13: Simulation result of population percentage of six strategies when *B*=6.3

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	4.50	4.51	5.79	8.66	6.16	4.59	4.69	3.36	5.75	5.24	2.54	3.58	4.71	5.22	4.56	4.93
Y	4.87	4.56	7.34	9.15	7.03	4.76	6.23	7.11	9.63	6.05	5.07	6.41	5.65	6.18	5.08	6.34
Z	25.6	18.1	25.2	26.0	24.9	25.2	20.8	20.7	22.7	21.5	21.8	20.3	25.2	20.0	22.6	22.7
W	33.7	42.3	33.0	27.0	29.6	29.5	36.2	41.7	29.0	39.1	39.9	47.4	38.0	45.6	36.2	36.5
V	21.5	22.1	18.9	18.9	21.5	25.4	22.1	18.9	20.6	19.3	19.5	14.6	18.6	14.6	22.7	20.0
C	9.65	8.31	9.57	10.1	10.7	10.3	9.90	8.05	12.0	8.59	11.0	7.59	7.67	8.19	8.71	9.36

Table A.14: Simulation result of population percentage of six strategies when *B*=7.0

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	6.27	5.78	5.52	4.54	4.14	6.86	5.37	7.43	4.48	7.06	3.46	3.59	4.29	5.55	5.84	5.35
Y	8.34	8.07	7.70	9.58	10.2	9.40	6.35	5.95	7.59	7.27	5.50	7.26	7.70	7.37	7.24	7.71
Z	33.8	31.6	36.4	31.8	31.9	30.3	28.6	30.1	32.0	30.9	30.3	30.2	28.8	32.9	35.6	31.7
W	15.8	16.5	11.8	17.4	18.3	16.0	16.2	20.3	9.77	15.1	16.8	21.5	25.3	21.9	16.4	17.3
V	23.7	25.8	25.3	24.6	23.3	24.0	30.6	23.5	34.5	25.6	31.9	26.5	22.3	19.9	21.0	25.5
C	11.9	12.0	13.1	11.8	11.9	13.2	12.6	12.4	11.5	13.9	11.9	10.7	11.4	12.2	13.8	12.3

Table A.15: Simulation result of population percentage of six strategies when *B*=18.6

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	3.46	4.88	4.40	6.12	5.28	3.70	3.50	2.35	3.23	2.83	4.29	4.86	5.27	4.07	3.35	4.11
Y	8.01	6.78	5.97	7.17	7.78	6.87	6.69	6.15	3.55	7.14	8.23	7.75	5.36	7.66	6.28	6.76
Z	28.3	34.4	36.7	35.4	32.8	35.1	32.5	29.9	30.8	32.7	33.9	33.0	34.0	31.1	32.9	32.9
W	17.2	11.3	11.7	13.0	13.1	10.4	15.4	12.3	13.8	10.6	12.0	10.3	11.3	16.4	19.1	13.2
V	28.4	31.5	29.5	24.5	28.1	28.3	28.7	32.9	33.4	31.4	27.7	29.8	29.3	29.0	24.7	29.1
C	14.4	11.0	11.6	13.6	12.7	15.3	13.0	16.2	15.0	15.1	13.6	14.1	14.6	11.6	13.6	13.7

Table A.16: Simulation result of population percentage of six strategies when *B*=55.8

B Collected Data from Applying both Corruptors and Hybrid-punishers Strategies to the PGG Model

In this appendix, the detailed data for applying both corruptors and hybrid-punishers to the PGG model is collected and listed. In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, corruptors, *C*, and hybrid-punishers, *H*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6 and 55.8. The results have been collected as follows:

Pop	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
X	2.88	3.29	2.42	2.9	4.07	5.72	2.82	3.70	2.44	2.23	2.05	2.65	2.06	6.35	2.67	3.22
Y	1.97	6.26	2.53	5.37	3.35	7.85	1.24	2.99	2.13	4.60	0.82	1.94	2.77	3.06	4.87	3.45
Z	2.80	3.71	3.47	5.23	5.72	6.06	1.87	3.32	2.25	4.45	0.85	2.98	4.10	6.56	4.60	3.86
W	90.7	85.1	89.3	84.5	83.6	75.7	92.6	88.7	90.6	87.0	95.0	91.2	88.7	78.4	86.4	87.2
V	0.38	0.36	0.89	0.50	0.47	0.76	0.19	0.69	1.19	0.31	0.09	0.41	0.32	1.41	0.43	0.56
C	1.09	0.78	0.69	0.87	1.00	1.95	0.65	0.39	0.81	0.96	0.63	0.36	1.25	2.96	0.30	0.98
H	0.10	0.42	0.65	0.50	1.71	1.84	0.54	0.16	0.49	0.33	0.51	0.32	0.70	1.20	0.62	0.67

Table B.1: Simulation result of population percentage of seven strategies when *B*=0.0001

Pop	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
X	5.04	5.59	6.07	2.63	4.73	5.05	1.77	5.19	4.99	5.67	4.24	4.32	4.42	2.28	6.87	4.59
Y	5.29	4.59	2.79	2.75	3.95	3.13	3.16	3.64	3.17	7.07	1.94	4.35	2.49	2.22	6.19	3.78
Z	4.43	6.23	5.05	2.40	5.54	5.31	2.14	3.45	3.14	7.52	2.94	4.84	7.90	4.06	7.30	4.82
W	80.7	79.5	84.8	91.1	82.6	80.4	91.1	85.3	86.1	76.3	88.5	84.7	80.9	90.2	75.3	83.8
V	1.11	0.25	0.36	0.12	0.52	0.85	0.97	0.30	0.22	0.62	0.54	0.38	0.20	0.16	0.61	0.48
C	1.42	1.65	0.47	0.81	0.66	2.61	0.57	1.35	1.26	1.95	1.28	0.37	1.97	0.21	2.13	1.25
H	1.89	2.07	0.36	0.14	1.92	2.60	0.22	0.74	1.00	0.75	0.50	1.00	2.07	0.84	1.53	1.18

