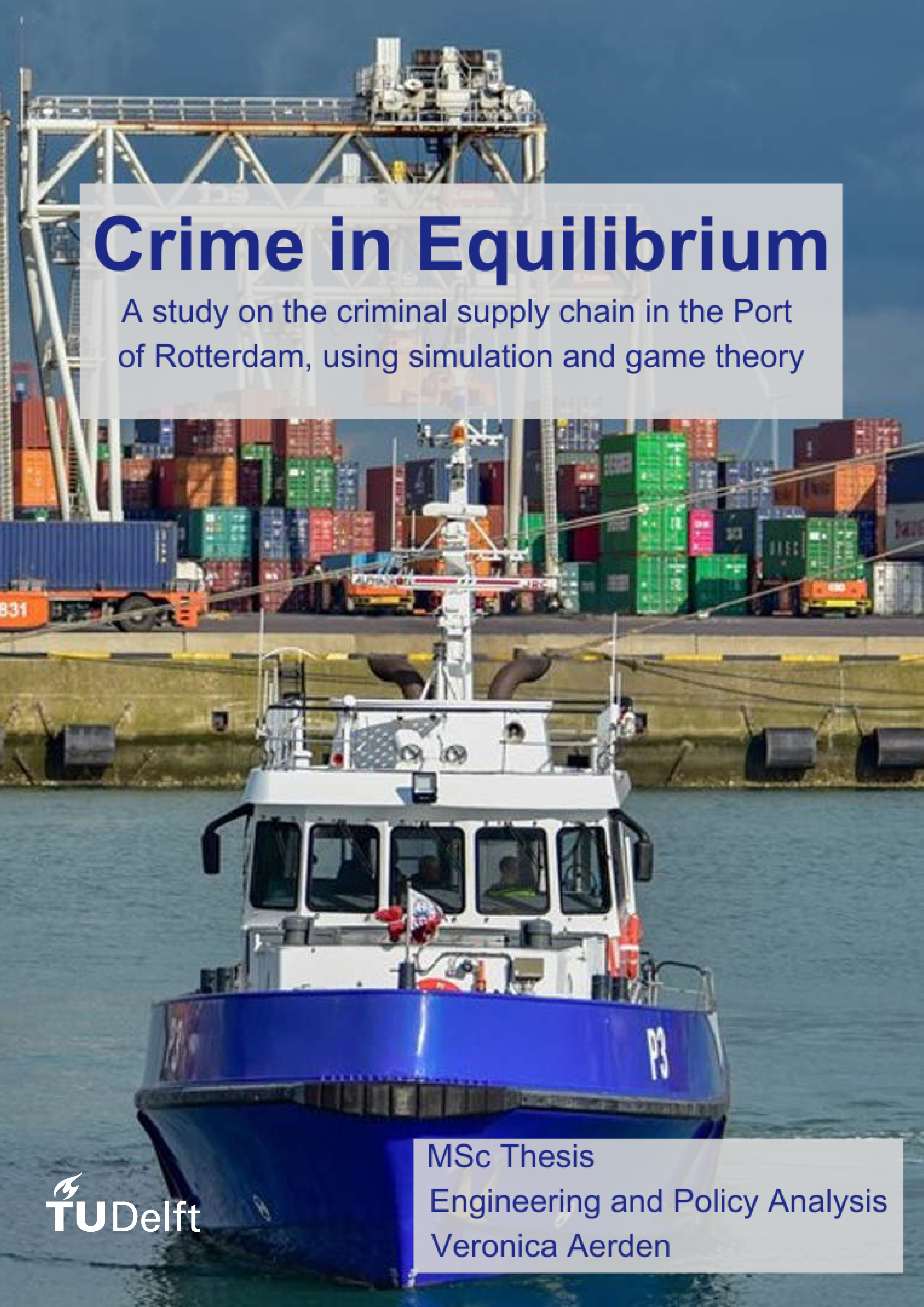

Crime in Equilibrium

A study on the criminal supply chain in the Port of Rotterdam, using simulation and game theory

MSc Thesis
Engineering and Policy Analysis
Veronica Aerden

TU Delft

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Veronica Aerden,
Technical University Delft,
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Summary

The Port of Rotterdam is the biggest port in Europe and with its great location an important place for trade between Europe and other continents. Record numbers of intercepted illegal goods show that criminals use this port to traffic illegal goods. A lot is still unknown about the criminal supply chain in the Port of Rotterdam and about the chance to catch illegal goods that are smuggled. Therefore this research provides insights into this criminal supply chain by looking into the effects of the distribution of resources by law enforcement agencies between methods that can be used to catch illegal goods on the chance to catch illegal goods.

This research looks at the criminal supply chain from South America to the Port of Rotterdam where it focuses on the smuggling methods used inside the Europe Container Terminals in the Port of Rotterdam. Criminals make use of four smuggling methods which are the pincode fraud method, the switch and pincode fraud method, the extraction method and the empty depot method. Law enforcement agencies have a scan and a surveillance method to catch illegal goods. The methods of law enforcement agencies can catch different smuggling methods and both have a chance to catch illegal goods smuggled with the empty depot method. Whereas criminals choose per illegal container which smuggling method will be used, this is not possible for law enforcement agencies. Therefore, a linear relationship between the part of resources appointed to a method and the accuracy of that method is assumed for the methods of law enforcement agencies.

An agent-based model is built to capture the complexity of this criminal supply chain and show the behaviour of the cat-and-mouse-like situation between criminals and law enforcement agencies. This agent-based model is combined with the Nash equilibrium known from game theory, as game theory can give insights into this situation using a mathematical framework. As these research methods have not been combined for the distribution of resources among methods in the Port of Rotterdam in earlier research, this research provides insights into how these research methods can be combined and whether they will provide similar results.

When combining the Nash equilibrium from game theory with the agent-based model it is expected that the distribution of resources for the two players, criminals and law enforcement agencies, in the agent-based model will eventually end up in or around the Nash equilibrium. This is because, in the Nash equilibrium, no player can get a higher expected payoff by deviating from the equilibrium. The players in the agent-based model update their distribution of resources every period of four weeks to adapt to the behaviour of the other player. This adaption is modelled with an updating rule. As literature indicated that the modelling of this updating rule can cause different behaviour in agent-based models, six different updating rules are tested in this research.

Given a chance to catch illegal goods of the scan of 0.18 for smuggling methods that can be caught by the scan and a chance of 0.8 for surveillance for methods that can be caught by surveillance, the Nash equilibrium is reached when law enforcement agencies appoint 40/49 of their resources to the scan and 9/49 to surveillance and criminals appoint 40/49 of their resources to the pincode fraud method and 9/49 to the switch and pincode fraud method and the extraction method combined. In the Nash equilibrium criminals will not appoint any resources to the empty depot method.

The six updating rules used in the agent-based model show different behaviours. Some updating rules cause the players in the agent-based model to appoint all their resources to only one method and others cause the players to end up in a cyclic pattern around the Nash equilibrium. The agent-based model also shows that by changing parameters of certain updating rules, the behaviour can change completely. For some updating rules the distribution of resources can get appointed according to an equilibrium which is not a Nash equilibrium as the payoffs of the methods are not equal to each other. Various difficulties arise when designing an updating rule. None of the six updating rules can guarantee the agent-based models to end up in or around the Nash equilibrium.

These difficulties include that resources should be distributed according to the payoff of methods according to game theory and should not be done according to the success rate of methods. Other difficulties arise when methods get appointed little or no resources. As it is the best response for players to distribute all their resources to one method when the other player is not playing according to the Nash equilibrium, the updating rule needs to be able to appoint zero resources to a method. Updating rules should also ensure that this method can be reappointed more resources when the other player changes its distribution of resources. Other difficulties include equilibria that are not a Nash equilibrium as mentioned above and the fact that players do not adapt in the same way when they do not have the same number of methods.

From this research, it can be concluded that in order to use an agent-based model for the situation between law enforcement agencies and criminals the knowledge about Nash equilibria should be considered while creating the model. This will not happen automatically as seen by the multiple difficulties this research showed. This research also shows that updating the distribution of resources by law enforcement agencies is important as they risk having an unnecessarily low chance to catch illegal goods when criminals adapt, while law enforcement agencies would not.

Therefore, it is recommended for law enforcement agencies to update the distribution of resources when it is expected that criminals will adapt as well, to not risk having an unnecessarily low chance of catching illegal goods. Furthermore, it is recommended to consider the Nash equilibrium while updating the distribution of resources and to carefully observe the distribution of resources of criminals when appointing all resources to only one method.

Limitations of this research include that there are only a limited number of methods included and players can not learn new methods. Due to the limited data about the criminal supply chain and about the methods that can be used by law enforcement agencies, there is deep uncertainty in model parameters, especially in the chances of catching illegal goods of the methods of law enforcement agencies. Therefore the results are not entirely valid and should only be used to analyse expected behaviour. Further research is needed on these chances of catching illegal goods and to test more updating rules as this research does not provide an updating rule that will ensure that an agent-based model will always end up in or around the Nash equilibrium.

Contents

List of Figures

List of Tables

1

Introduction

In 2021, the border patrol in the Port of Rotterdam caught a record amount of illegal goods (Rijnmond.nl, 2021). The Port of Rotterdam is the largest seaport in Europe due to multiple factors such as its easy access to the sea and its great connections, it has a total throughput of 436.8 million tonnes of goods (Port of Rotterdam Authority, 2020). This port is also, directly and indirectly, responsible for 196,713 jobs (Port of Rotterdam Authority, 2020). The Port of Rotterdam is an important gateway to Europe with facilities of high quality, however, this also attracts organised crime groups (Roks et al., 2021). These criminal groups use this port to traffic illegal goods (Roks et al., 2021). The smuggling of illegal goods causes all sorts of threats to society. Not only does the usage of illegal goods have a destructive effect on people and society, but the transport also causes increasingly lethal violence, threats, bribery and intimidation. In addition, the Port of Rotterdam deals with disturbances in logistic processes due to criminal activity and fear among employees, making criminal activity in the Port a threat to the good business climate (Port of Rotterdam, 2021). Using the framework of Alford and Head (2017), this problem can be labelled as a wicked problem. This is because, even though it could be argued that everyone agrees that it is a big problem, it is not clear how the criminal supply works and therefore it is not clear what the magnitude of the problem is since most parts of the criminal supply chain remain hidden from the law enforcement agencies. When looking at the stakeholders of this problem, it is clear that the parties that are involved have different incentives, because the criminals want to smuggle illegal goods and the law enforcement agencies want to stop them.

1.1. Problem statement

To counter the criminal supply chain, law enforcement agencies can use different methods to detect and stop criminals from smuggling illegal goods into the Netherlands. To investigate the effects of the possible methods to catch the smuggling of illegal goods and to investigate how these crime groups can traffic such big amounts of illegal goods, more insight is needed into the supply chain of these criminals. The difficulty with methods that catch the smuggling of illegal goods is that the criminals can adjust their behaviour. The result of changes in the methods of law enforcement agencies is a cat-and-mouse game where every time law enforcement agencies change their methods, criminals adapt. An example of this behaviour comes from the study of Roks et al. (2021). They found that increasing security measures directed at physical spaces (whether the strategy is from the public sector or private actors) results in a displacement of crime instead of the desired reduction. Criminals can move their criminal activity to new spaces in and around the Port of Rotterdam (Roks et al., 2021). This interaction makes it difficult to know how what the effects are of methods that law enforcement agencies can take to try and reduce the throughput of illegal goods in the Port of Rotterdam.

1.2. Scientific research gap

Few studies are done about the criminal supply chain in ports. According to Eski (2011), the criminological and public interest is remarkably scarce, even though ports form an intersection of crime and crime control. Ferwerda and Unger (2016) look into why the Netherlands is particularly attractive for trafficking illegal goods and other forms of transit crimes. They conclude that the trade and finance orientation of the Netherlands together with its central geographical location next to the North Sea and large other European counties, combined with the big Port of Rotterdam and airport Schiphol make the country this attractive for (illegal) trade. Bâdea and Zavergiu (2017) also state that ports are always vulnerable to criminal activity because of their open location, their big size and because ports are intersection points of multiple streams of transportation.

Other research has been done on the drivers and dynamics behind drug crime in the Port of Rotterdam by Staring et al. (2019). This study found, among other things, that criminals take advantage of the gaps in supervision and that the transport sector, fruit lines and textile trade are vulnerable to smuggling crime. The study of Eski and Buijt (2016) investigates the corrupt employees in the Port of Rotterdam itself by looking at employees who took part in illegal trade by being involved in rip-off cases. Rip-off cases are cases which use legitimate cargo and containers to hide illegal goods. To analyse the reasons behind this corruption, a qualitative thematic analysis has been done of the official police files in 2014. This study shows that corrupt employees are not only financially motivated to help in rip-off cases but that these financial motivations are intertwined with social justifications. This means that employees are also motivated by taking care of their families, which can be amplified by seductions to engage in criminal activity by their colleagues. Roks et al. (2021) study how organised groups of criminals involved in trafficking illegal goods get their way by taking advantage of socio-spatial relations or adapting to these relations in the Port of Rotterdam.

The findings of the study of Roks et al. (2021) also demonstrate that increasing security directed at physical spaces by either public or private actors will result in a displacement to new spaces either in or around the port of Rotterdam. Another finding of this shows that the current socio-spatial relations make the aspect of the people that work in and around the port of Rotterdam increasingly indispensable. Storti et al. (2022) study different ports as a hub for criminal activities and argues that organised crime groups do not only exploit maritime shipping on high seas but also through ports, of which many are privately owned or managed. This gives insight into the importance of the role that the port authorities can play either independently or together with state authorities to manage the threats to the security of the ports associated with (organised) crime.

Currently, the majority of shipments containing illegal goods are not intercepted by the current criminal detection practices of the Dutch National law enforcement agencies(Klaassen, 2021). Different sources in Europe and America and international law enforcement estimate that around 15 to 20 percent of shipments from the criminal supply chain are seized (McDermott et al., 2021). This shows how little is known about the full size of the criminal supply chain in the Port of Rotterdam. Therefore it is necessary to increase detection in the criminal supply chain and look at different methods which can capture and intervene in more parts of this criminal supply chain. Klaassen (2021) and van der Plas (2022) already looked into the criminal supply chain in the Port of Rotterdam and possible strategies, however, there is still a research gap in how the criminals will react to different methods and how their behaviour will influence the effectiveness of the different methods of the law enforcement agencies.

The study of Roks et al. (2021) shows that more research is needed into the behaviour of criminals as a consequence of different methods and how this behaviour can be anticipated. This is why this research will combine an agent-based model with game theory. To gain more insight, an agent-based model can be built to model the possible behaviour of criminals in the Port of Rotterdam. The agent-based model can test different methods from both law enforcement agencies to catch the smuggling and from criminals to smuggle illegal goods, the agent-based model can then see what would happen when these methods are executed. In addition, game theory is a tool that is useful when analysing supply chains with multiple agents who often have conflicting objectives and do not only depend on their actions (Cachon & Netessine, 2014). Many studies also propose game theoretic approaches to improve security (X. Liang & Xiao, 2013). This is because game theory can model these problems and provide a mathematical framework to help analyse these problems (X. Liang & Xiao, 2013).

Another research gap is how these methods can be combined and if it is necessary to use both these methods. Earlier research from Krause et al. (2006) compared an agent-based model with the Nash equilibrium for a different subject where they found that their agent-based model using a Q-learning algorithm has a high likely hood of converging to the Nash equilibrium if there is only one equilibrium and that their model behaves cyclically when there two Nash equilibria are present. Another study by Y. Liang et al. (2020) discovered for a different topic that their agent-based model could converge to the Nash equilibrium with complete information and even with incomplete information. The study of Page (2012) also shows that any learning rule in agent-based modelling that moves to a higher payoff will not move from a Nash equilibrium. However, the stability of this equilibrium depends on the learning rule, and different learning rules do not necessarily give the same equilibrium and the existence of a stable or even symmetric equilibrium does not guarantee that it will be generated by an agent-based model (Page, 2012). This shows that the way an agent-based model is modelled matters a lot when you compare it to game theory, specifically how the agent-based model updates which methods to use. This will determine whether the agent-based model will give similar results by reaching the same equilibria and how stable these results are.

1.3. Research goal and scope

This research provides insight into the different methods of law enforcement agencies and what their effects are while taking into account the different methods of the criminals that are active in the Port of Rotterdam. Since according to expert knowledge most criminal activity happens in the Europe Container Terminals (ECT) Delta, this research will focus on this terminal and will focus on the supply chain from South America to the Port of Rotterdam. To keep the study manageable only the most important methods of the law enforcement agencies and criminal smuggling methods will be included. Next to providing insights into the effect of law enforcement methods while taking into account the criminals' adaptions, for which both agent-based modelling and game theory are necessary, this research also provides insights into combining these research methods. Therefore this research looks into how law enforcement should update their strategy on how to use their resources among their methods to capture illegal goods.