Table B.2: Simulation result of population percentage of seven strategies when *B*=0.1

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	3.98	1.27	3.16	2.50	3.36	3.89	1.01	3.60	3.27	0.76	1.69	2.10	2.54	3.29	1.83	2.55
Y	2.34	2.36	2.96	2.13	5.53	3.81	2.21	2.89	4.37	0.98	1.21	1.75	1.46	2.29	2.07	2.56
Z	4.23	3.80	5.13	7.63	5.97	6.07	3.07	9.94	6.41	2.14	1.80	2.96	5.71	6.12	2.43	4.89
W	69.1	80.3	41.7	68.2	62.6	43.4	21.6	43.8	26.2	17.8	53.6	58.0	60.5	65.8	16.3	48.6
V	3.00	2.19	3.81	4.97	4.07	3.06	6.91	9.08	5.48	1.38	2.09	0.85	2.47	4.30	4.45	3.87
C	2.11	0.64	2.47	2.62	2.84	2.30	1.56	3.16	3.03	0.40	0.61	0.33	1.90	1.32	1.31	1.77
H	15.1	9.38	40.6	11.9	15.5	37.3	63.6	27.4	51.1	76.5	38.9	33.9	25.3	16.8	71.5	35.6

Table B.3: Simulation result of population percentage of seven strategies when *B*=0.7

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.92	0.79	2.20	0.52	2.03	1.04	1.01	1.37	2.96	1.13	0.69	3.81	2.10	3.44	3.44	1.83
Y	1.54	2.01	4.24	1.11	1.41	1.55	1.10	2.27	2.54	1.21	0.97	4.05	1.80	1.65	1.65	1.94
Z	5.29	3.30	5.32	6.43	6.82	3.97	3.97	5.55	9.18	4.76	5.18	9.26	8.35	8.34	8.34	6.27
W	20.5	21.7	6.92	5.43	23.6	25.6	19.1	35.1	46.4	28.9	27.4	29.1	58.4	18.3	18.3	25.6
V	6.56	4.15	8.20	10.0	7.46	6.56	5.27	4.25	10.8	6.11	6.26	4.91	5.00	7.22	7.22	6.67
C	2.09	1.03	3.40	3.62	3.51	1.50	2.01	1.38	4.04	1.90	1.34	3.47	3.05	3.33	3.33	2.60
H	63.0	66.9	69.6	72.8	55.0	59.7	67.4	50.0	23.8	55.9	58.0	45.3	21.1	57.6	57.6	54.9

Table B.4: Simulation result of population percentage of seven strategies when *B*=2.1

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	1.23	0.43	1.59	0.45	0.30	0.48	1.51	1.27	1.00	0.40	0.33	2.31	0.54	1.16	0.43	0.90
Y	1.36	1.94	2.82	3.56	1.64	1.18	2.40	1.08	1.02	0.91	0.33	3.40	3.06	3.64	0.31	1.91
Z	3.43	6.84	4.28	6.54	4.93	4.45	7.25	4.21	6.25	4.04	1.69	7.94	4.86	8.41	3.04	5.21
W	0.21	3.62	5.21	3.88	1.52	0.10	4.17	0.23	6.11	0.13	0.54	5.60	3.68	16.9	3.48	3.70
V	4.15	7.84	3.57	6.17	6.30	6.99	9.94	5.63	5.59	3.03	3.29	12.9	4.61	8.85	3.97	6.19
C	2.66	4.56	1.22	2.07	1.41	2.26	5.29	1.79	2.73	2.47	0.62	3.75	3.02	4.87	1.82	2.70
H	86.9	74.7	81.2	77.3	83.8	84.5	69.4	85.7	77.2	88.9	93.1	64.0	80.1	56.0	86.9	79.3

Table B.5: Simulation result of population percentage of seven strategies when *B*=7.0

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.61	0.63	0.45	2.01	1.00	0.37	0.63	0.25	0.54	1.64	1.50	0.40	1.04	0.39	1.55	0.87
Y	0.78	2.57	1.92	4.67	3.41	0.40	0.60	2.13	1.47	1.52	1.84	1.39	2.18	1.16	1.14	1.81
Z	5.87	4.53	3.59	12.4	8.27	4.97	4.32	5.24	4.77	5.30	5.70	3.20	8.80	6.63	5.66	5.95
W	0.84	1.40	0.53	4.68	0.90	2.14	1.41	0.55	1.58	1.75	0.69	1.47	2.12	0.35	0.07	1.37
V	7.80	7.56	6.77	13.8	10.0	5.19	7.34	9.38	5.20	2.61	7.41	8.46	11.0	4.56	7.97	7.68
C	3.30	4.21	2.83	5.51	3.77	2.82	2.04	3.91	3.65	2.45	3.14	2.07	5.24	1.08	2.45	3.23
H	80.7	79.0	83.8	56.8	72.5	84.0	83.6	78.5	82.7	84.6	79.6	82.9	69.5	85.8	81.1	79.0

Table B.6: Simulation result of population percentage of seven strategies when B=18.6

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.63	1.05	1.08	0.18	0.30	0.38	0.77	0.25	0.15	0.62	0.24	0.05	0.59	0.91	0.62	0.52
Y	1.38	1.93	1.99	0.25	0.90	1.15	2.33	0.70	0.69	1.70	0.89	0.21	0.88	0.75	1.70	1.16
Z	4.41	7.48	10.7	6.45	5.45	4.93	9.77	3.46	6.02	9.24	5.26	2.68	6.87	1.36	5.04	5.95
W	0.53	1.66	2.68	0.66	1.10	1.67	3.09	1.09	2.20	1.12	0.44	0.72	0.59	0.31	0.46	1.22
V	8.53	12.3	10.8	12.4	10.8	9.86	8.33	5.60	8.45	10.7	4.46	5.59	10.5	3.05	11.4	8.87
C	2.86	4.76	5.07	1.72	3.40	2.62	3.50	1.46	2.42	3.99	2.55	1.08	1.90	1.83	4.14	2.89
H	81.6	70.7	67.5	78.2	77.9	79.3	72.1	87.4	80.0	72.5	86.1	89.6	78.6	91.7	76.5	79.3

Table B.7: Simulation result of population percentage of seven strategies when B=55.8

C Collected Data from Studying the Social Welfare

In this appendix, the detailed data for different settings of the PGG model is collected and listed to study the correlation of social welfare to strong stability of centralized authority, to corruption and to legitimate hybrid-punishers.

C.1 Collected Data from Applying the PGG Model

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, and peer-punishers; W, and N players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8, where *B* = 0.7 is the default value that was used by Sigmund et al. (2010) model. The social welfare has been collected corresponding to each *B* value as follows:

B	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
0.0001	0.439	0.486	0.471	0.432	0.469	0.463	0.485	0.476	0.478	0.448	0.465	0.468	0.479	0.431	0.482	0.465
0.06	0.455	0.463	0.477	0.452	0.458	0.468	0.456	0.459	0.468	0.451	0.462	0.455	0.475	0.467	0.462	0.462
0.7	0.334	0.373	0.375	0.324	0.483	0.323	0.361	0.336	0.480	0.364	0.322	0.343	0.321	0.322	0.322	0.359
2.1	0.322	0.359	0.320	0.322	0.323	0.322	0.324	0.323	0.329	0.353	0.324	0.340	0.322	0.337	0.332	0.331
6.3	0.324	0.321	0.323	0.322	0.322	0.324	0.324	0.323	0.323	0.325	0.322	0.323	0.324	0.326	0.323	0.324
7.0	0.322	0.322	0.323	0.322	0.323	0.322	0.323	0.322	0.327	0.323	0.324	0.323	0.322	0.323	0.322	0.323
18.6	0.319	0.318	0.321	0.320	0.321	0.320	0.319	0.316	0.319	0.320	0.319	0.320	0.318	0.319	0.458	0.329
55.8	0.309	0.308	0.310	0.308	0.309	0.310	0.310	0.309	0.307	0.309	0.309	0.309	0.307	0.309	0.309	0.309

Table C.1: Simulation result showing social welfare of five strategies for various *B* values, second-order punishment severity

C.2 Collected Data from Applying Corruption to the PGG Model

In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, and corruptors, *C*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. The corruptor parameter *K* = 0.5. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.06, 0.7, 2.1, 6.3, 7.0, 18.6 and 55.8. The social welfare has been collected corresponding to each *B* value as follows:

B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
0.0001	0.466	0.441	0.442	0.464	0.462	0.448	0.424	0.469	0.461	0.462	0.476	0.477	0.458	0.459	0.450	0.458
0.06	0.422	0.452	0.462	0.481	0.452	0.401	0.469	0.437	0.461	0.470	0.459	0.464	0.465	0.448	0.461	0.454
0.7	0.440	0.429	0.479	0.436	0.442	0.462	0.435	0.439	0.454	0.397	0.388	0.432	0.396	0.434	0.448	0.435
2.1	0.437	0.444	0.391	0.458	0.408	0.403	0.394	0.422	0.413	0.475	0.430	0.411	0.423	0.441	0.448	0.427
6.3	0.311	0.336	0.339	0.336	0.320	0.333	0.309	0.364	0.332	0.331	0.314	0.342	0.356	0.319	0.320	0.331
7.0	0.324	0.349	0.319	0.305	0.311	0.316	0.328	0.338	0.297	0.338	0.329	0.351	0.337	0.351	0.333	0.329
18.6	0.267	0.270	0.257	0.265	0.263	0.265	0.277	0.283	0.262	0.267	0.276	0.283	0.287	0.279	0.265	0.271
55.8	0.248	0.253	0.254	0.248	0.246	0.231	0.253	0.238	0.252	0.237	0.237	0.235	0.242	0.257	0.255	0.246

Table C.2: Simulation result showing social welfare of six strategies for various *B* values, second-order punishment severity

C.3 Collected Data from Appling Corruptors and Hybrid-punishers to the PGG Model

In a population; *M*; which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, corruptors, *C*, and hybrid-punishers, *H*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6 and 55.8. The social welfare has been collected corresponding to each *B* value as follows:

B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
0.0001	0.478	0.455	0.473	0.456	0.462	0.433	0.485	0.475	0.477	0.462	0.490	0.480	0.468	0.451	0.462	0.468
0.1	0.452	0.451	0.470	0.476	0.460	0.453	0.475	0.466	0.469	0.436	0.475	0.463	0.455	0.477	0.438	0.462
0.7	0.435	0.455	0.382	0.429	0.409	0.384	0.350	0.382	0.348	0.351	0.414	0.421	0.421	0.430	0.344	0.398
2.1	0.346	0.351	0.312	0.315	0.348	0.358	0.346	0.372	0.383	0.363	0.362	0.351	0.408	0.340	0.340	0.354
7.0	0.310	0.304	0.319	0.308	0.313	0.310	0.303	0.314	0.319	0.311	0.321	0.308	0.307	0.319	0.321	0.313
18.6	0.306	0.299	0.304	0.290	0.295	0.310	0.312	0.298	0.304	0.310	0.304	0.310	0.295	0.310	0.308	0.304
55.8	0.297	0.290	0.290	0.305	0.297	0.299	0.291	0.307	0.300	0.292	0.299	0.309	0.302	0.305	0.292	0.299

Table C.3: Simulation result showing social welfare of seven strategies for various *B* values, second-order punishment severity

D The Competition between Pool-punishers and Hybrid-punishers along Time Evolution in the Absence of Corruption

D.1 Applying Hybrid-punishers to the PGG Model

Corruption and hybrid punishment strategies are applied to the Sigmund et al. (2010) PGG model described in chapter 3, In a population; *M*, which consists of cooperators; *X*, defectors; *Y*, loners; *Z*, pool-punishers; *V*, peer-punishers; *W*, and hybrid-punishers, *H*, where *N* players are arbitrarily picked to join the PGG where second-order punishment is applied. Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6 and 55.8, where *B* = 0.7 is the default value that was used by Sigmund et al model. The results have been collected and analyzed as follows:

As shown in Figures A.1 and A.2, also in Tables A.1 and A.2, when *B* = 0.0001and *B* = 0.1 (weaker pool punishment), peer-punishers dominate and perform better than pool-punishers and hybrid-punishers. Peer-punishers promote and maintain the cooperation evolution.