1.4. Research questions

The main research question that this study will try to answer is:

- *RQ: What is the effect of different updating rules on the distribution of resources between methods of law enforcement agencies on the chance of illegal goods being caught in the Port of Rotterdam using simulation and game theory?*

Resources of law enforcement agencies are all resources that can be distributed over different methods, meaning machinery, labour hours and financial resources. This research does not focus on the volume of illegal goods that are caught but rather focuses on the number of separately smuggled illegal goods. This means that the chance of illegal goods being caught can be defined as the likelihood, that when illegal goods are being smuggled inside a container, they are caught by law enforcement agencies. To answer this research question, it is necessary to first know more about the criminal supply chain in the Port of Rotterdam and to know which methods are used by criminals to smuggle illegal goods and which methods law enforcement agencies have to catch these illegal goods. Furthermore, insights are needed into the different variations of updating rules that law enforcement agencies could be using and how the research methods that are used compare to each other. The following sub-questions will be answered using literature, interviewing experts and the previously mentioned agent-based model and game theory.

- *SQ1: What are the most used methods of criminals and law enforcement in the Port of Rotterdam?*
- *SQ2: What are possible updating rules?*
- *SQ3: How does the simulation model compare to game theory?*

2 Research Methods

This research combines both qualitative and quantitative research methods. The qualitative research provides the information needed for the quantitative research, to know the structure and inputs of the simulation model and game theory used. Models are simplifications of systems with which it is possible to test reactions to changes to the system. However, models are only valuable if their structure is based on knowledge of the actual system (Clarke, 2014). This chapter will explain in-depth which research methods are used and why these research methods are suitable for studying the interaction between law enforcement agencies and criminals in ports.

2.1. Qualitative Research

First, this research investigates how the legal supply chain from South America to the Port of Rotterdam is structured and how criminals make use of this legal supply chain for their illegal activities. From the supply chain, this research focuses on what is happening in the Port of Rotterdam itself. When it is clear how this (illegal) supply chain is structured and what the most common smuggling methods are that criminals use, this research conducts a literature search to see what methods law enforcement agencies have to increase the chances of illegal goods being caught in Rotterdam. Through this literature review, it becomes clearer what possible methods exist, what the current state of these methods from law enforcement agencies is, as well as the smuggling methods employed by criminals. This literature also indicates which knowledge is missing, providing insights into where the expertise of professionals is needed to fill some of these gaps. This research obtains this expert knowledge through interviews with experts from the Dutch National Police whenever possible. Next to literature about the criminal supply chain, this research conducts a literature search about different game theory models that could be applicable to the situation between criminals and law enforcement agencies in the Port of Rotterdam.

2.2. Quantitative Research

2.2.1. Agent-based model

After knowing the possible methods that law enforcement agencies can make use of and therefore which methods are most interesting to take into account, it is essential to assess their effects and observe the impact of different distributions of resources among these methods. To examine these effects, this research creates an agent-based model. This model is designed to be comparable to the chosen game theoretical model.

Agent-based models share their origins with cellular automata in the work of von Neumann, Ulam, and Conway (Clarke, 2014). Agent-based modelling has increased in popularity because of the increasing complexity of the world (Macal & North, 2009). The research method of agent-based modelling has many applications, including the study of supply chains (Macal & North, 2009). It is a research method that can explore systems that include interactive, adaptive and diverse actors (de Marchi & Page, 2014). It is a proven approach for handling the challenge of capturing the complexity of a socio-technical system (van Dam et al., 2013). Agent-based modelling can be of decision support in large-scale interconnected network systems, where the behaviour of these systems is influenced by multiple actors with different objectives in a multi-level environment (van Dam et al., 2013). Agent-based models are models that make use of micro-level processes from which higher-level patterns can emerge (Payette, 2012). Agents can interact with each other, move in space and interact with other agent types (Clarke, 2014).

The biggest limitation of this research design is the very limited amount of data that is available. Since the model is about criminal activity there are a lot of uncertain parameters, as much is unknown about criminal processes. A limitation of agent-based modelling is that due to these uncertain parameters, a model can give unreliable results (Rand & Stummer, 2021). The best response to overcome this limitation is by making sure the model is well validated (Rand & Stummer, 2021). That is why the assumptions of Appendix A are validated by an expert. Another criticism of agent-based modelling is that it is computationally expensive and that it can be very dependent on the quality of the assumptions made (Rand & Stummer, 2021). This large computing power combined with the intensive labour costs to build an agent-based model makes it interesting to compare this research method to a game theoretic model. Since this research is about the situation between criminals and law enforcement agencies in which it is expected that both these players change their distribution of resources among their methods based on the distribution of resources between the methods of the other player, game theory is the right research method to analyse this situation. This is because game theory helps to understand situations where players interact (Osborne, 2000).

2.2.2. Game Theory

Game theory was shaped around the 1950s when von Neumann and Morgenstern published their work Theory of Games and Economic Behavior (Von Neumann & Morgenstern, 1944). Their definition of a game is every situation where agents interact that is governed by a set of rules that determine the moves of the participants and the outcomes for each possible combination of moves. After this book, more researchers started to work on game theory. Some examples are two papers by Nash about the Nash equilibrium (Nash, 1950b) and the bargaining problem (Nash, 1950a) and on stochastic games by Shapley (1953a) and on the coalition games by Shapley (1953b), to name a few. Many applications of game theory can be found in economics but it also has applications in other social sciences and in evolutionary biology (Tijs, 2003). Game theory has been successful in modelling strategic behaviour in situations where the outcome of each player may depend not only on their own actions but also on the actions of other players (Tijs, 2003). The interaction between law enforcement agencies and criminals in ports is interesting to look at using game theory since the success rate of the strategies of both the law enforcement agencies and criminals depend on the strategy of the other player as well, meaning that the number of illegal goods that law enforcement agents can catch depends on the smuggling methods used by criminals. Game theory can be used to find the optimal action for an individual player, given his preferences. Therefore game theory is an interesting research method to use when trying to see the effects of strategies from law enforcement agencies that are aimed to reduce criminal activity. Game theory consists of a collection of different approaches to solve different types of games (Osborne, 2000). The following section will attempt to narrow down which approach will be suitable to study the game between law enforcement agencies and criminals.

Types of Game theory

The type of game theoretical approach depends (among other things) on the payoff structure of the game. The payoff of a player represents the value of the outcome for the player, this can for example be the financial compensation or desirability of each outcome for a specific player (Osborne, 2000). The first distinction that is needed is the one between cooperative and non-cooperative game theory. In cooperative game theory, players are free to negotiate, have tools to enforce agreements, and can form coalitions. The situation between law enforcement agencies and criminals is a non-cooperative game as no cooperation is expected between law enforcement agencies and criminals. For simplicity reasons, the game in this research is assumed to be a two-player game, where both players make their choices rationally, meaning that only one criminal network is taken into account and that the law enforcement agencies are combined into one player as well.

The second distinction that is needed for this research is the one between evolutionary game theory and classical game theory. In evolutionary game theory strategies are inheritable traits rather than rationally chosen (Smith, 1982). Therefore, this research will focus on classical game theory with the assumption that the players, law enforcement agencies and criminals, will make their choices rationally. Classical game theory can be seen as an umbrella for theory for the rational side of social sciences (Aumann & Hart, 1992). The payoff structure of a game can be either zero-sum or non-zero-sum. In a zero-sum game everything that one player wins is lost by the other player (Owen, 2013). In a non-zero-sum game, the combined payoffs can differ per scenario and thus do not sum up to a zero. For the scope of this research, the game between criminals and law enforcement agencies will be assumed to be a zero-sum game, where either criminals get the illegal goods past security or law enforcement agencies intercept them making the sum of the payoffs zero as the payoff of criminals is the negative payoff of law enforcement agencies. However, this excludes the costs of the different strategies used, such as costs of security measures for law enforcement agencies and costs of bribery money for criminals. It is an assumption of this research that these other costs are not relevant to the game.

Nash equilibrium
In non-cooperative game theory, the concept of the Nash equilibrium plays a central role (Nash, 1951). A Nash equilibrium is a strategy profile for each player where no single player can obtain a higher payoff by unilateral deviation of their action (Nash, 1951). This definition also applies to a mixed-strategy Nash equilibrium, where a player puts probabilities on his pure strategies to give him the greatest expected payoff (Kreps, 1989). The theory of Nash (1951) is based on the assumption that each player acts independently. In this theory Nash (1951) proved a finite non-cooperative game always has at least one equilibrium. This can be either an equilibrium consisting of pure strategies, or an equilibrium where players will play a mixed strategy. A mixed strategy of a player is a collection of probabilities which have a direct correspondence with the pure strategies of the player which sum up to 1 (Nash, 1951). Rationally each player will start the game with a belief on the strategies of his opponent and play his best response to this assumed action (Kalai & Lehrer, 1993). When all players maximise their expected payoff, eventually the Nash equilibrium will be played (Kalai & Lehrer, 1993). It is interesting to compare the previously mentioned agent-based model to the theory about the Nash equilibrium to see if the distribution of resources among methods used by law enforcement agencies and criminals also ends up in this equilibrium and if it can be explained when it does not end up there.

3
Case study

This chapter explains the supply chain from South America to the Port of Rotterdam. It gives a clear overview of the process that legal and illegal goods go through. After a broad overview, it will show the part of the supply in the Port of Rotterdam in more in-depth, as this is the scope of this research. It also shows specifically which criminal smuggling methods are used and which ones are included in the agent-based model as explained in chapter 5, more specific information about the supply chain can also be found in Appendix A. Information on the criminal supply chain is gathered through expert knowledge and based on the study of van der Plas (2022). Furthermore, this chapter shows which methods law enforcement agencies can make use of to capture the illegal goods that are being smuggled by criminals in the Port of Rotterdam. It will also show which methods are then most interesting to include in this research and which actors are involved in these methods.

3.1. Legal supply chain

The focus of this research lies on the supply chain from South America to the Port of Rotterdam. The whole supply chain starts off in South America where the goods, for example bananas or mangoes, are being produced. These goods are then transported in containers by trucks to a port. In the port, they are loaded onto big container ships. These ships transport the containers to the Port of Rotterdam. After about two to three weeks and notifying the Port on time, the ships arrive in Rotterdam where they will be unloaded with big cranes and put in the terminal until a truck, train or smaller ship comes to pick it up. After the goods have been brought to their destination the containers are brought back to the Port of Rotterdam (often empty) where they will wait in the empty depot or the terminal for a ship to take them back to South America to get a new load of products and start over again. Figure 3.1 shows the complete overview of this supply chain. The rest of this chapter will explain the supply chain more in-depth and will focus on a smaller scope of this supply chain namely what happens in the Port of Rotterdam. Figure Figure 3.2 shows where the ECT Delta, that this research will focus on, lies in the Port of Rotterdam.

3.1.1. Into the Port

Before focusing on the criminal supply chain it is important to know how the legal supply chain works, especially since the criminal supply chain often makes use of this legal route. The legal supply chain starts off with containers getting filled with goods in South America. When the containers are transported to a port, they are loaded onto big container ships that will travel to a port in Europe. This trip takes about two to three weeks before they reach Europe. This research will focus on the Port of Rotterdam. Before they arrive in the Port, the ships need to notify when they will arrive 72 hours in advance so the load can be cleared by customs. This is done by specifying the container numbers and their unique pin code. This is also the time when they will hear which containers will be checked with a communicated check. Once they arrive it can take anywhere from 2 hours to 2 days until all containers are loaded off the ship and have a place in the terminal. The containers are removed from the ship by large cranes called quay cranes (QC). Depending on which terminal the ships arrive at, the crane

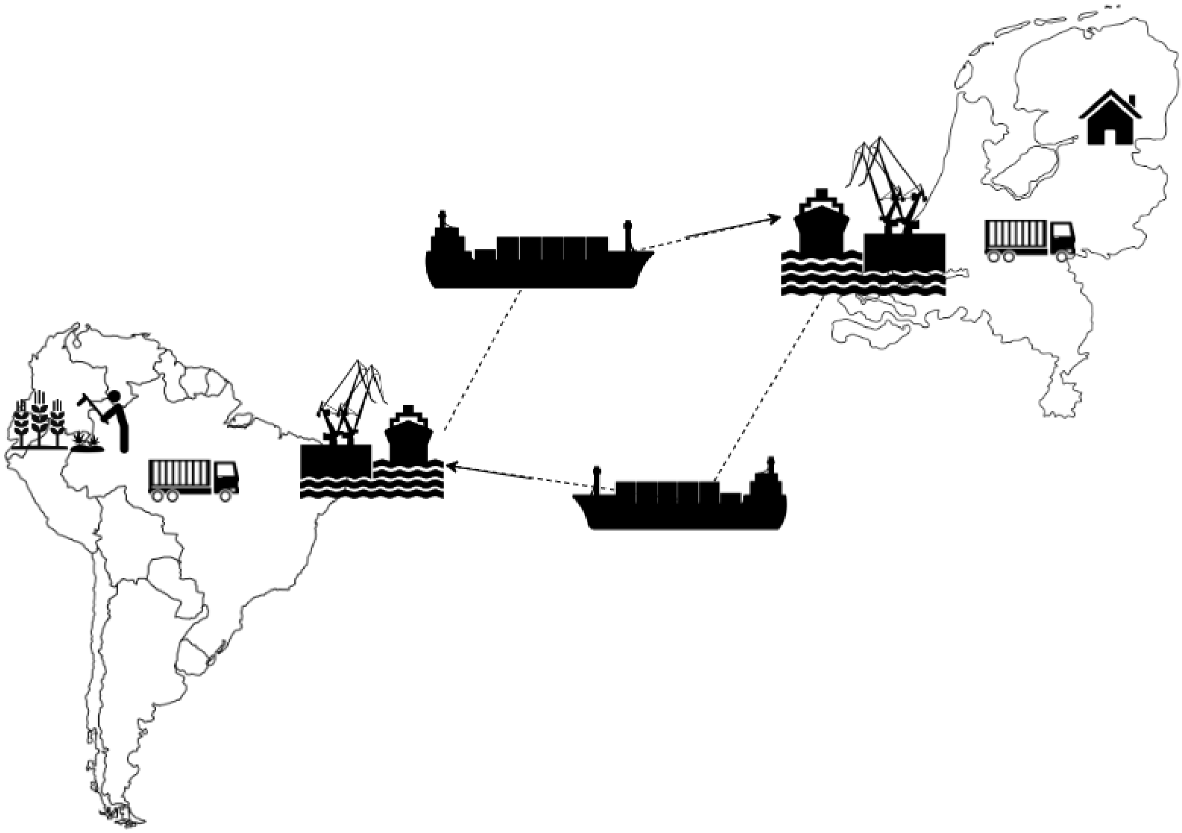


Figure 3.1: Overview supply chain (inspired by van der Plas (2022))

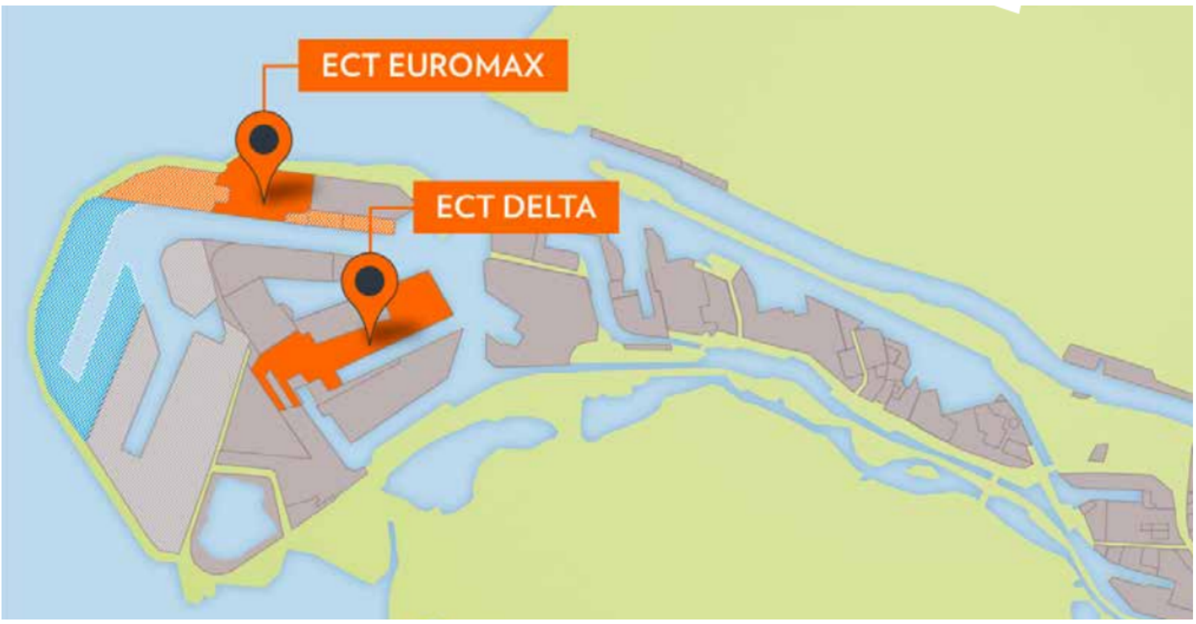


Figure 3.2: Europe Container Terminals in the Port of Rotterdam (from Rotterdam (2019))

is either operated automatically by people behind cameras or manually by people on top of the crane. The ECT Delta terminal is controlled manually by people on top of the crane. From this crane, it is transported to its place in the terminal with an automatic vehicle that brings the container to its spot in the terminal.

3.1.2. Inside the Port

The place in the terminal where a container is placed is determined by whether or not it has to be cooled and what its next type of transportation will be. Containers that will go further by train will be set next to the railway, containers that will continue on a smaller ship to go into the country will be put together and containers that will continue by truck are placed together. This research will focus on the containers that will continue their route by truck. Cool containers, also called reefers, will be placed together to make it easier to keep them cool and repair anything if needed. The containers will be transported from the quay cranes to the right terminal stack using automated guided vehicles (AGV) that bring the containers to the automatic tackling cranes (ASC) that then put the containers in the right spot. When the containers are in the terminal they can either be checked by customs or not. When they are checked, they are digitally blocked until the test results come back negative. If the test results are positive or suspicious the container will be checked manually. To determine whether or not a container will be checked is based on a risk analysis that is performed on each container. There are different ways to check a container. Most of the checks are performed using a scan. Each terminal has its own scan. Most scans include X-ray techniques and reflection (backscattering), which provide 3D information on the load where artificial intelligence helps to analyse the content of the container (van der Heijden, 2022). Other methods include using dogs to sniff containers, separating a container to manually check it from the outside and if needed inside or taking samples of the scent so dogs or a machine can check the scent later on.

3.1.3. Getting out of the Port

The company that ordered the container will hire a truck driver to pick up the container from the terminal and drive it to the company that needs it. In order to pick up the container, the container number and its pincode are needed. Depending on the terminal the truck drivers can either go up to the terminal the get the container themselves or have another employee get the container for them with a straddle-carrier (SC) to put it onto the truck. In the ECT terminal, this happens with a human-operated straddle carrier. For the overview of the different steps in the terminal, see Figure 3.3. When the container returns to the port it is often empty and will go to an empty depot to wait for a ship to take it back to South America. When the ship is expected to take the container, the container will either go to the empty stack or back in the terminal for a short amount of time so it will be ready for the ship to pick it up. This way the container can be filled again in its destination and the journey can start over.

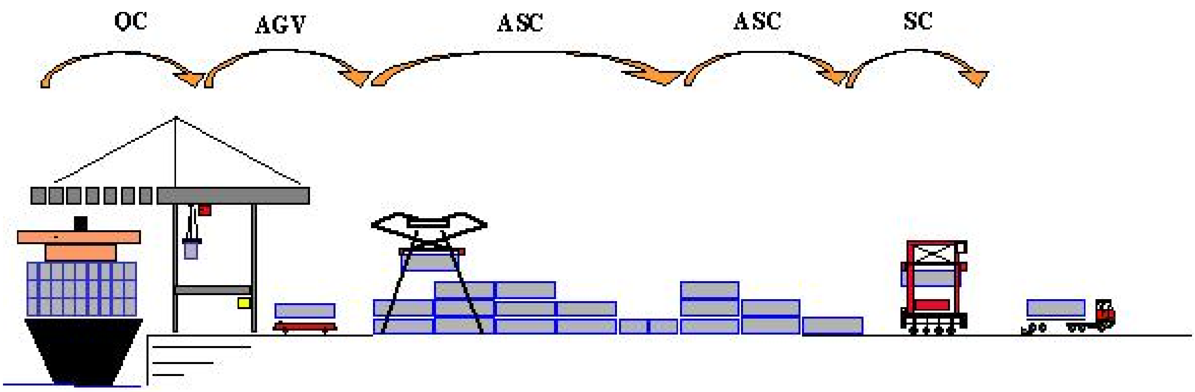


Figure 3.3: Overview ECT terminal from Europe Container Terminals (2023)

3.2. Smuggling methods

This research will focus on the rip-off method where criminals use the legal supply chain to smuggle illegal goods, often without the shipping company knowing this. Criminals make use of different smuggling methods for getting illegal goods out of a legal container without anyone noticing. The following sections will explain the most commonly used smuggling methods.

3.2.1. Pincode fraud

The first smuggling method that is often used in pincode fraud. This means that criminals need information from inside to know the pincode of the container they need. They then need to bribe a truck driver to pick up that container. This truck driver needs to be at the Port to pick up this container before the actual legal truck or other legal transportation is there to pick it up. The bribed truck will then bring the container to a place where the illegal goods can be removed. After this extraction, the container can either be brought to the designated company as perceived by the bribed truck driver or returned to the port.

3.2.2. Switch

In this case, criminals want to move illegal goods from one container to another while still being in the terminal. This often happens with Trojan horse containers, meaning that a truck driver drives a container inside the terminal with people inside it. The criminals will come out of this container when they think no one will see them and they will switch the load from one container to another container that the criminal organisation has in its control. For this method, criminals will need to know the exact location of the container containing illegal goods. They will preferably have a bribed planner plan their Trojan horse container close to the full container.

3.2.3. Extraction

It is also possible that the illegal goods get removed from the terminal right away. This often happens when bribed port employees go to connect the cooling containers and quickly extract some bags of illegal goods from these or other containers as well. This smuggling method is used when there are illegal goods inside of the cooling compartment or in (sports) bags in other containers in such a way that the illegal goods can quickly be removed. The bribed port employees then have to take these bags in their work van and quickly move them to their own car to take them outside of the Port. The transition of the work van to their own is an action that could be seen on camera by other port employees and is therefore visible by surveillance. Since the illegal goods can be extracted before they can be scanned or before they can be checked after a positive scan result, the scanning method will not catch this method depending on how fast these bribed employees are able to extract.

3.2.4. Empty depot

The empty depot is the place on the Port where containers go if they are empty or need to be repaired. This is a place where containers are stored that are not expected to be needed for a while. It is a place where fewer people work and can therefore be attractive to criminals or bribed repairmen. In this method, these bribed repairmen or criminals can extract illegal goods out of the structure of the container. A tricky part of this smuggling method is that containers do not always end up in the empty depot. Criminals could take their chances, but if they want to make sure the container that they need will end up here, they will need to bribe a planner.

3.3. Law enforcement agencies

To know the effects of different methods that the law enforcement agencies have in the Port of Rotterdam it is first necessary to know which method they currently have and which parties are involved in this process. To counteract the smuggling of illegal goods Customs first performs a risk analysis on containers and ships which determines which container to check with the help of scans or dogs (Douane, 2023). If these inspections result in suspicion of illegal goods, the Hit and Run-Cargoteam (HARC) will take over. This HARC team consists of Customs, the Police, the prosecution and the Fiscal Information and Investigation Service (Douane, 2023). Figure 3.4 shows an overview of the most important parties that are involved in catching illegal goods in the Port of Rotterdam. From these parties, the Police is responsible for fighting crime while Customs supervises the transport of goods and performs inspections. The HARC team specialises in investigating illegal goods and criminal networks. The Port Company Rotterdam is responsible for the safety and planning of the Port while the Port Terminals are responsible for the safety of the terrain of the Port (Port of Rotterdam, 2021).

Figure 3.4: Info graphic law enforcement agencies (modified from Port of Rotterdam (2021))

3.4. Process of catching illegal goods

In an interview with Nicolle Coenen who is part of the HARC team done by Davidse (2022), Coenen explains that most findings of illegal goods happen because of inside information that Customs gets from their international collaboration. If the HARC team receives a tip for a suspicious container, a so-called A-inspection takes place. This means that law enforcement agencies will inspect this container with the scan, dogs and people who will unpack the content of the container to inspect it. However, Coenen also mentions that their tips are not always this specific. In that case, the HARC team can walk on the ship with a dog in the hope that this dog will smell the illegal goods in one of the containers or in the compartments of the ship. Other ways of finding illegal substances are when the HARC team notices pincode fraud before it happens or when someone spots extractors (Davidse, 2022).

Other kinds of measures to catch or prevent the smuggling of illegal goods include keeping a close eye on the employees working in the Port. Terminal companies take countless measures including camera surveillance, searching clothes when people leave the terrain, checking who checks which system and when and using dogs to sniff personal lockers. This is because research shows that the smuggling of illegal goods is not possible without inside help (Pals, 2023). Especially employees that can directly influence the planning of the containers or have access to the pincodes of containers are attractive for criminals, where bribes can run up to hundreds of thousands of euros (Pals, 2023). Next to checking the employees, trainings are given to help the employees become more resilient against criminal networks who try to get these employees involved in their criminal activity (Pals, 2023).

3.5. Methods to catch illegal goods

Custom owns modern investigative techniques such as cameras, drones, scans and endoscopes which can look into a container (van der Werff, 2023). However, regional director of Customs Jan Kamp also emphasises that it is a job where humans are needed for the diving team that looks underneath the water if there are any illegal packages welded to a ship and for looking to see if there are any extractors in the terminal who are trying to smuggle illegal goods (van der Werff, 2023). Kamp claims that in order to stop the illegal trade the Police and Customs need to catch 70 to 80 percent of the illegal goods because then the costs will become too high for criminals to continue (van der Werff, 2023). According to expert knowledge, there are several options that law enforcement agencies can make use of. These methods include the scan, using dogs, walking around and looking inside the container and using scent samples that can later be checked by a dog or a machine.

However, often these methods are used to check a container after the scan results show a reason to suspect illegal goods. That is why for this research all these methods are included as one method namely the scan. The ECT Delta has its own container scan (Hutchisonports, 2018). Next to scanning containers, it is also important to focus on surveillance of the terminals. The camera surveillance has been extended and now Customs, the Police and the Portmaster can check the camera live (Pals, 2023). together with looking at cameras, there are also cars driving around looking out for suspicious behaviour. Since there is very little public data available on how most methods work in detail only two methods are used in this research. These two methods include the scan and surveillance. These methods are a combination of smaller methods. The scan method also includes all methods which are used to check the container after the scan results come back positive, and the surveillance method includes surveillance by cameras and surveillance by cars.

Due to the limited available data, the accuracy of these methods is estimated as can be seen in Appendix A. Therefore, the accuracy should not be seen as valid but is only used to show behaviour. For this research, the accuracy of the methods from law enforcement to capture illegal goods smuggled with the smuggling methods of criminals need to be linear with the distribution of resources appointed to the method of law enforcement agencies. The accuracy of the scan method is assumed to be 0.18 for smuggle methods that can be caught by the scan and 0 for the remaining smuggle methods. This means that a container with illegal goods and a smuggling method that can be caught by the scan has a chance of 0.18 to be caught. The surveillance method is assumed to be accurate for 80 percent when all resources are appointed to this method for the smuggling methods that can be caught by surveillance. Meaning that when an illegal container is smuggled with a method that can be visible, these illegal goods have a chance of 0.8 to be caught if law enforcement agencies fully focus on the surveillance method. When looking at the previously mentioned smuggling methods it becomes clear that some smuggling methods cannot be caught by both methods of law enforcement agencies. This is because the pincode fraud method does not have a component where criminal activity can be spotted by surveillance by car or camera and other smuggling methods extract illegal goods before the scan can detect them. The following chapter will explain what these accuracies mean for the interaction between criminals and law enforcement agencies.

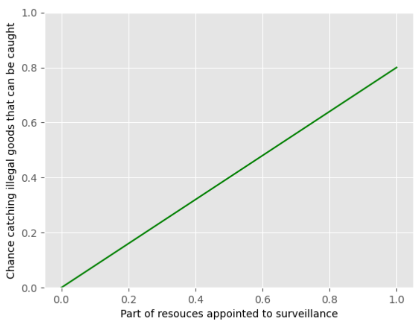
4

Game theoretical analysis

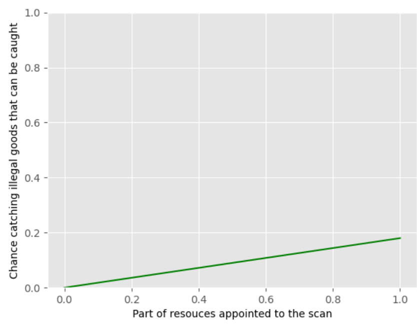
This chapter will explain how the situation between law enforcement agencies and criminals can be seen as a game when analysed using game theory. This chapter will include the methods from law enforcement agencies and criminals as seen in chapter 3 in a game format so it can be analysed. This chapter also calculates the Nash equilibrium of this game as explained in chapter 2.

4.1. The interaction as game

The methods from law enforcement have a certain accuracy that depends on the distribution of resources between the two methods, as seen in chapter 3. This relationship between the part of resources attributed to a method and its accuracy is assumed to be linear to enable mixing methods similarly to that of a mixed Nash equilibrium. These linear relationships between the accuracies and the part of the resources appointed to a method can be seen in Figure 4.1. Mind that the plots in Figure 4.1 are only applicable to the criminal methods that can be caught by that method of the law enforcement agencies. This means that for the combinations where a method from law enforcement agencies is not able to capture a smuggling method this linear relationship is just a zero, independent of the amount of resources appointed to the method of the law enforcement agencies, meaning that the graph of the chance to catch this criminal method is also zero. To structure the interaction between law enforcement agencies and criminals as a game, a bi-matrix game is shown in Table 4.1. The numbers inside this matrix represent the payoff for both players. This payoff is assumed to be the same as the chance of illegal goods getting caught for each combination of smuggle and law enforcement methods in the situation where only these methods are played. For law enforcement agencies these chances are positive and they will want to maximise their payoff. For criminals, the payoffs are the negative chance of illegal goods getting caught as goods getting caught is not desirable by criminals. Criminals will therefore try to minimise their negative payoffs in this zero-sum game. In this matrix, it is also visible which combinations of methods have no chance of catching any illegal goods.



(a) Chance of catching visible criminals with surveillance



(b) Chance of catching illegal goods with a scan

Figure 4.1: Chance of catching illegal goods per police method for criminal methods that can be caught using that method

Methods	Pincode fraud	Switch and pincode fraud	Extraction	Empty depot
Scan	0.18 , -0.18	0 , 0	0 , 0	0.18 , -0.18
Surveillance	0 , 0	0.8 , -0.8	0.8 , -0.8	0.8 , -0.8

Table 4.1: Game visualisation of smuggling methods and methods to catch illegal goods

In Table 4.1 the methods of law enforcement agencies are displayed in the rows and the methods of criminals are displayed in the columns. Per combination of methods the table first shows the payoff of the law enforcement agencies then the criminal payoff which is negative value of the payoff of law enforcement agencies. Noticeable is that given these payoffs that represent the chances of illegal goods being caught inside the matrix, one smuggling method is never a better option than the others, namely the empty depot method. This is because this method can be caught by the scan and by surveillance with the same chances as other smuggling methods, while all other smuggling methods can only be caught by one of the two. Criminals are always better off not choosing the empty depot method. This is because when law enforcement agencies appoint all their resources to one method, criminals are better off choosing a method that cannot be caught by the method of law enforcement agencies and when law enforcement agencies use both their methods, criminals are still better off using another method as this has a lower chance to be caught than the empty depot method as this method can be caught by both law enforcement methods. This means that there is no rational explanation based on these chances to apply this method for criminals. The second observation to consider is that the switch and pincode fraud method and the extraction method have the same chances of getting caught, meaning that these methods are interchangeable. Therefore it would make sense to only include one of these methods as a dominating method. As for the methods of the law enforcement agencies, both methods provide different chances of catching illegal goods for different smuggling methods and most importantly for smuggling methods where one method is not able to catch anything, the other method does have a chance to catch the illegal goods, making them both interesting dominant methods.

Variable	Explanation
D_x	Part resources appointed to method x, where x can be scan, surveillance, pincode fraud, switch, extraction or empty depot
$E(p)$	Expected value of p, where p can be the payoff of any method
U_x	Payoff of x, where x can be scan, surveillance, pincode fraud, switch, extraction or empty depot
$P_{a,b}$	Chance of catching a with b, where a can be pincode fraud, switch, extraction or empty depot and b can be scan or surveillance
$C_{a,b}$	Number of containers with illegal goods and smuggle method a that are caught by b, where a can be pincode fraud, switch, extraction or empty depot and b can be scan or surveillance
T_s	Number of containers using smuggle method s, where s can be pincode fraud, switch, extraction or empty depot

Table 4.2: Explanation variables used in equations

4.2. Payoff calculation

The payoff of the criminal smuggling methods is determined by this chance of getting caught per smuggling method in combination with a law enforcement method times the part of resources appoint to that law enforcement method plus the chance of getting caught for the combination of the smuggle method and the other law enforcement method times the part of resources appointed to that law enforcement method. One example of the expected payoff can be seen below in Equation 4.1 where it shows that the expected payoff of the pincode fraud method of criminals is the chance of pincode fraud being caught by the scan times how much the scan is used plus the chance of pincode fraud being caught by surveillance times the part of the resources of law enforcement agencies that is appointed to surveillance. In

Table 4.2 the explanation of the variable names can be found.

$$E(U_{pincode}) = D_{scan} * P_{pincode,scan} + D_{surveillance} * P_{pin,surveillance} \tag{4.1}$$

For law enforcement agencies, the payoffs are calculated similarly yet oppositely to the payoffs of criminal methods. In this case, the payoff of one law-enforcing method is the sum of the part of resources appointed to each smuggling method times the chance of catching this smuggling method with the law-enforcing method. One example of the expected payoff for a method of law enforcement agencies can be seen below in Equation 4.2. There it shows that the expected payoff of the scan method is the part of criminal resources appointed to the pincode fraud method times the chance of catching the pincode fraud method with the scan plus the part of criminal resources appointed to the switch method times the chance of catching the switch method with the scan plus the part of criminal resources that is appointed to the extraction method times the chance of catching the extraction method with the scan plus the part of criminal resources appointed to the empty depot method times the chance of catching the empty depot method with the scan.

$$\begin{gathered} E(U_{scan}) = D_{pincode} * P_{pincode,scan} + D_{switch} * P_{switch,scan} \\ +D_{extraction} * P_{extraction,scan} + D_{emptydepot} * P_{emptydepot,scan} \end{gathered} \tag{4.2}$$

4.3. Nash equilibrium

As described in chapter 2 if both players play rationally, this game will converge to the Nash equilibrium. The Nash equilibrium is the equilibrium point where no player can get a higher expected payoff without a change in the other player's action. This means that appointing the resources according to the Nash equilibrium is the best response when the other play is distributing their resources according to this equilibrium as well. To calculate the distribution of resources for one player in the Nash equilibrium, the expected payoffs of the different dominant methods of the other player are equalised. As explained before, the dominant strategies for criminals are pincode fraud and the switch, because since the switch and extraction methods are interchangeable only one is chosen. For law enforcement agencies these methods include both the scan and the surveillance method. For the distribution of resources among the methods of law enforcement agencies, an example of the calculation is shown in Equation 4.3 where the expected payoff of the pincode fraud method is equalised with the expected payoff of the switch method which makes it possible to know the distribution of resources of law enforcement agencies. As law enforcement agencies only have two method the part of resources appointed to surveillance is equal to one minus the part of resources that is appointed to the scan.

$$\begin{gathered} E(U_{pincode}) = E(U_{switch}) \\ = \\ D_{scan} * P_{pincode,scan} + D_{surveillance} * P_{pin,surveillance} = D_{scan} * P_{switch,scan} + D_{surveillance} * P_{switch,surveillance} \\ = \\ D_{scan} * 0.18 + (1 - D_{scan}) * 0 = D_{scan} * 0 + (1 - D_{scan}) * 0.8 \end{gathered} \tag{4.3}$$

This Equation 4.3 results in the part of resources appointed to the scan being equal to 0.8 / (0.18- -0.8) which is equal to the fraction 40/49. This means that of the resources available 40/49 should go to the scan, which automatically means that 9/49 of the resources of law enforcement agencies should go towards surveillance. A similar calculation for the smuggling methods, where the expected payoff of the scan is equalised to the expected payoff of the surveillance method, results in a distribution of 40/49 of the containers containing illegal goods having the smuggling method pincode fraud and 9/49 of illegal containers using the switch method. Keep in mind that since the switch and pincode fraud method and the extraction method are interchangeable there are an infinite number of Nash equilibria that divide this 9/40 between these two methods. In this Nash equilibrium, the expected payoff for law enforcement agencies is 36/245 which is around 0.147, for criminals this automatically means that the expected payoff is - 0.147.