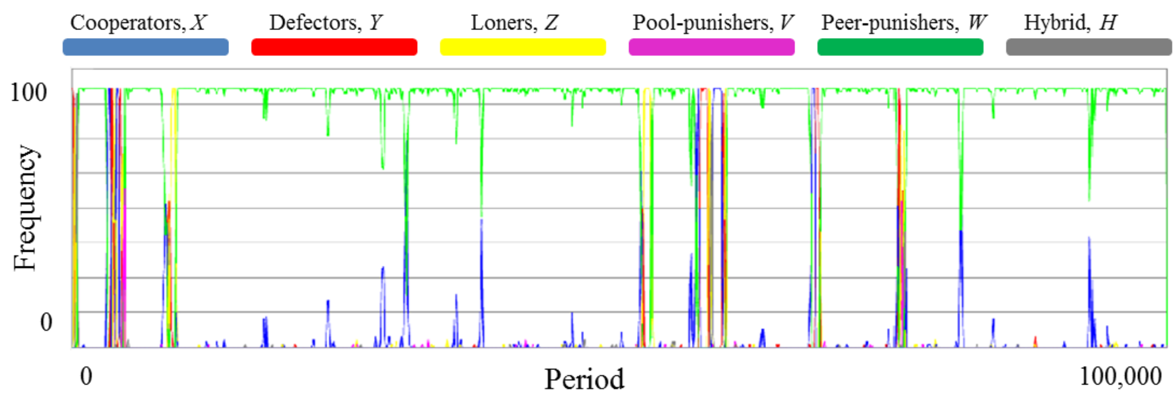

Figure D.1: Simulation result for pool punishment and hybrid punishment competition when *B*=0.0001

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	9.40	9.15	8.92	6.62	13.4	10.2	10.4	3.71	7.68	7.64	3.02	8.20	8.34	9.66	3.45	8.00
Y	5.24	8.00	6.80	4.91	8.30	6.09	10.0	2.87	3.83	4.96	1.48	4.45	5.76	5.63	1.81	5.35
Z	5.51	4.53	6.18	4.35	9.24	4.06	6.80	2.69	3.18	2.93	1.79	4.70	3.72	6.34	1.65	4.51
W	77.6	74.2	76.3	82.5	66.5	78.6	70.4	89.9	83.8	83.6	92.8	80.6	80.5	76.9	92.7	80.5
V	1.19	1.01	1.17	0.34	0.63	0.61	0.60	0.27	1.03	0.31	0.14	0.70	0.70	0.69	0.13	0.63
H	0.99	3.00	0.56	1.18	1.72	0.31	1.65	0.51	0.43	0.50	0.71	1.33	0.92	0.66	0.16	0.98

Table D.1: Simulation result for pool punishment and hybrid punishment competition when *B*=0.0001

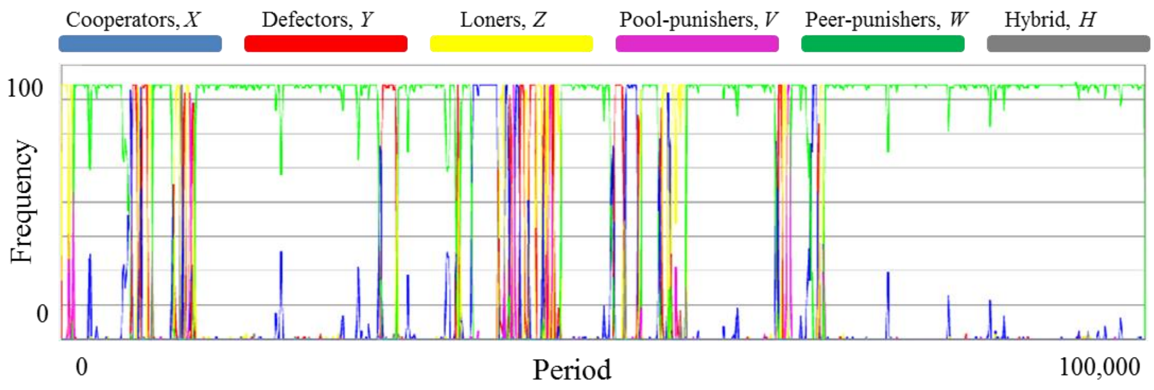

Figure D.2: Simulation result for pool punishment and hybrid punishment competition when B=0.1

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	5.76	3.96	5.05	6.08	9.68	6.05	2.78	3.19	9.85	7.78	5.00	8.08	5.08	9.68	5.76	6.25
Y	5.55	2.28	3.80	3.70	8.39	5.53	2.75	2.12	7.43	7.01	3.09	3.67	4.98	8.39	5.55	4.95
Z	6.15	2.68	1.75	3.17	7.27	4.69	1.83	2.29	6.75	7.93	2.88	4.25	2.46	7.27	6.15	4.50
W	80.2	88.4	88.1	85.3	73.3	82.0	91.8	91.8	73.3	75.3	88.4	82.8	86.6	73.3	80.2	82.7
V	0.63	0.34	0.88	0.69	0.88	0.51	0.25	0.45	1.35	1.37	0.35	0.20	0.41	0.88	0.63	0.66
H	1.64	2.27	0.36	0.96	0.41	1.09	0.46	0.11	1.21	0.56	0.23	0.94	0.42	0.41	1.64	0.85

Table D.2: Simulation result for pool punishment and hybrid punishment competition when B=0.1

As shown in Figures A.3, A.4, A.5, A.6, and A.7, also in Tables A.3, A.4, A.5, A.6, and A.7, when B = 0.7, B = 2.1, B = 7.0, B = 18.6 and B = 55.8 (intermediate to strong pool punishment), There are strong competition between pool-punishers and hybrid-punishers. Pool-punishers perform slightly better than hybrid-punishers. Although pool-punishers prevail for some time, the hybrid-punishers invade and gain ground but pool-punishers remerge and stabilize again.