4.4. Sensitivity

With the values provided in Table 4.1, a sensitivity analysis can be done to see how the expected payoff would change for law enforcement agencies when the accuracy of a method would increase by 10%. Next to showing how sensitive this Nash equilibrium is to these subtle changes, this is also interesting for law enforcement agencies to see which accuracy would be worth investing more resources into once more resources become available. Table 4.3 shows the expected payoff for law enforcement agencies when one accuracy of one method is increased by 10%. Since the expected payoff for criminals is equal to the negative payoff of law enforcement agencies, this payoff is not shown. Table 4.3 shows that using the accuracies as estimated in this research the expected payoff would be 0.09 higher when the accuracy of the surveillance increases compared to when the accuracy of the scan method increases. Therefore based on these estimated accuracies it would be recommended to invest any extra resources into improving the accuracy of the surveillance method. However this could be the results of the fact that a 10% increase in accuracy of the surveillance method means a rise of 0.08 while a 10% increase in the scan method means an increase of 0.018. Therefore Table 4.4 shows that expected payoff in the Nash equilibrium when the methods are individually get their accuracy increased 0.1. In this case, investing in the scan would result in a higher expected payoff for law enforcement agencies. Thus, where to invest in depends on how law enforcement agencies are able to invest.

Table 4.3 also shows the expected payoff when criminals improve the accuracy of one of their methods, this means that the chance of catching illegal goods using this smuggling method decreases by 10% for both the scan and surveillance. Noticeable is that when criminals would improve their empty depot method, the Nash equilibrium would not change as this method is still worse than their other methods and therefore will not be used. As expected improving the switch method or the extraction method results in the same expected payoff which is only a little better for criminals than the expected payoff in the original Nash equilibrium. Since criminals prefer a lower expected payoff of law enforcement agencies, meaning a higher expected payoff for them, the pincode fraud method is the method which they are most likely to improve upon. Therefore law enforcement agencies should be mindful of this pincode fraud method and whether it is changing and not blindly only improving their one of their methods as the surveillance method can not catch pincode fraud. These tables also show that as expected, the expected payoff will change even with a small change in the accuries. As the accuracies of these methods are uncertain, more research is needed before determining where law enforcement agencies should invest in.

Test	Payoff law enforcement agencies
Base case	0.147
Increasing accuracy scan	0.159
Increasing accuracy surveillance	0.249
Increasing accuracy pincode fraud	0.135
Increasing accuracy switch	0.144
Increasing accuracy extraction	0.144
Increasing accuracy empty depot	0.147

Table 4.3: Expected payoff when increasing the accuracy by 10% for one method

Test	Payoff law enforcement agencies
Base case	0.147
Increasing accuracy scan	0.207
Increasing accuracy surveillance	0.150

Table 4.4: Expected payoff when increasing the accuracy with 0.1

5 Model implementation

This chapter will explain in-depth how the criminal supply chain and the method of criminals active in the Port of Rotterdam and the method of law enforcement agencies as seen in chapter 3 is implemented into the agent-based model. A more detailed list of all choices that are included in the model can be found in Appendix A and all input and output variables can be seen in Appendix B. The agent-based model in this study is made using NetLogo. NetLogo is one of the most popular open source-based software toolkits for individuals to build agent-based models (Rand & Stummer, 2021). As explained in the chapter 2) agent-based models are models that make use of micro-level processes from which higher-level patterns can emerge. Therefore this chapter will explain which process the agents go through, first by giving an overview and then by a detailed explanation of the different steps.

5.1. Overview

The agent-based model of this research focuses on the part of the supply chain that is set in the Port of Rotterdam. It most closely shows the throughput of containers that come into the Port of Rotterdam and leave the port on a truck, 56% of containers leave on trucks from the Port of Rotterdam (Havenkrant, 2021). The time steps (so-called ticks) represent one hour and the model will only run for a couple of years. To see how the model looks, see figure 5.1 and figure 5.2, mind that even though the empty depot is displayed inside the Port it is not in the same place as the terminal. To start the model one first has to specify the scenario that the model should start in. The scenarios are based on the different distributions of resources between the methods of law enforcement agencies and criminals and the six different updating rules. Both players can either start the model with only one method, all methods in equal resource distributions or start their resource distributions among their methods according to the Nash equilibrium as explained in chapter 4.

After the scenario has been specified, the model can be started by pressing the setup button and subsequently pressing the go button. When the model starts to run, ships start to arrive on the left of the interface. These ships bring the containers that are imported to Rotterdam. These containers follow the route as explained in chapter 3 until they leave the model when they are picked up by a truck (or other form of transportation). Containers that contain illegal goods will start the process with a selected smuggling method where either a criminal, port employee or repairman will come into the model to smuggle the illegal goods outside the port. In the meantime, the containers that are exported from the Port of Rotterdam arrive on the right side of the interface and will move onto the ship once the import containers have left te ship.

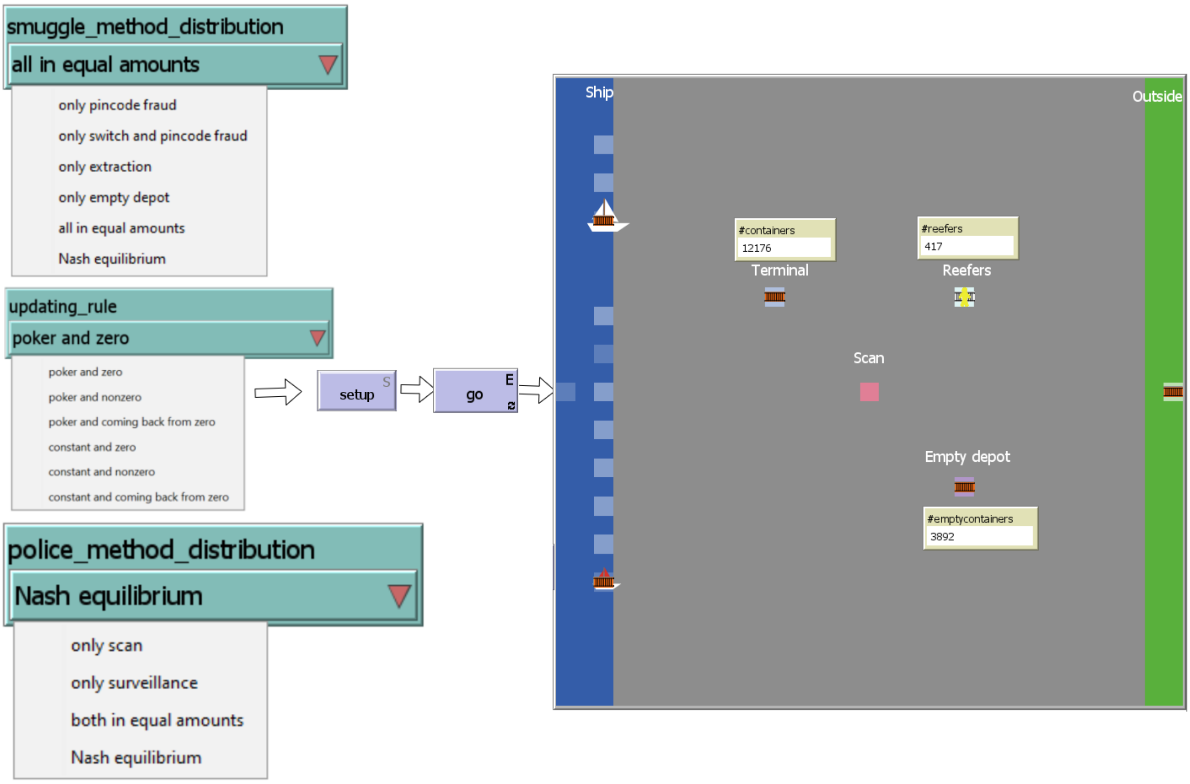


Figure 5.1: Interface of the model

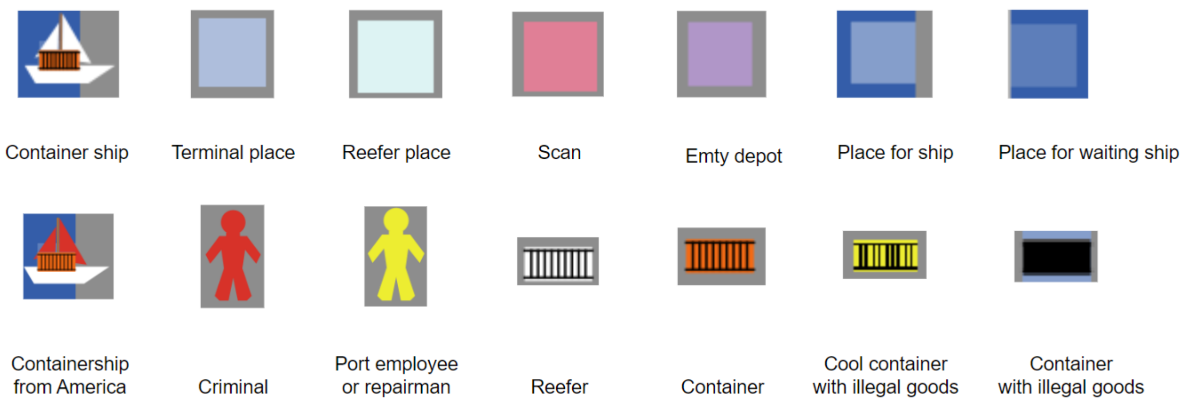


Figure 5.2: Legend of the interface

5.2. Ships arrive at the port

The model starts off with ships arriving at the Port. When ships arrive is random with a uniform distribution. The size of the ship is also randomly distributed according to the frequency among the different sizes. Containers that come from the Port of Rotterdam and are ready to be loaded onto this ship are called export containers. A week before the ships want to arrive in the port, the export containers that will be exported by that ship appear in the model, these export containers can either be full or empty. When they are empty they will start in the empty depot. When they are full they will start outside of the port with a waiting time that is between a week to a day before the ship will actually arrive. Once this waiting time is over the full export containers will move to the terminal. The flow of these export containers can be seen in Figure 5.3.

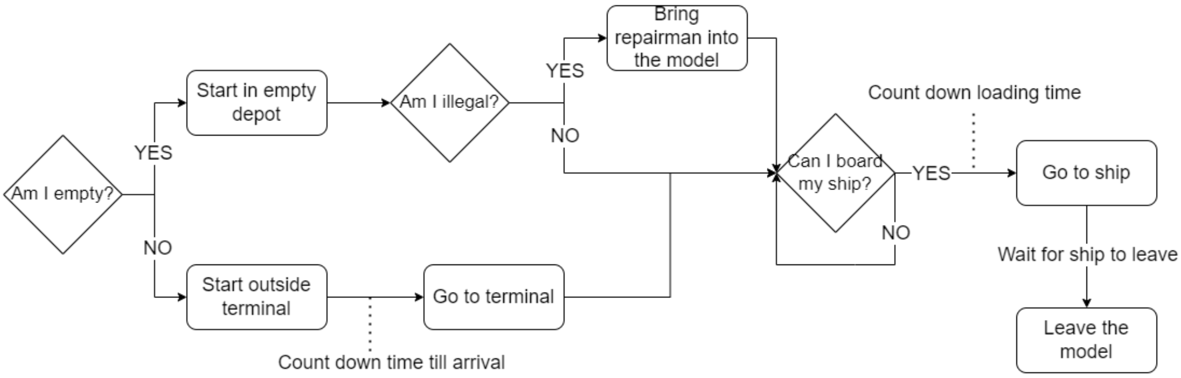


Figure 5.3: Flow chart export containers

When the ship arrives in the port, the import containers appear in the model, the number of import containers depends on the size of the ship. The ship can either be from America or from another destination. When the ship comes from America, the import containers have a chance to contain illegal goods. If a container does contain illegal goods it also needs to determine its smuggling method. This smuggle method is determined randomly based on the distribution of the criminal smuggle method that the model has at that point in time. Figure 5.4 shows how the model determines the smuggling method of every import container, where the chances to get each smuggling method are determined by the current distribution of resources of criminals.

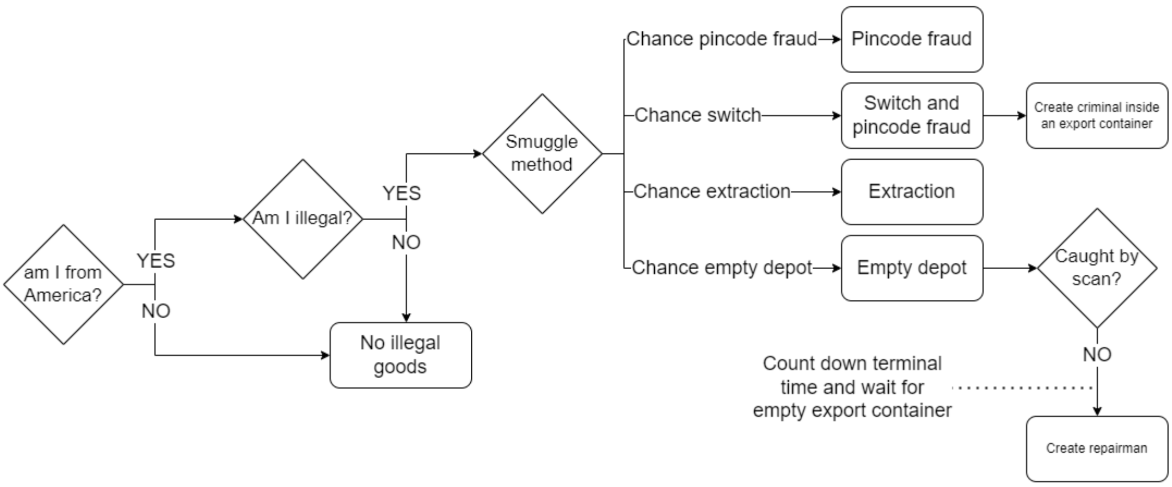


Figure 5.4: Flow chart illegal goods in import containers

Next to determining whether or not a container contains illegal goods, this is also the moment that it is determined in the model whether or not the container will be scanned. Since risk analysis is done by Customs, it is known that containers from America can be a risk and therefore it is assumed that these are also the only containers that the scan will check. Depending on the size of the ship, each import container has a random unloading time uniformly distributed with a maximum equal to the maximum hours it can take to unload the ship. These unloading times count down at the same time and once the unloading time of a specific container is up, it will move from the ship into the port.

5.3. Containers inside the port

Once the import container will move into the terminal. the model first checks if the import container needs to be scanned and whether the scan is free. Containers that need to be cooled are called reefers and they will go to a separate stack in the terminal where a port employee will connect them to electricity. Containers that need to be scanned will move into the scan once it is free and will then move (back) into the terminal where they will be digitally blocked until the results come back. When the results are positive, the container will be checked to see if the illegal goods are still there and can be intercepted. The containers that are not digitally blocked will spend a certain amount in the port until they are picked up and removed from the model. The flow of the import containers can also be seen in Figure 5.5.

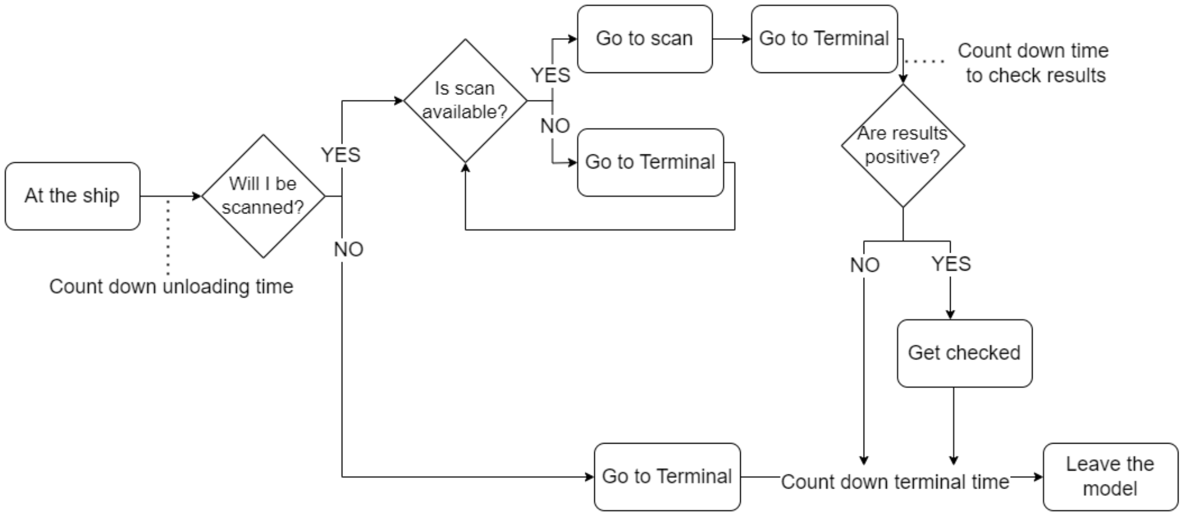


Figure 5.5: Flow chart import containers

5.3.1. Pincode fraud

Containers that contain illegal goods start the process of smuggling these illegal goods when they first appear in the model as can be seen in Figure 5.4. For the pincode fraud method, a bribed truck driver will come to get the import container. Since no one can be visible by surveillance in this method, there is no agent needed to include this smuggling method in the model. Therefore if an import container with pincode fraud is not caught by the scan, it will simply await its time in the port and then it is considered as successfully smuggled.

5.3.2. Switch and pincode fraud

For the switch and pincode fraud method, the process is a bit more complex. In that method, a criminal is smuggled into the port by being inside a container. In the agent-based model, one of the export containers will get a criminal inside which that will go to the import container once both the export and the illegal import container are in the terminal. This is the moment that the criminal is visible by the surveillance and has a certain chance that it will be caught. If this criminal has successfully switched the illegal goods, it will go to another import container that either has already been checked or will not be checked. Since this method also uses pincode fraud, a truck driver will pick up the criminal and the illegal goods soon after the switch. when this import container is picked up and therefore removed from the model, the criminal is removed as well. Figure 5.4 shows that a criminal will appear in the model when this smuggling method is selected for an illegal import container. Figure 5.6 shows the process that this criminal follows.

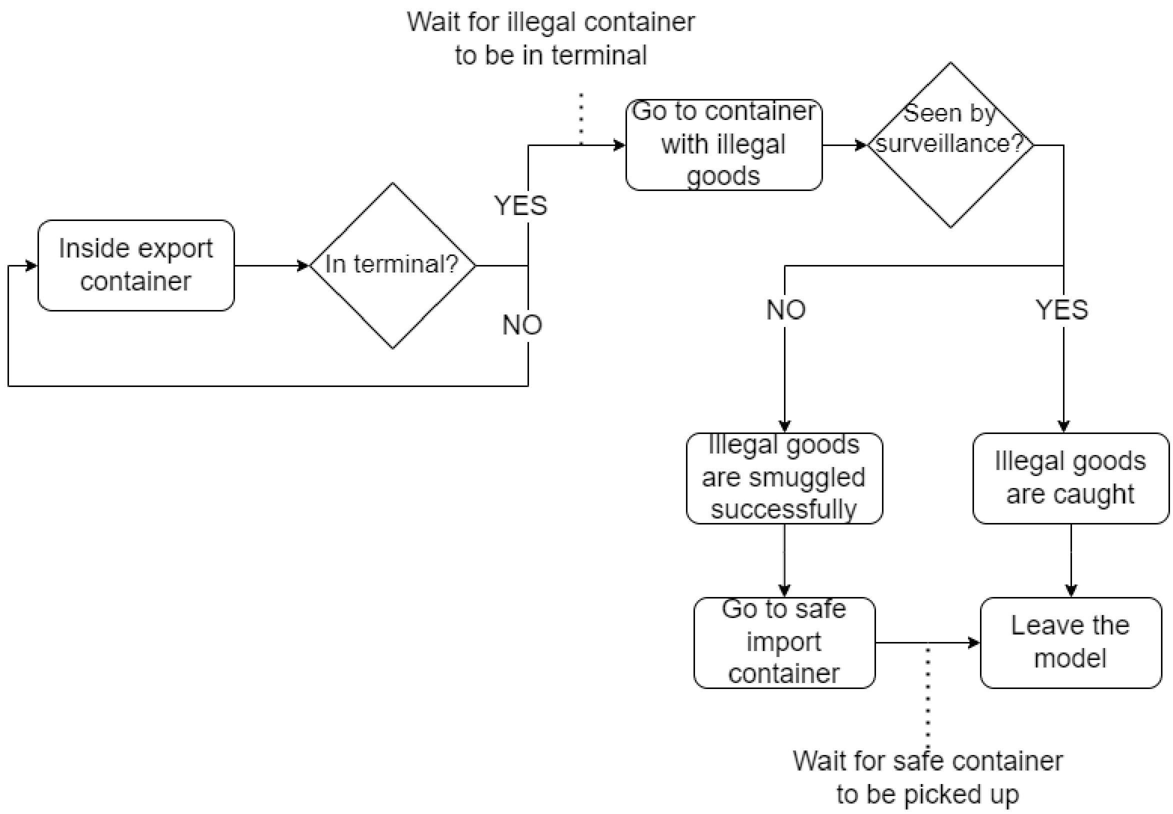


Figure 5.6: Flow chart switch and pincode fraud

5.3.3. Extraction

The extraction method happens when a reefer is connected to electricity by a port employee while illegal goods are inside a container that has been selected to have the smuggling method of extraction. The port employee in the model will check if there is a container that needs to be extracted. It is assumed that criminals will always find an employee that will extract it for them but it can only happen once an employee is there to connect a reefer. When this port employee is extracting it has a chance to be seen by surveillance and therefore a chance to be caught. Figure 5.7 shows the process of the port employees in the agent-based model.

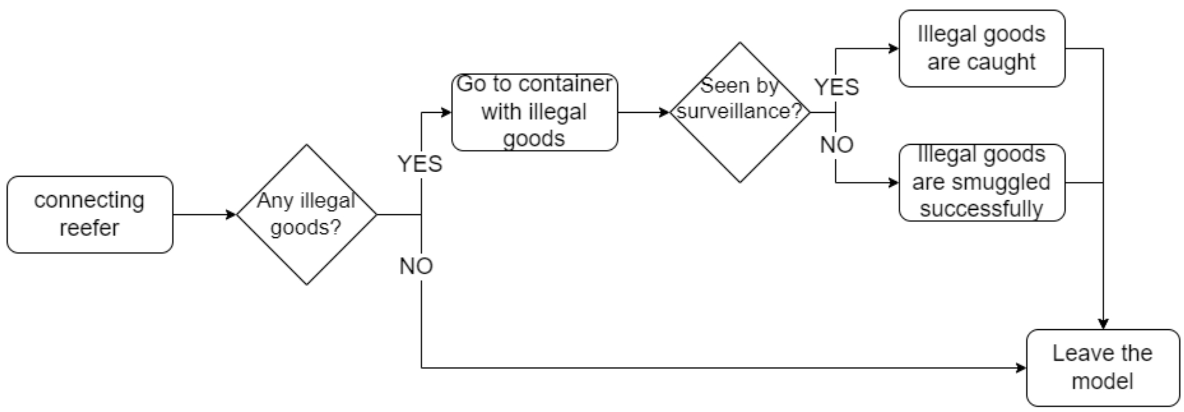


Figure 5.7: Flow chart extraction

5.3.4. Empty depot method

For the empty depot method, the illegal goods are first in an import container where these goods can either be caught by the scan or not. When the import container leaves the model because it is picked up by its truck, the method is not over if the illegal goods are not caught, since they are also not smuggled yet. The model then appoints one export container that has a destination in America to continue this method and contain the illegal goods. When an export container contains illegal goods, a repairman (or criminal) appears in the model as can be seen in Figure 5.4. This repairman comes to extract the illegal goods from the structure of the container. This repairman can then be seen by surveillance which has a certain chance to be caught by surveillance as can be seen in Figure 5.8. When the repairman has tried to smuggle the illegal goods he is removed from the model.

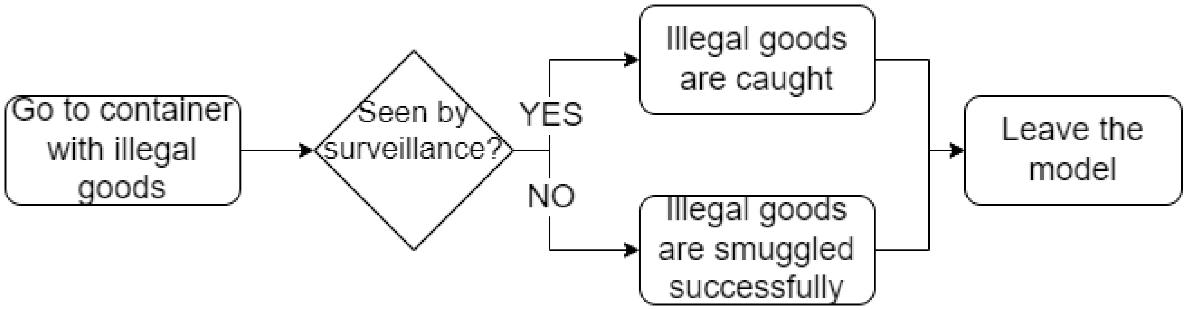


Figure 5.8: Flow chart empty depot method

5.4. Getting out of the Port

Once all its import containers have left the ship, the loading time of the export containers will start to count down as can be seen in Figure 5.3. The loading time of export containers has been determined in the same way as the unloading time of the import containers of that same ship. Once the loading time of an export container has ended it will move to the ship. Once all of its export containers are on the ship, the ship will move out of the port and will be removed from the model. This also means that the export containers that are on the ship will be removed from the model. The place that the ship had occupied then has a small waiting time to ensure the travel of the ship. After this time a new ship can arrive if one is waiting.

5.5. Statistics

The agent-based model updates its statistics every time a container that started with illegal goods is removed from the agent-based model. The model then counts which smuggling method this container used and whether or not it was caught. If the illegal goods were caught by law enforcement agencies it is counted whether it was caught by the scan or by surveillance. All smuggling methods can be measured when the import container is removed from the agent-based model, apart from the empty depot method which returns as an export container. This means that the statistics are updated every time an import container is picked up by its next transportation and every time a ship leaves with export containers from which one export container contained illegal goods. This also means that there is a slight delay in the statistics as a container can be caught earlier but then still passes some time before it leaves the model and updates the statistics. To maintain simplicity in the statistics it is assumed that the smuggle method is always tried once before the container leaves the model and that only one method is used per container. It is also assumed that when smugglers are caught by surveillance, the container with illegal goods will also be caught. The values that the model will report based on these statistics are the payoffs, the distribution of resources and the success rate for every method from criminals and law enforcement agencies, as can be seen in Appendix B.

5.6. Payoff implementation

After each period of four weeks, the model looks at its statistics and calculates the payoffs per method for each player. A period of four weeks is chosen as this is estimated to be a realistic time to evaluate methods as it is not known how often and whether law enforcement agencies evaluate the distribution of resources among their methods in determined periods. This four weeks period is chosen because the agent-based model shows reliable results as can be seen in Appendix C while still ensuring some stochastic behaviour. As this research combines the agent-based model with game theory, the payoffs of each method are calculated in the same way as in chapter 4. The part of resources appointed to a method as discussed in the game theoretical chapter is for criminals translated into the chance an illegal import container will receive this smuggling method. This ensures that this distribution of resources among methods will be represented in an actual distribution of smuggling methods among the illegal import containers. Since the chance of catching a certain smuggling method by a method of law enforcement agencies needs to have a linear relationship with the distribution of resources appointed to this method, for the scan this is implemented with a linear relationship with the distribution appointed to the scan and the number of containers that will go to the scan. For the surveillance method, a linear relationship is implemented in such a way that the accuracy of catching a criminal that is visible by surveillance is linearly dependent on the distribution appointed to the surveillance method as also seen in chapter 4.

The payoffs in the agent-based model need to be calculated the same way as the expected payoff in chapter 4 while using the statistics that come from the agent-based itself to ensure the stochastic behaviour that comes from this more realistic agent-based model. To understand the calculation of payoffs using the statistics of the agent-based model, it is needed to dissect the examples of Equation 4.1 and Equation 4.2 in more detail to see how the numbers in the agent-based model can be used. For the calculation of the payoff of the smuggle methods Equation 5.1, showing the payoff of the method pincode fraud, is shown as an example for all smuggle methods. As an example of the methods from law enforcement agencies, Equation 5.2 shows the calculation of the payoff of the scan method.

Equation 5.1 and Equation 5.2 start off by showing the payoff as explained in chapter 4. Equation 5.1 then shows that the resources appointed to the scan method times the chance of the scan catching a container using the pincode fraud is equal to the statistics of the containers using the pincode fraud method that are caught by the scan divided by the total number of containers that used this pincode fraud method. Similarly for the surveillance method which ultimately means that the payoff of the pincode fraud is the total number of containers with the smuggling method pincode fraud that is caught by either the scan or surveillance divided by the total number of containers with the smuggling method pincode fraud.

$$\begin{gathered} U_{pincode} \\ = \\ D_{scan} * P_{pincode,scan} + D_{surveillance} * P_{pincode,surveillance} \\ = \\ C_{pincode,scan}/T_{pincode} + C_{pincode,surveillance}/T_{pincode} \\ = \\ C_{pincode}/T_{pincode} \\ = \\ (total\ caught\ pincode\ fraud)/(\ total\ containers\ with\ pincode\ fraud) \end{gathered} \tag{5.1}$$

Equation 5.2 shows how the payoff of the scan method can be translated using agent-based model statistics to the total number of containers that the scan caught divided by the total number of containers that contained illegal goods and by the part of resources that is appointed to the scan which is known by the part of the scan that is in use. This is because the payoff of a method should not include the part of resources that is appointed to that method which is included in the total number of containers that the scan caught as this depends on how much the scan is used. Therefore the payoff also divides by this part scan in use so as to not include it in the payoff.

$$U_{scan} = D_{pincode} * P_{pincode,scan} + D_{switch} * P_{switch,scan} + D_{extracting} * P_{extracting,scan} + D_{emptydepot} * P_{emptydepot,scan} = C_{pincode,scan}/(T_{illegal} * D_{scan}) + C_{switch,scan}/(T_{illegal} * D_{scan}) + C_{extracting,scan}/(T_{illegal} * D_{scan}) + C_{emptydepot,scan}/(T_{illegal} * D_{scan}) = C_{illegal,scan}/(T_{illegal} * D_{scan}) = total\ containers\ caught\ by\ scan/\ (total\ illegal\ containers\ *\ part\ scan\ in\ use) \tag{5.2}$$

Notable about these equations is that while the calculation for the smuggle methods only makes use of statistics coming from the simulation model, the calculation of methods from law enforcement agencies still uses a number from the input of the agent-based model, namely the resources appointed to the scan or as it is called in the model the part scan in use. This is a small limitation to increase simplicity in the statistics of the agent-based model. Another thing to keep in mind is that since this situation is structured as a zero-sum game, the payoffs of the smuggling methods should be negative, but for simplicity's sake the payoffs are kept as a positive number in the agent-based model where for the updating rules the payoff of criminals are subtracted from one as to ensure that both players want to maximise their payoffs.

5.7. Updating rules

After each period of four weeks, when the model calculated the current payoffs for each method based on its statistics of the previous period, the updating rule determines how part of the resources will be (re)distributed among the methods for the next period of four weeks. For this research, six different updating rules are tested. The parameters used in these updating rules are a cutoff of 0.01 for rules that are not allowed to have any methods where the part of resources appointed to the method goes to zero and a reoccur value of 0.05 for the methods that come back from having zero resources appointed last period. Every time the agent-based model updates the distribution of resources, law enforcement agencies reappoint 0.1 of their resources and criminals reappoint 0.2 of their resources every period.

Every updating rule starts the process of updating by first trying to subtract a part of the resources that is appointed to each method. From each method the updating rule tries to subtract 0.05 of the total resources for that player, the sum of these subtracted resources will be redistributed among the methods of that player according to the payoffs of the method compared to the total payoff of that player. Therefore law enforcement agencies can reappoint 0.1 of their resources while criminals can reappoint 0.2. The updating rule then calculates the sum of the payoffs per player and redistributes the part of the resources that each player can redistribute according to the payoff of a method divided by the total payoff for that player.