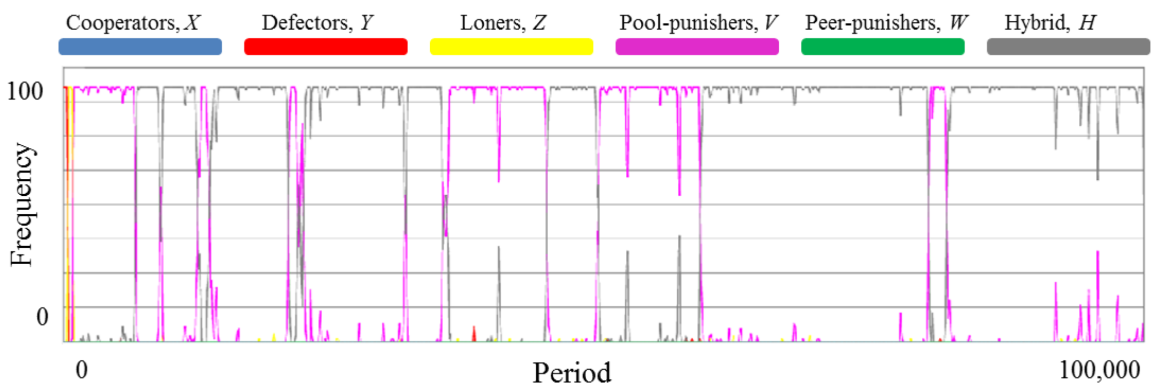

Figure D.3: Simulation result for pool punishment and hybrid punishment competition when B=0.7

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	1.56	0.53	0.16	0.06	0.07	0.06	0.06	0.06	0.07	1.46	0.35	0.61	0.06	0.74	0.06	0.42
Y	2.84	2.48	0.64	0.20	0.94	0.16	0.49	0.54	0.18	1.42	1.36	0.89	0.17	0.76	0.16	0.78
Z	1.29	1.18	0.53	0.49	0.43	0.34	0.21	0.59	0.52	0.64	0.63	0.82	0.32	1.00	0.21	4.34
W	1.98	5.02	3.27	0.06	0.07	0.06	0.06	0.06	0.06	15.8	3.95	10.9	0.06	14.4	0.06	3.60
V	57.2	14.3	39.9	45.9	49.6	42.2	46.2	28.9	36.9	73.5	64.2	80.1	42.3	57.2	73.5	48.6
H	35.0	76.4	55.4	53.1	48.8	57.1	52.9	69.8	62.2	7.06	29.4	6.52	56.9	25.7	25.9	44.1

Table D.3: Simulation result for pool punishment and hybrid punishment competition when *B*=0.7

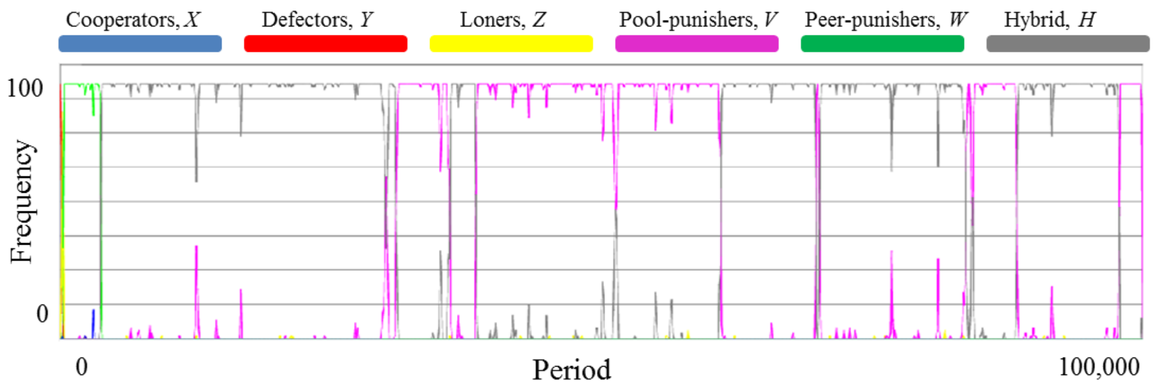

Figure D.4: Simulation result for pool punishment and hybrid punishment competition when *B*=2.1

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.06	0.07	0.06	1.02	1.91	0.07	0.08	0.06	0.06	0.80	0.06	0.06	0.06	0.06	0.06	0.30
Y	0.14	0.43	0.13	0.63	1.14	0.22	0.26	0.12	0.66	0.62	0.15	0.27	0.11	0.54	0.27	0.38
Z	0.36	0.72	0.31	1.03	0.73	0.25	0.28	0.17	0.28	1.48	0.41	0.31	0.82	0.50	0.31	0.53
W	0.06	0.06	0.06	8.88	14.0	0.06	3.50	0.07	0.06	17.3	0.07	0.07	0.06	0.06	0.07	2.97
V	59.9	43.9	54.9	44.3	30.6	25.4	34.6	49.8	35.5	50.6	65.3	50.4	70.1	61.7	50.4	48.5
H	39.3	54.7	44.4	44.0	51.4	73.9	61.2	49.6	63.3	29.0	33.9	48.8	28.7	37.0	48.8	47.2

Table D.4: Simulation result for pool punishment and hybrid punishment competition when *B*=2.1