A difficulty arises when there are methods from which it is not possible to subtract 0.05 part of the resources of that player as the method has a smaller part of the resources already. This is resolved in two different ways. The first way is where the updating rule will still subtract the part of the resources that this method does possess, which is lower than the 0.05 part of resources. The updating rule then forms a separate "side pot" where all methods of that player have only subtracted this smaller part of resources and will redistribute this part according to the payoffs of the methods. For the methods from which 0.05 can be subtracted the remaining part is still subtracted and this other 'pot' of resources that can be distributed is only redistributed according to the payoffs of the methods included. This means that in the case that a method has too few resources appointed to subtract this 0.05 the total part of resources that will be redistributed for that player also becomes smaller. As this updating rule corresponds well-known poker game where separate pots can be formed when someone goes ”all-in” this updating rule is called ’poker’.

Another way of dealing with the situation where some methods have too few resources appointed to them to be able to subtract 0.05 part of the resources of that player is by subtracting the remaining part of resources from the other methods evenly. This then ensures that for every period the players have the same part of their resources that they can redistribute among their methods. Since this part of resources that can be redistributed stays the same for each period, this updating rule is called ’constant’. In this rule, all methods are appointed the part of the resources that can be redistributed according to the payoff of the method compared to the total payoff for that player.

Furthermore, it should be specified what happens when a method gets zero resources appointed by the updating rule. When a method is not used, its payoff will be zero and therefore both the ’poker’ updating rule and the ’constant’ updating rule will not appoint any resources to this method for the rest of the model run. The updating rules that allow this to happen are called ’poker zero’ and ’constant zero’.

Another variant that is tested for this situation ensures that methods can never be appointed fewer resources than a certain cutoff value, in this case, 0.01 part of the resources of that player as mentioned earlier. This happens by only letting the updating rule subtract the part of the resources that should be subtracted up until this cutoff value. More can not be subtracted. This variant creates the updating rules ’poker non zero’ and ’constant non zero’. The difference between these updating rules is that when a method only got this cutoff value appointed the ’poker non zero’ updating rule still does not allow this method to receive a bigger part of resources as no part can be subtracted from this method, while the ’constant non zero’ method still redistributes the part of the resources that can be redistributed according to the payoff without taking the current distribution into account.

The last variants create a chance for methods that are appointed zero resources to get reappointed 0.05 part of the resources of a player. Every fourth period of four weeks, this updating rule checks if there is a method that has zero resources appointed and provides it with a chance of 1/4 to get 0.05 part of the resources appointed. This happens after the updating rule has redistributed a part of the resources according to the payoffs of the methods of a player with either the ’poker’ variant or the ’constant’ variant. When a method of a player gets zero resources and is reappointed this 0.05 part of the resources of this player, this part is subtracted evenly from the part of resources that were appointed to the other method of that player. It is possible for multiple methods to reoccur at the same time from getting zero resources appointed. With this variant, the last two updating rules are created, namely ’poker back zero’ and ’constant back zero’. As an overview all updating rules are listed below.

- ’poker zero’
- ’poker non zero’
- ’poker back zero’
- ’constant zero’
- ’constant non zero’
- ’constant back zero’

5.8. Biggest assumptions and simplifications

As previously mentioned all assumptions can be found in the confidential Appendix A. The most important assumptions and therefore the most important limitations of this agent-based model are the assumption that criminals will only attempt one smuggling method, that criminals will always attempt this smuggling method before the container leaves the port and that law enforcement agencies will always find the illegal goods when the surveillance method spots illegal activity in the Port of Rotterdam. Other assumptions include assuming linearity for the accuracies of the methods of law enforcement agencies which, as explained in chapter 4, was needed for this research. Furthermore, some simplifications were made, mostly due to limited data, in terms of random uniformly distributing activities over day and night such as ships' arrival and container pickups by truck while in reality, this will happen more often during the day time.

5.9. Verification & Validation

The agent-based model has been thoroughly verified. Multiple single containers have been checked to ensure that each of them has different and logical values for variables as to which ship they belong, what their waiting times are and whether they are checked when they should be checked by the scan. Furthermore, multiple single runs have been followed carefully all variables have been printed and checked for every step of the mode. However, the most reliable verification is the ones where only one method was used for each player were checked to see if the payoffs resembled the probabilities of the matrix in chapter 4. The results of this verification can be seen in Appendix C where it shows that all payoffs correspond to the ones in chapter 4 meaning that all smuggling methods and law-enforcement methods are implemented correctly. As explained in chapter 2, all assumptions mentioned in Appendix A are validated by an expert. Assumptions that could be improved according to expert knowledge are indicated in the text in Appendix A as differences with reality, but original assumptions are still used in the agent-based model. This is because they were discovered late in the process of this research and are not expected to change the behaviour of the model.

6

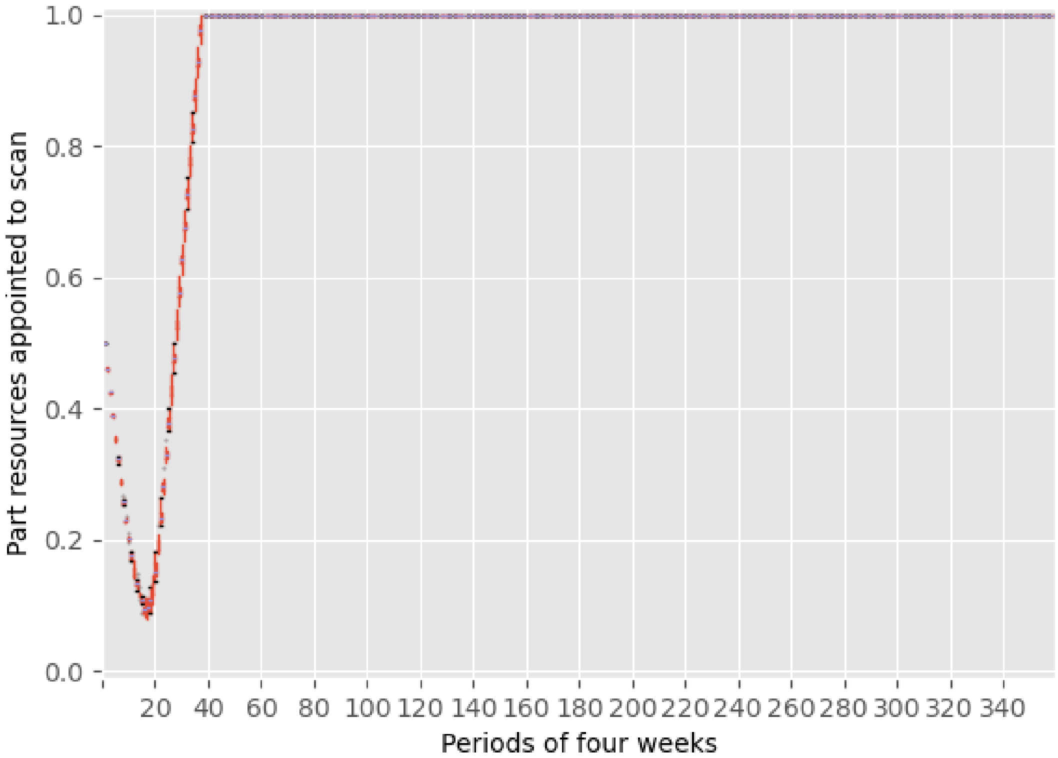
Analysis with agent-based model

This chapter will show the results that come from the agent-based model as presented in chapter 5. The figures are made using a box plot showing the results for each period of four weeks for 8 replications. The boxplot shows the outcome of the model for each period for all replications and shows the median and the interquartile range of the data. This means that the box represents 50% of the data points, and the whiskers show the minimum and maximum data points, without including outliers. A data point is considered an outlier when it is lower than the first quantile minus 1.5 * the interquartile range or higher than the third quantile plus 1.5 * the interquartile range. This chapter shows the output for all six tested updating rules. The parameters used in these updating rules are a cutoff of 0.01 for rules that are not allowed to have any methods where the part of resources appointed to the method goes to zero and a reoccur value of 0.05 for the methods that come back from having zero resources appointed last period. Every update law enforcement reappoint 0.1 of their resources and criminals reappoint 0.2 of their resources every period. More results where these updating rules are tested and all payoffs of results displayed in this chapter can be seen in Appendix D.

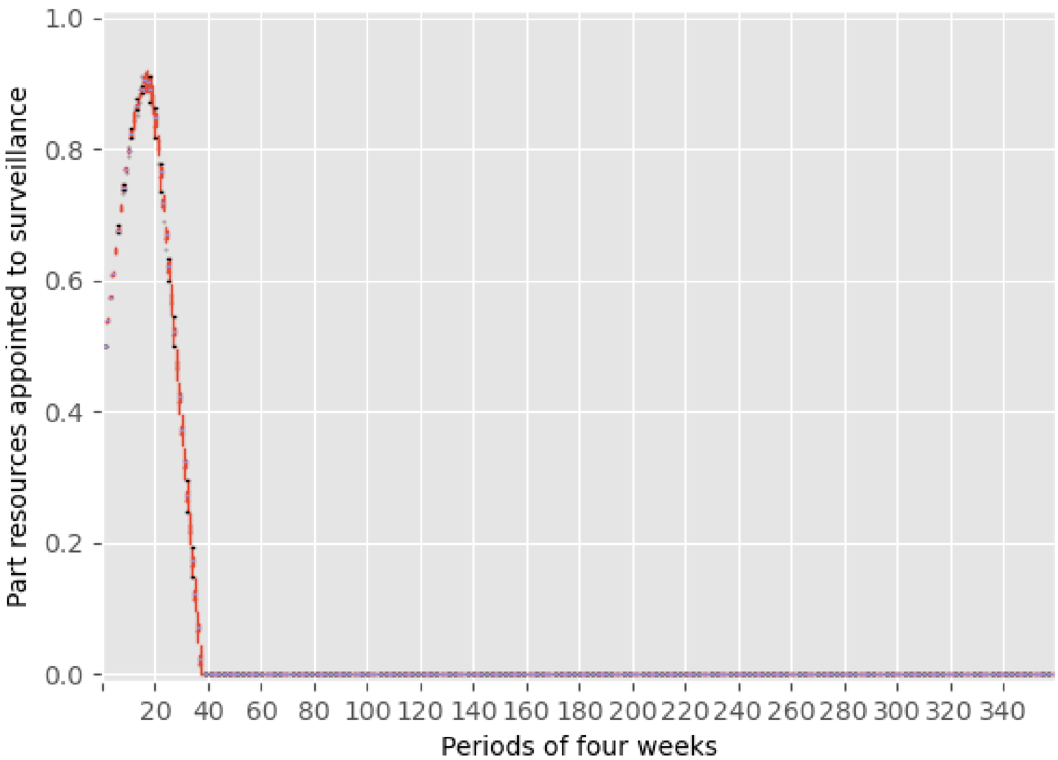
6.1. Poker zero

The first updating rule to look at is the 'poker' rule in this case, it is possible for a method to get zero resources appointed. Figure 6.1 shows the behaviour of the agent-based model when this rule is applied. This figure shows that law enforcement agencies start off by appointing the same part of their resources to each of their methods but that this distribution of resources quickly changes. Immediately law enforcement agencies start appointing more of their resources to the surveillance method. When looking at Figure 6.2 it shows that criminals also quickly adjust their distribution of resources. Figure 6.2 shows that criminals immediately appoint most of their resources to the pincode fraud method. It also shows that a little after the 20th period, criminals are only using this pincode fraud method for the rest of the run time. This is because using the updating rule 'poker zero' ensures that the distribution of resources can no longer be changed once only one method is used.

When looking at the distribution of resources of the law enforcement agencies in Figure 6.1, a clear switch in behaviour is visible a little before the 20th period. This is at the same time that criminals cross the Nash equilibrium as calculated in chapter 4. This can be seen because when the graph of the pincode fraud method of criminals passes 0.816, the graph of the law enforcement agencies shifts completely. From that point, Figure 6.1 changes by appointing more of the part of the resources that will be redistribution from the surveillance to the scan method. This makes sense as the pincode fraud method from criminals can only be caught by the scan method from law enforcement agencies, as seen in chapter 4. Again the agent-based model will no longer be able to change the distribution of resources, this time for law enforcement agencies, with the current updating rule once only one method is used.

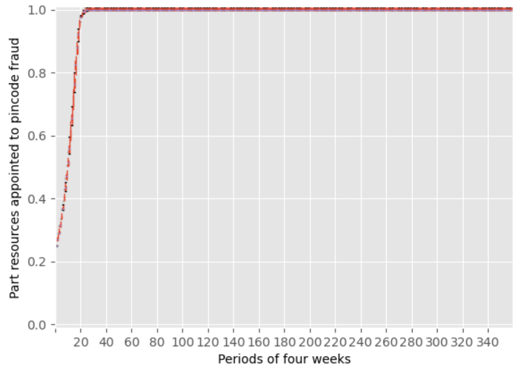


(a) Part resources appointed to scan

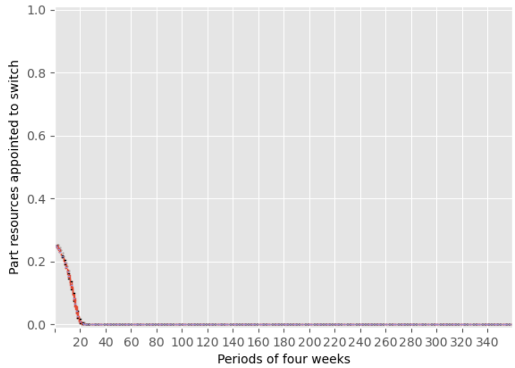


(b) Part resources appointed to surveillance

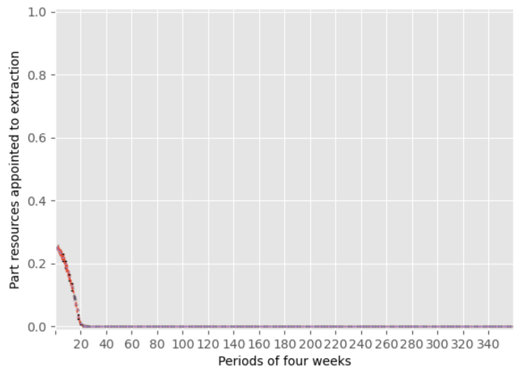
Figure 6.1: Distribution law enforcement agencies methods with poker zero equal



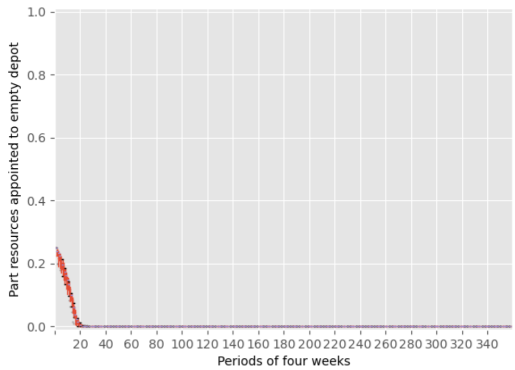
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud



(c) Part resources appointed to extracting

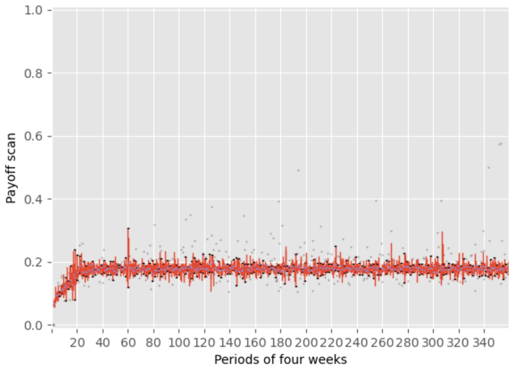


(d) Part resources appointed to empty depot

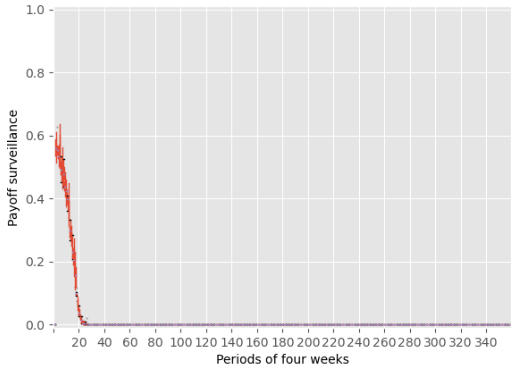
Figure 6.2: Distribution criminal poker zero equal

To explain these graphs, the payoffs are also represented for each method in Figure 6.3 and Figure 6.4. These figures show that the payoff of the pincode fraud method in Figure 6.4 is a lot higher than the payoff of the other smuggling methods, explaining why criminals appoint their resources to this pincode fraud method. Figure 6.3 shows that the payoff of the surveillance methods starts off a lot higher but drops to zero as criminals increasingly use the pincode fraud. These figures also show that once law enforcement agencies appoint more of their resources to the scan method, the payoff of the smuggling method pincode fraud drops. This makes sense as the payoff of the scan method and the pincode fraud method will be around 0.18 and for law enforcement agencies. This corresponds to the payoffs as seen in the matrix in chapter 4. Figure 6.3 and Figure 6.4 also show that a method always has a payoff of zero when no resources are appointed to this method.

Furthermore, Figure 6.3 and Figure 6.4 show that the payoffs of the methods have some outliers. Outliers appear due to the stochastic components in the agent-based model. It is also noticeable that methods with a small part of resources appointed to them have a larger boxplot and more extreme outliers. This can be seen in the methods of the switch, extraction and empty depot around the 20th period in Figure 6.4. This can be explained by the fact that these smuggling methods are only used rarely, meaning that only a few containers containing illegal goods will use these methods. When only a few containers use a certain smuggling method in a period of four weeks, the payoff of this method highly depends on whether these containers are caught or not and therefore gives a less balanced payoff graph.

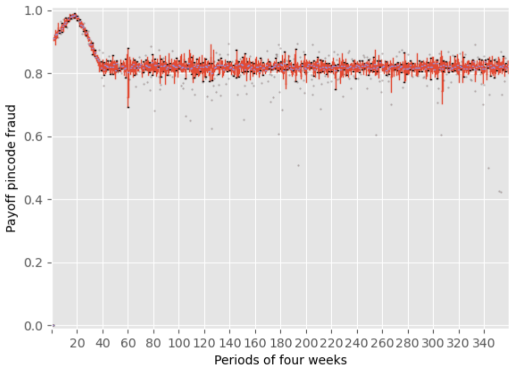


(a) Payoff scan

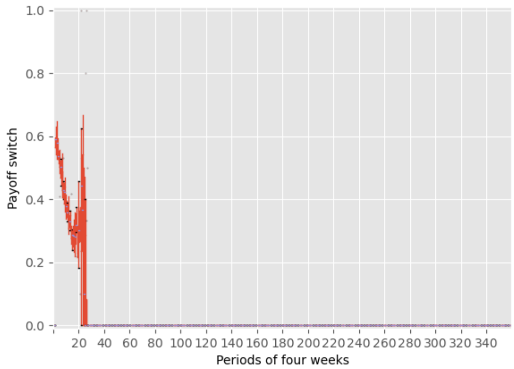


(b) Payoff surveillance

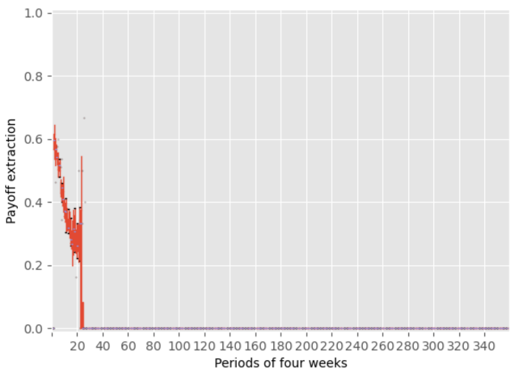
Figure 6.3: Payoff law enforcement agencies methods with poker zero equal



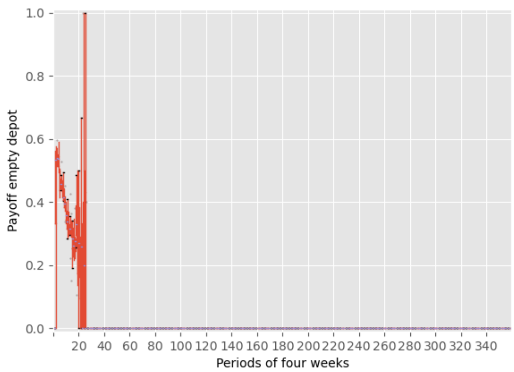
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud



(c) Payoff extracting



(d) Payoff empty depot

Figure 6.4: Payoff criminal poker zero equal

Figure 6.5 shows the success rate of law enforcement agencies, meaning which part of containers that contained illegal goods is caught. The success rate of the criminals is the opposite of this graph as it is one minus the success rate of law enforcement agencies. This success rate confirms that law enforcement agencies need to make a switch around the 20th period, as around this point the success rate decreases rapidly. Since in this scenario law enforcement agencies end up only using the scan and criminals only use the pincode fraud method, the success rate is around 0.18. This is expected as this is the accuracy of the scan when criminals only make use of the pincode fraud method.

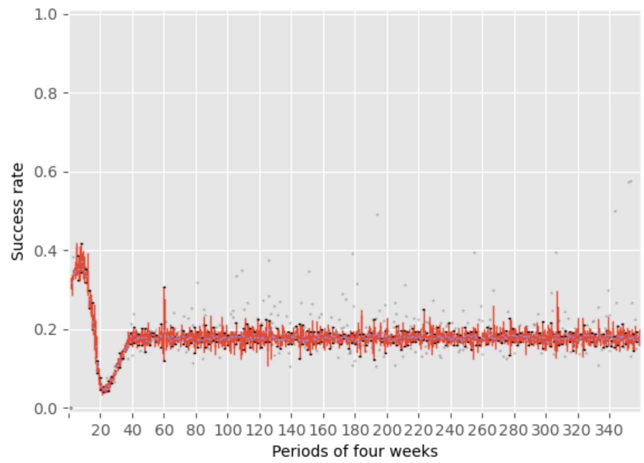


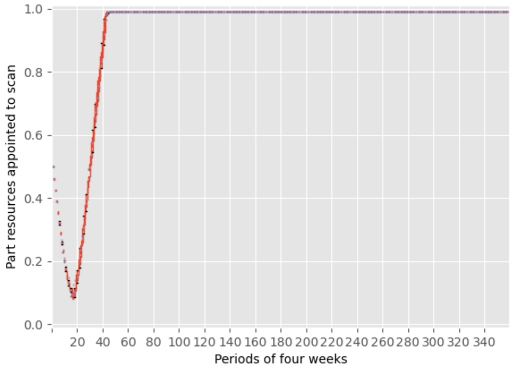
Figure 6.5: Success rate law enforcement agencies poker zero

6.2. Poker non zero

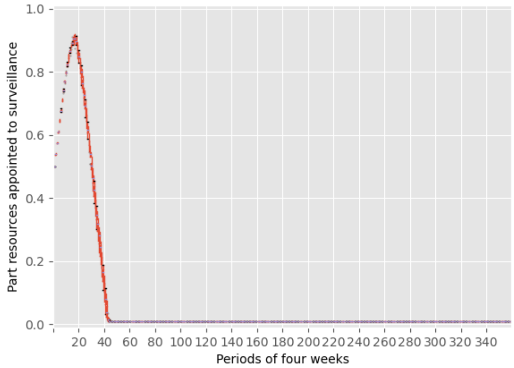
The second updating rule is the 'poker' rule where the part of resources appointed to a method is not able to become zero but is stuck a little above zero. This automatically means that it is not possible for one method to get all resources appointed since the other methods are not allowed to get less than 0.01 part of resources. Figure 6.6 shows the behaviour of law enforcement agencies in the agent-based model when this rule is applied. This figure shows very similar behaviour to Figure 6.1. However, instead of appointing their resources fully to the scan, this time 0.01 part of the resources remain appointed to the surveillance method. It is however still the case that, with this updating rule, it is not possible to change the distribution of resources once this distribution of resources is reached where all methods expect are appointed 0.01 part of the resources. Therefore the graphs of law enforcement look similar as Figure 6.1, however when looking at the graphs of the resource distribution of criminals in Figure 6.7 these graphs seem very different.

The behaviour in Figure 6.7 needs some further explanation as the boxplots do not provide all information necessary. For the graphs of the extraction and switch method, the graphs clearly show that two out of the eight replications show different behaviour than the other replications. As the interquartile range is calculated including these outliers, it looks as if the other replications also rise above 0.01, however, this is not the case. In the graphs of the switch and the extraction method, two replications appoint around 0.97 part of the resources to one of these methods. Thus, in these methods, only two replications will move to a point where they receive around 0.97 part of the resources, while the other six replications stay around 0.01 part of the resources and can not be changed anymore. The graph of the pincode fraud method in Figure 6.7 has very large boxplots, but as can be understood by looking at the graphs of the switch and extraction method, this means that four replications are around 0.97 part of resources and the other four replications are around the 0.01

This at first sight strange behaviour is easy to explain. This happens because when criminals have not reached the point from which they can not change their distribution of resources while law enforcement agencies have reached that point, criminals are able to respond to this. This can happen because criminals adapt similarly but not in the exact same way, due to the different payoff calculation and having more methods. This means that when only the scan method is used and the criminals are still able to change their distribution of resources to one or more methods, criminals will choose to appoint all of the resources they can appoint to a method which can not be caught by the scan.

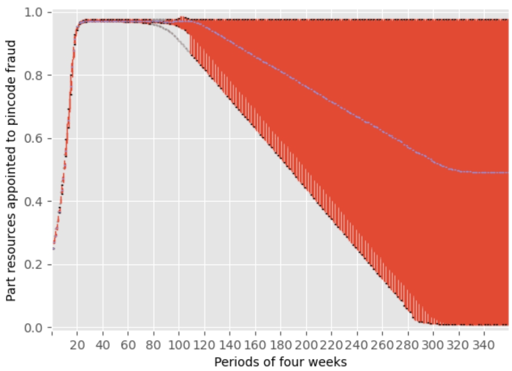


(a) Part resources appointed to scan

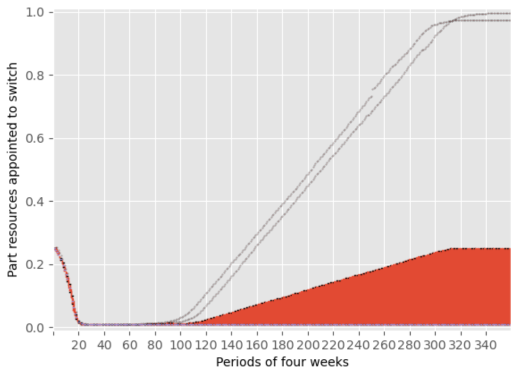


(b) Part resources appointed to surveillance

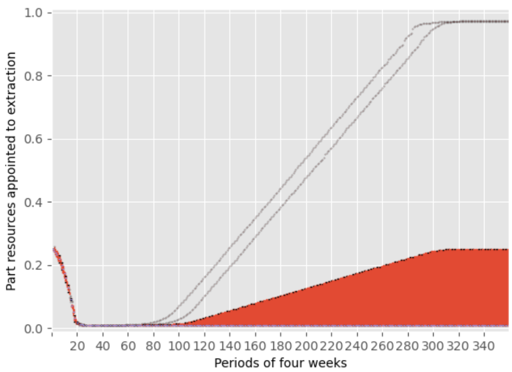
Figure 6.6: Distribution law enforcement agencies methods poker non zero equal



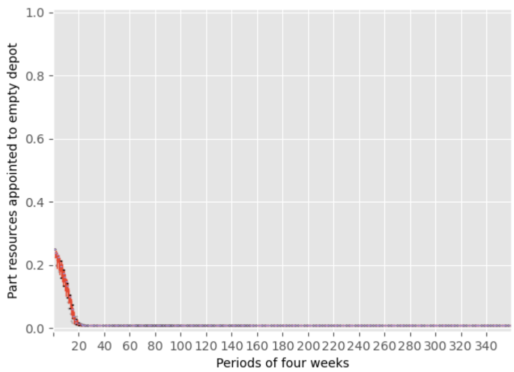
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud



(c) Part resources appointed to extracting



(d) Part resources appointed to empty depot

Figure 6.7: Distribution criminal methods poker non zero equal

The payoffs per method for this updating are seen in the Appendix D. There it shows that the payoff for the surveillance method is very high, while the payoff for the methods that can be caught by this surveillance method is high as well. This is because the payoffs are not dependent on the part of resources appointed to a method. The payoff graphs also show that the empty depot method has a very high variance which, as explained before, is due to the fact that this method is not used often. Figure 6.8 again shows a similar behaviour as the success rate of the updating rule 'poker zero' at the start of the graph. However, since criminals are able to adjust their distribution of resources in a few replications while law enforcement agencies are not, the success rate of law enforcement agencies becomes zero for those replications.

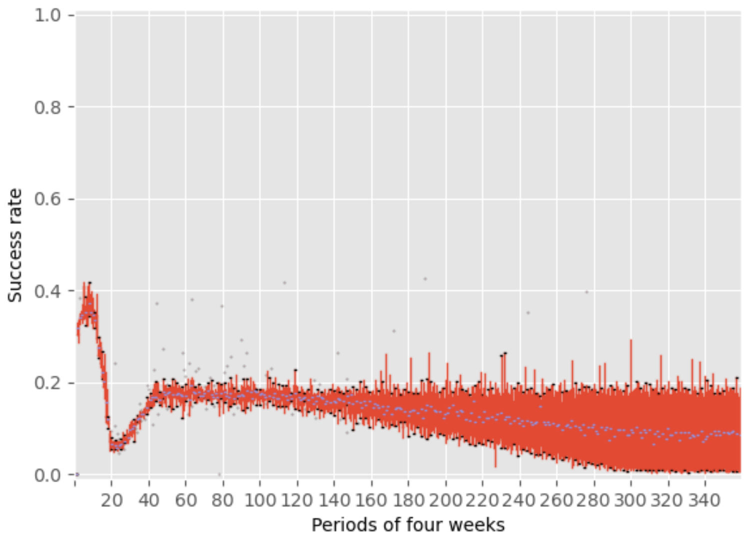
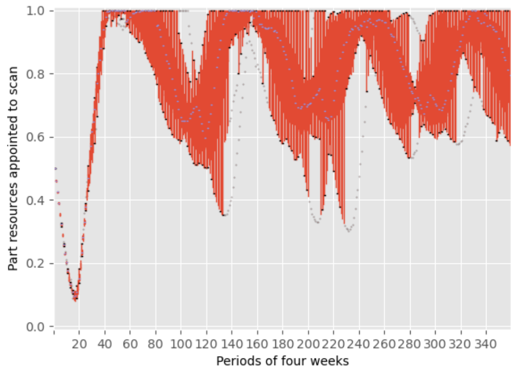


Figure 6.8: Success rate law enforcement agencies poker non zero

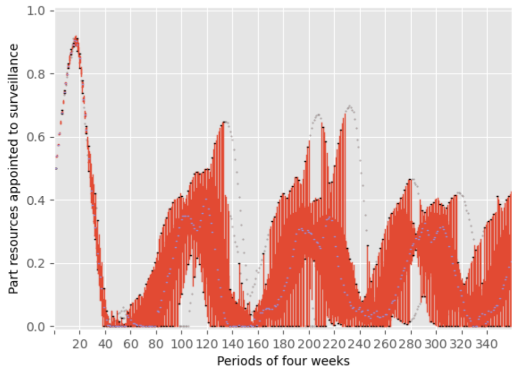
6.3. Poker coming back from back zero

As seen in the results of the previously mentioned updating rules, the agent-based gets stuck in a distribution of resources where (almost) all resources go to one method. Therefore it is interesting to see an updating rule where the distribution of resources can change from a point where all resources all appointed to one method. In this updating rule, methods have a chance to get back from getting zero resources to getting 0.05 part of resources appointed. Figure 6.9 shows that this updating rule causes a cyclic pattern where law enforcement agencies keep changing the distribution of resources between the scan and the surveillance method. As seen in the previously mentioned updating rules, the resources first mostly go to surveillance until the 20th period when law enforcement agencies start to increase the resources appointed to the scan method until this is the only method that is used.

However, this time the agent-based model is not stuck in this solution and the distribution can still change. This causes law enforcement agencies to change their mind and start appointing more of their resources to the surveillance method. This behaviour is rewarded with a high payoff for the surveillance method because criminals are also using multiple methods, some of which can be caught by surveillance. When both law enforcement agencies and criminals keep on reacting to each other, this cyclic pattern arises where every time the surveillance method is appointed little resources, criminals will start using methods that are visible which then again means that the surveillance method becomes successful until criminals adjust accordingly and so on. The distribution of resources of criminals can be seen in Appendix D, where it is visible that criminals also appoint their resources in a cyclic manner between their methods. It also shows that the empty depot method, which is the least successful method for criminals, is hardly used because every time it gets some resources appointed, criminals quickly realise that this method should not be used. The behaviour of law enforcement agencies and criminals also shows that the cyclic pattern of their graphs moves roughly around the Nash equilibrium as calculated in chapter 4.



(a) Part resources appointed to scan



(b) Part resources appointed to surveillance

Figure 6.9: Distribution law enforcement agencies methods with poker back zero equal

Figure 6.10 shows the success rate of the updating rule 'poker back zero'. This figure shows again that the success rate starts relatively high and dips around the 20th period, after which it is adjusted and goes up a little. Despite the big cyclic pattern in the distribution of resources among the methods of law enforcement agencies and criminals, the success rate is quite constant. It is however a little lower than the success rate of the first updating rule where the success rate was equal to the chance of the scan catching the pincode fraud method.