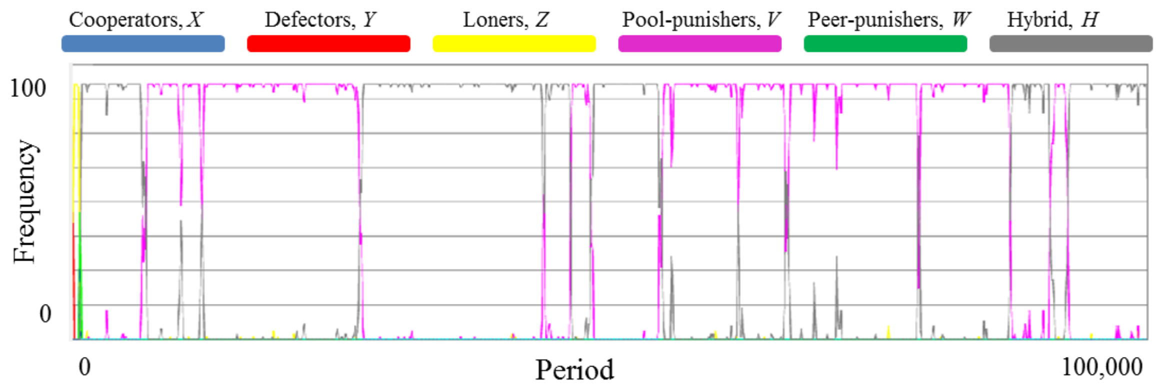

Figure D.5: Simulation result for pool punishment and hybrid punishment competition when B=7.0

Pop	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
X	0.11	0.06	0.06	0.06	0.36	0.06	0.05	0.07	0.14	0.06	0.06	0.06	0.06	0.11	0.35	0.11
Y	0.30	0.39	0.32	0.25	0.49	0.29	0.61	0.35	1.25	0.25	0.49	0.45	0.98	0.26	0.36	4.76
Z	0.18	0.21	0.41	0.62	0.50	0.25	0.19	0.35	1.19	0.27	0.33	0.23	0.46	0.28	0.40	0.39
W	0.76	0.07	0.06	0.06	0.06	0.07	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.59	0.06	0.15
V	74.8	69.0	45.9	46.9	40.3	59.9	63.1	70.1	34.3	64.5	81.9	75.3	43.4	68.1	52.6	59.3
H	23.8	30.1	53.2	52.0	58.2	39.4	35.9	29.0	62.9	34.7	17.0	23.8	54.9	30.5	46.1	39.4

Table D.5: Simulation result for pool punishment and hybrid punishment competition when B=7.0

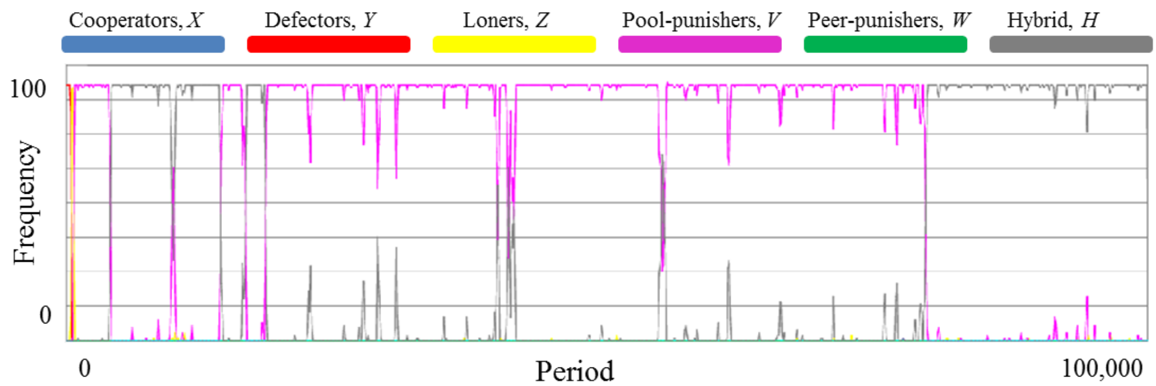

Figure D.6: Simulation result for pool punishment and hybrid punishment competition when B=18.6

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.11	0.07	0.07	0.06	0.07	0.07	0.06	0.06	0.07	0.06	0.07	0.07	0.06	0.06	0.06	0.07
Y	0.23	0.49	0.61	0.46	0.15	0.55	0.17	0.12	0.95	0.09	0.68	0.57	0.67	0.22	0.21	0.41
Z	0.26	0.20	0.44	0.16	0.29	0.38	0.24	0.20	0.32	0.24	0.33	0.25	0.66	0.44	0.25	0.31
W	0.11	0.06	0.06	0.06	0.07	0.06	0.09	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07
V	29.6	70.2	64.8	67.3	46.1	65.3	79.7	69.8	61.2	60.9	66.7	50.1	57.3	60.2	52.0	60.1
H	69.5	28.8	33.9	31.8	53.2	33.5	19.6	29.6	37.3	38.5	32.1	48.8	41.2	38.9	47.3	38.9

Table D.6: Simulation result for pool punishment and hybrid punishment competition when *B*=18.6

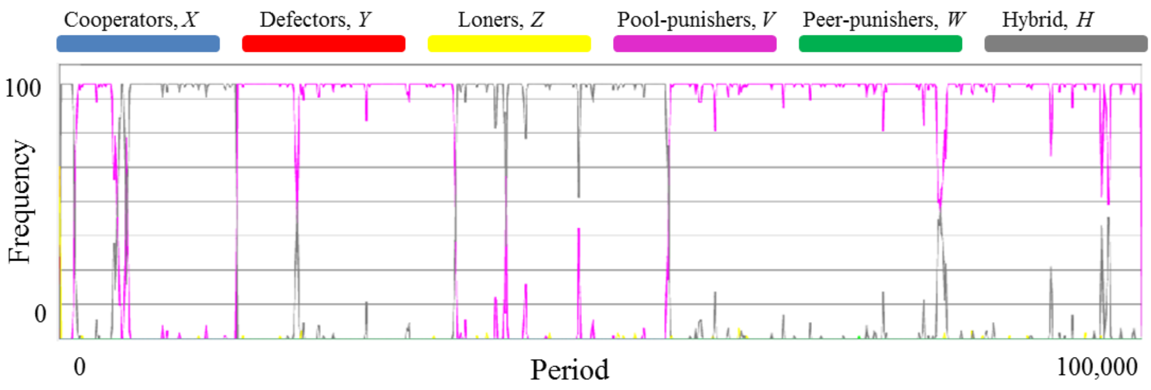

Figure D.7: Simulation result for pool punishment and hybrid punishment competition when *B*=55.8

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.07	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07	0.07	0.06	0.06
Y	0.14	0.18	0.13	0.53	0.33	0.10	0.72	0.38	0.43	0.21	0.51	0.13	0.14	0.22	0.31	0.30
Z	0.51	0.56	0.35	0.27	0.47	0.12	0.20	0.25	0.26	0.27	0.25	0.23	0.22	0.27	0.30	0.30
W	0.06	0.26	0.49	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.11
V	64.7	33.3	60.8	48.7	48.9	59.9	43.6	51.8	35.8	71.6	58.4	66.9	41.9	32.6	65.4	52.3
H	34.4	65.5	38.0	50.2	50.1	39.6	55.2	47.3	63.2	27.7	40.6	32.5	57.5	66.7	33.7	46.8

Table D.7: Simulation result for pool punishment and hybrid punishment competition when *B*=55.8

As shown in Figure A.8 and Table A.8 when B = 70.0(stronger pool punishment), surprisingly, although there are strong competition between pool-punishers and hybrid-punishers, hybrid-punishers perform slightly better than pool-punishers. When hybrid-punishers prevail for some time, the pool-punishers invade and gain ground but pool-punishers remerge again.

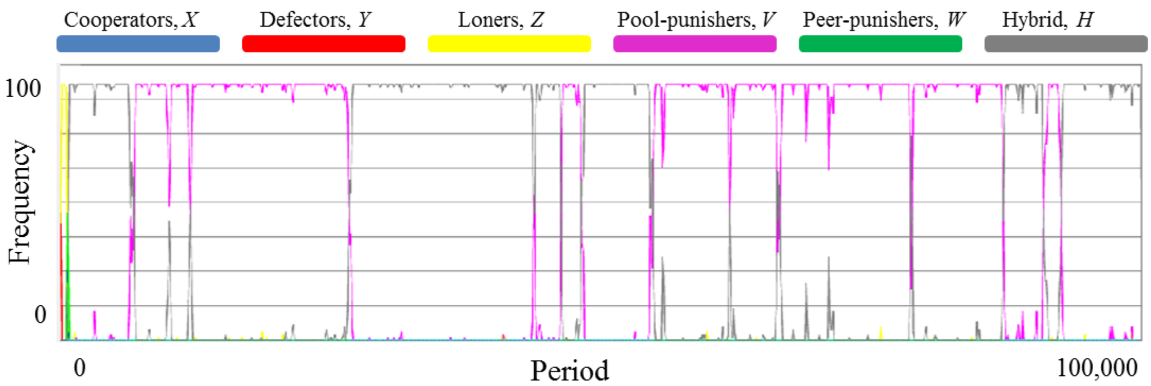

Figure D.8: Simulation result for pool punishment and hybrid punishment competition when *B*=70.0

Pop	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
X	0.06	0.19	0.06	0.09	0.06	0.06	0.06	0.06	0.14	0.06	0.06	0.06	0.06	0.06	0.06	0.08
Y	0.61	0.52	0.31	0.21	0.15	0.15	0.15	0.35	0.50	0.22	0.51	0.29	0.23	0.15	0.37	0.31
Z	0.43	0.38	0.33	0.70	0.24	0.22	0.31	0.26	0.31	0.21	0.36	0.25	0.22	0.25	0.36	0.32
W	0.17	0.23	0.06	0.14	0.06	0.07	0.06	0.06	0.06	0.26	0.06	0.06	0.23	0.20	0.07	0.12
V	63.6	38.3	31.6	55.0	31.2	29.4	58.3	29.7	60.7	40.0	31.1	56.4	57.5	51.1	34.4	44.5
H	35.1	60.2	67.6	43.8	68.2	69.9	41.0	69.4	38.2	59.1	67.8	42.8	41.6	48.2	64.6	54.5

Table D.8: Simulation result for pool punishment and hybrid punishment competition when *B*=70.0

D.2 Results and Discussion

Fifteen sample simulation runs were executed for different values of *B* parameter. Each sample simulation run contains 100,000 period steps including one million generations. *B* values varied along wide range, from weak pool punishment (low *B* values) to strong pool punishment (high *B* values). Various *B* values are chosen to be 0.0001, 0.1, 0.7, 2.1, 7.0, 18.6, 55.8 and 7.0 as shown in Table A.9 and Figure A.9.

B	0.0001	0.1	0.7	2.1	7	18.9	55.8	70.0
X	8.003	6.257	0.427	0.304	0.116	0.072	0.068	0.082
Y	5.350	4.955	0.783	0.3854	4.761	0.417	0.301	0.319
Z	4.515	4.507	4.347	0.535	0.396	0.316	0.308	0.327
W	80.508	82.766	3.606	2.970	0.149	0.0715	0.109	0.124
V	0.6391	0.660	48.692	48.544	59.375	60.139	52.349	44.598
H	0.9810	0.852	44.184	47.258	39.486	38.981	46.861	54.548

Table D.9: Simulation result showing average population for pool punishment and hybrid punishment competition for various *B* values, second-order punishment severity

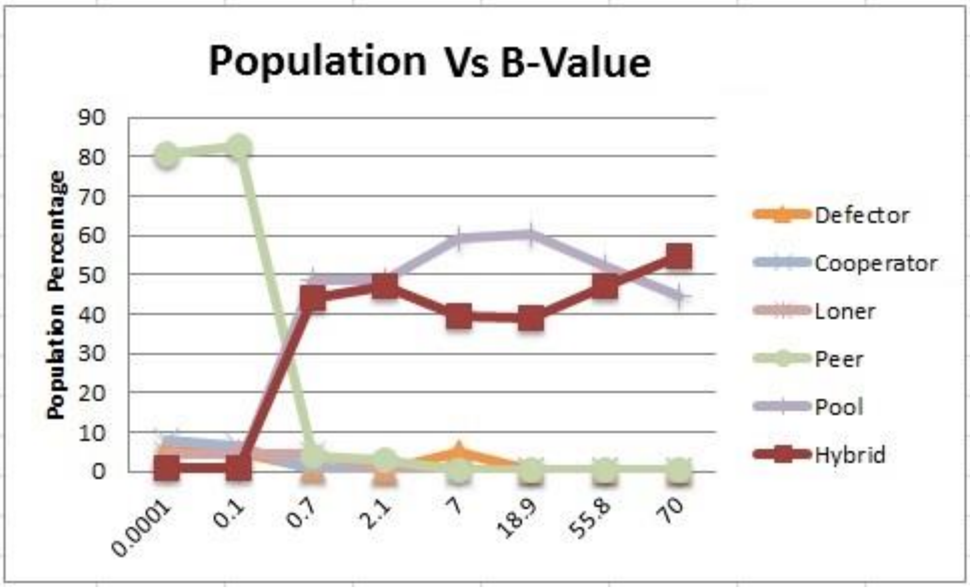

Figure D.9: Simulation result showing average population for pool punishment and hybrid punishment competition for various *B* values, second-order punishment severity

Under weak centralized punishment, peer-punishers dominate and perform better than pool-punishers and hybrid-punishers. Peer-punishers promote and maintain the cooperation evolution.

While centralized punishment is severe, peer-punishers are totally diminished. Hybrid-punishers and pool-punishers dominate and promote the cooperation evolution.

Briefly, in the absence of corruption, peer-punishers maintain cooperation under weak centralized authority, while pool-punishers and hybrid-punishers maintain it under severe centralized punishment. Further investigation must be done to study the competition between hybrid-punishers and pool-punishers in the absence of corruption.

B	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
0.0001	0.459	0.445	0.450	0.464	0.435	0.460	0.432	0.479	0.472	0.469	0.489	0.465	0.462	0.457	0.488	0.462
0.1	0.454	0.479	0.476	0.472	0.441	0.461	0.481	0.484	0.444	0.444	0.477	0.471	0.470	0.441	0.454	0.464
0.7	0.321	0.325	0.329	0.324	0.322	0.324	0.323	0.322	0.324	0.350	0.328	0.342	0.324	0.348	0.324	0.412
2.1	0.324	0.323	0.324	0.339	0.348	0.324	0.329	0.324	0.322	0.352	0.324	0.324	0.324	0.322	0.324	0.329
7.0	0.323	0.323	0.322	0.323	0.32	0.323	0.322	0.322	0.319	0.323	0.321	0.323	0.320	0.323	0.323	0.323
18.6	0.320	0.320	0.318	0.319	0.320	0.320	0.320	0.320	0.318	0.320	0.320	0.318	0.318	0.320	0.320	0.320
55.8	0.311	0.312	0.312	0.312	0.312	0.313	0.309	0.312	0.310	0.312	0.310	0.313	0.312	0.311	0.312	0.312
70.0	0.308	0.307	0.310	0.310	0.310	0.308	0.310	0.310	0.307	0.310	0.308	0.310	0.310	0.310	0.307	0.309

Table D.10: Simulation result showing social welfare for pool punishment and hybrid punishment competition for various *B* values, second-order punishment severity

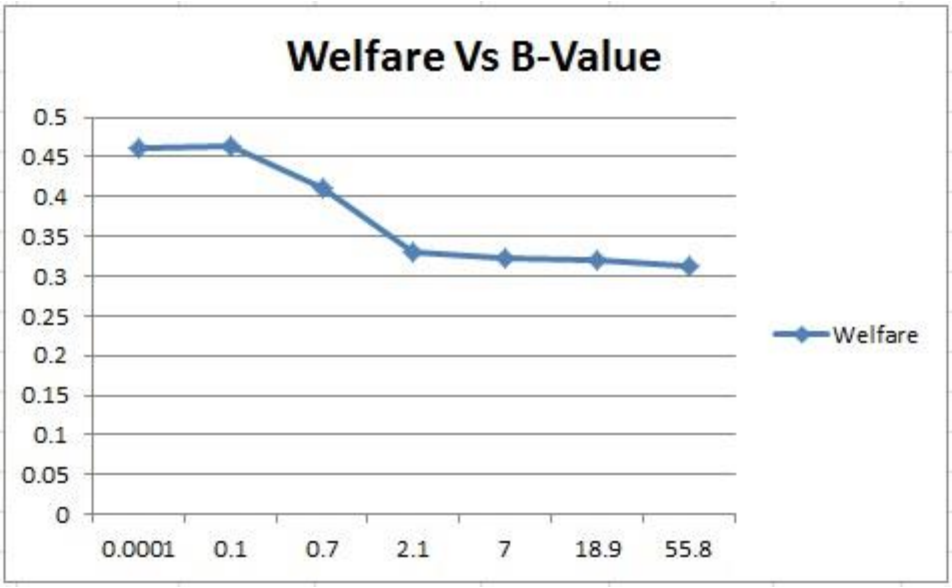

Figure D.10: Simulation result showing social welfare for pool punishment and hybrid punishment competition for various *B* values, second-order punishment severity

As shown in Table A.10 and Figure A.10, under weak centralized punishment, peer-punishers dominate and the social welfare is relatively high. While under strong centralized punishment, pool-punishers and hybrid-punishers dominate and the social welfare relatively decreases. This is due to the fact that pool-punishers and hybrid-punishers pay the fixed amount to the common pool punishment even in the absence of free-riders.