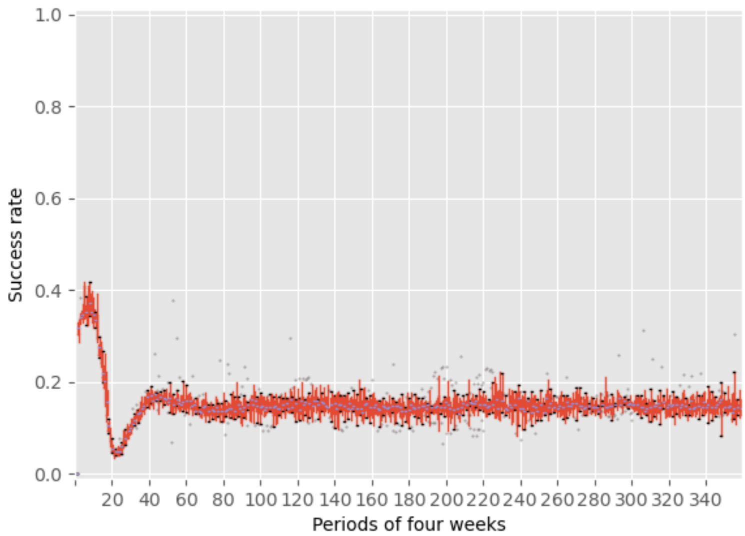
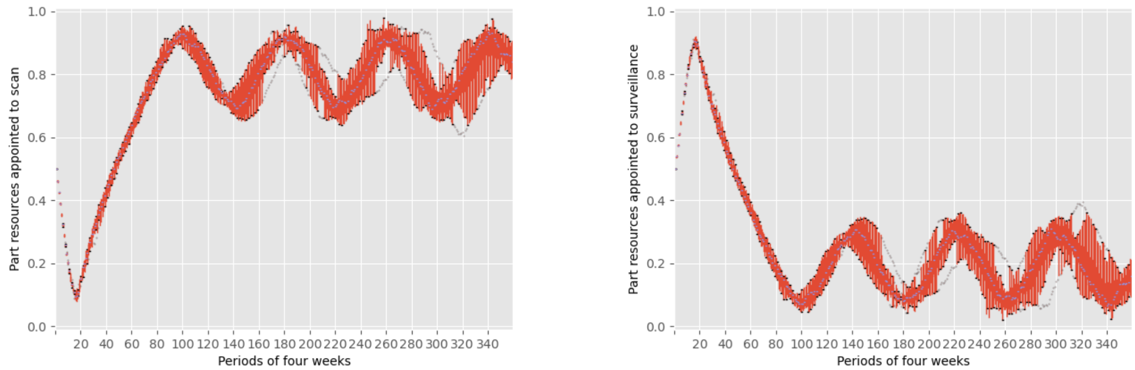


Figure 6.10: Success rate law enforcement agencies poker back zero

6.4. Constant zero

The next three updating rules make use of the 'constant' variant which ensures that law enforcement agencies and criminals will only rarely be able to appoint zero resources to one of their methods. Figure 6.11 shows the behaviour of law enforcement agencies that follows from using this updating rule. When starting with appointing the same part of the resources to each method, law enforcement agencies quickly adapt by increasing the resources appointed to their surveillance method till around the 20th period as also seen in the previously shown updating rules. However, where the 'poker' updating rules continue this movement to a point where law enforcement agencies only use the scan method, this updating rule does not. Around this period, this updating rule starts a clear cyclic pattern which can be explained in the same manner as Figure 6.9 by the adaption of criminals and law enforcement agencies to the behaviour of each other.

This cyclic pattern around the Nash equilibrium does however not always happen, as this is very dependent on the parameter settings for this updating rule. This can be seen in Appendix D where for other parameter settings very different behaviour is shown. For the parameter settings as specified at the beginning of this chapter, criminals also react in a cyclic pattern around the Nash equilibrium where pincode fraud is used most often and the switch and extraction methods are used the same amount. The empty depot method is again not used much. This updating rule does not cause zero resources to be appointed to this empty depot method but it does appoint very little, around 0.03 part of the resources of criminals.



(a) Part resources appointed to scan

(b) Part resources appointed to surveillance

Figure 6.11: Distribution law enforcement agencies methods with constant zero equal

As for the success rate of this updating rule, Figure 6.12 shows that even though the behaviour is similar to the graphs of the previously mentioned updating rules, the dip around the 20th period is less deep. This can be explained by the fact that law enforcement agencies do not spend all their resources on one method which can make them vulnerable to being taken advantage of. Furthermore, the success rate is, like the previous updating rules, stable at a value a little below the known 0.18 which was shown in Figure 6.5.

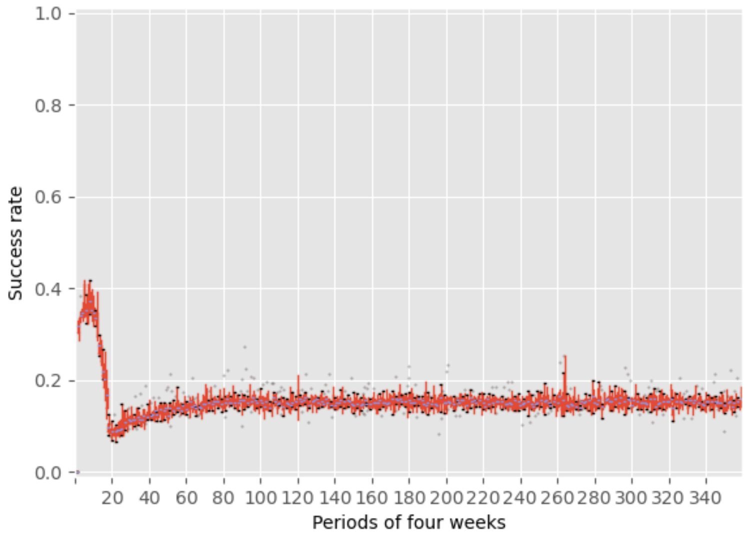
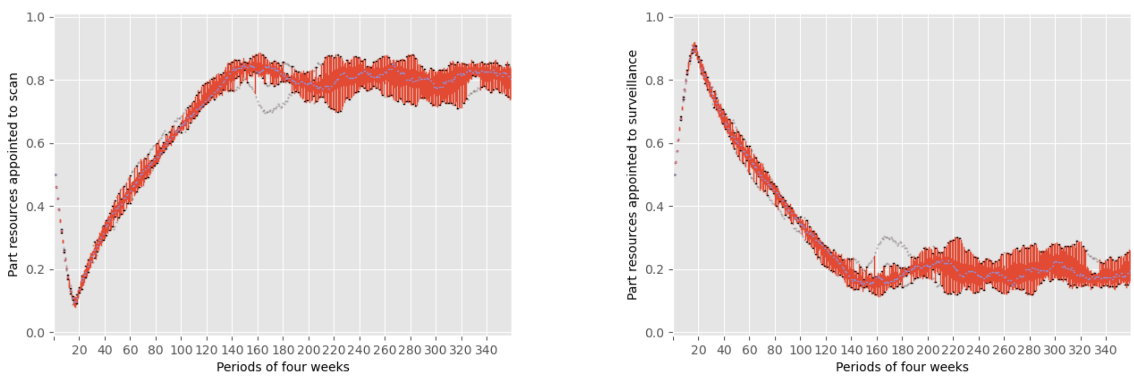


Figure 6.12: Success rate law enforcement agencies constant zero

6.5. Constant non zero

The updating rule 'constant non zero' is similar to the updating rule 'constant zero' as both updating rules ensure that it is not easy to spend all resources on a single method. This updating rule even makes it impossible for a method to get zero resources appointed, as every method will at least get 0.01 part of the resources at all times. In terms of behaviour, Figure 6.13 shows that the agent-based model behaves quite similarly to the previously updating rules where it shifts from increasing the part of resources appointed to the surveillance method to increasing thepart of the resources appointed to the scan method around the 20th period. Unlike the 'constant zero' updating rule, this updating rule takes a lot longer to increase the resources appointed to the scan. This also causes the cyclic pattern that Figure 6.13 also shows to start later. This can be explained by looking at the behaviour of criminals using this updating rule in Appendix D, as criminals seem to react in a lot smaller steps. This is because criminals have methods which are appointed little resources and since this updating rule still appoints resources to these methods, a smaller part of the resources can be appointed to the method with a big part of the resources. Criminals also show a small cyclic behaviour in Appendix D, but law enforcement agencies show a more clear cyclic pattern around the Nash equilibrium.



(a) Part resources appointed to scan

(b) Part resources appointed to surveillance

Figure 6.13: Distribution law enforcement agencies methods constant non zero equal

Figure 6.14 shows the success rate for this updating rule where it is noticeable that this updating rule has an ever smaller dip around the 20th period as compared to the previously mentioned updating rules. This can be explained by the fact that this updating rule does allow appointing resources in an extreme manner which holds true for law enforcement agencies and criminals. Therefore the success rate is more stable. The success rate after this point is similar to the one from the 'constant zero' updating rule which again is stable a little below 0.18.

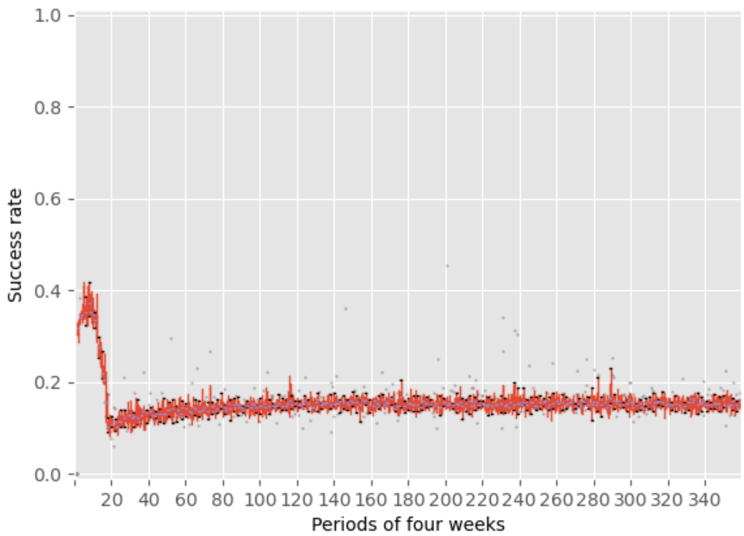
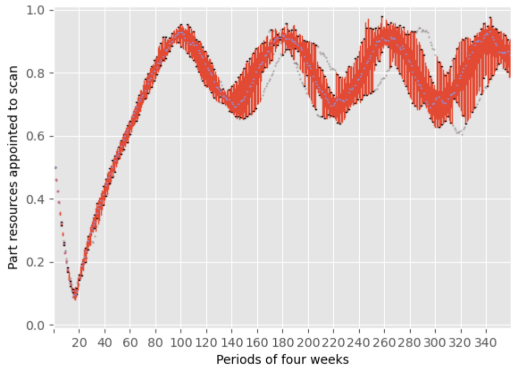


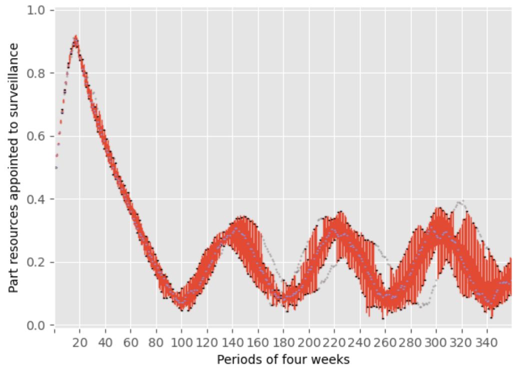
Figure 6.14: Success rate law enforcement agencies constant non zero

6.6. Constant back zero

The last updating rule that has been tested using the agent-based model is the 'constant back zero' updating rule. This rule makes sure that when zero resources are appointed to a method, this method gets a chance to return. However, as seen in Figure 6.11 the updating rules using the 'constant' variants are never appointing zero resources to a method because the 'constant' rule ensures that this does not happen easily. The behaviour as can be seen in Figure 6.11, shows that law enforcement agencies show the same behaviour when using the 'constant back zero' rule as the 'constant zero' rule. This also holds true for the behaviour of criminals, where the updating rules 'constant zero' and 'constant back zero' show the same behaviour as criminals also do not appoint zero resources to any of their methods. This also means that the success rate as seen in Figure 6.16 is the same as the success rate of the 'constant zero' rule. The behaviour is the exact same as the same random seed is used for the agent-based model meaning that all random choices are equal for these two updating rules in the shown replications.



(a) Part resources appointed to scan



(b) Part resources appointed to surveillance

Figure 6.15: Distribution law enforcement agencies methods with constant back zero equal

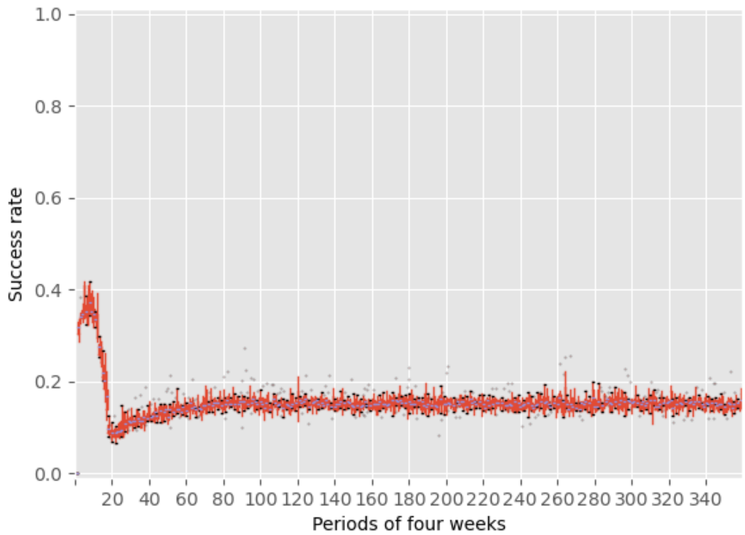


Figure 6.16: Success rate law enforcement agencies constant back zero

7 Discussion

This chapter will reflect on and discuss the results seen in chapter 6 and chapter 4, and show how the agent-based model as seen in chapter 5, and the Nash equilibrium in chapter 4 compare with each other. It will also reflect on the research questions as seen in chapter 1 and attempt to answer them. Furthermore, this chapter will discuss the strength and limitations of this research, and point out which further research is needed and which recommendations follow from this research for law enforcement agencies.

7.1. Interpretation of the results

The results as displayed in chapter 6 and Appendix D show that the six different updating rules result in different behaviour in the agent-based model as the distribution of resources of each player ends up being distributed in different ways. This confirms that these updating rules, although similar to each other, result in very different behaviour of the agent-based model. As seen in chapter 1, it was expected that when comparing an agent-based model to the Nash equilibrium this updating rule is very important. As expected from this literature in chapter 1, it highly depends on the updating rule whether the agent-based model ends up distributing the resources according to the Nash equilibrium.

While all six updating rules can ensure that the agent-based model behaves in a cyclic pattern around the Nash equilibrium when the agent-based model starts with a distribution of resources according to this Nash equilibrium as can be seen in Appendix D, not all updating rules will ensure that the agent-based model ends up around this Nash equilibrium when the agent-based model starts off by distributing the resources of a player equally among their methods, as can be seen in chapter 6. This is mostly due to some updating rules causing the agent-based model to get stuck in a solution where both players only use one method. However as can be seen in section D.3, the 'constant' updating rules can also cause the agent-based model to get stuck in a distribution of resources that, game-theoretically, should not be an equilibrium when different parameter settings are used. Using different parameter settings for the 'constant' updating rules even causes the model behaviour of the agent-based model to completely change when the agent-based model starts off in the Nash equilibrium.

When comparing the results of the different updating rules, chapter 6 shows that the 'poker zero' and the 'poker non zero' updating rules will result in a distribution of resources of law enforcement agencies where (almost) all resources are appointed to the scan method and that law enforcement agencies will no longer be redistributing their resources when this happens, as the updating rules do not allow it. This happens because when the criminals are not playing according to the Nash equilibrium, the best response for law enforcement agencies is to only use one method. However not being able to change your distribution in this situation is not rational because in reality criminals will adapt when they realise this and therefore law enforcement agencies should also continue to be able to adapt their distribution of resources.

The ’poker back zero’ updating rule shows different behaviour, as with this rule players are able to appoint a part of the resources to a method that was previously appointed zero resources and therefore has a payoff of zero. Noticeable about this ’poker back zero’ updating rule is that even though it shows a large cyclic behaviour around the Nash equilibrium, the resources of law enforcement are still often appointed to the scan only. This happens because when criminals are not appointing their resources according to the Nash equilibrium, the best response for law enforcement agencies is to move their resources to only one method because this gives the highest payoff. However, as criminals notice that law enforcement agencies only use one method, they will adapt. This adaption of criminals causes the payoff of law enforcement agencies to be higher when law enforcement agencies start reappointing a part of their resources to the method that was not used in the previous period.

When comparing the updating rules using the ’constant’ variants to the ’poker’ variants using the same parameter values, chapter 6 shows that even though the behaviour starts off the same, the big difference is that the ’constant’ updating rules will never let a player distribute all of its resources to one method. These ’constant’ updating rules, ensure that it is not easy to appoint zero resources to any method for a player. When using the right parameters this results in both players distributing their resources in a clear cyclic pattern around the Nash equilibrium as both players keep on reacting to each other and therefore keep adapting their distribution of resources this cyclic pattern continues for the rest of the run time. However as mentioned before, the parameter settings matter a lot for the ’constant’ updating rules, as other parameter settings can cause very different behaviour as can be seen in section D.3.

7.2. Risks of combining agent-based models and game theory

Difficulties when combining agent-based models with the Nash equilibrium should be discussed as these difficulties are a risk of using agent-based models and policymakers in situations where a player wants to evaluate the distribution of its resources while taking into account that the other will evaluate their methods and adapt as well. Therefore these difficulties should act as a warning for people using agent-based models and policymakers for similar situations.

The first difficulty is that the updating rule should redistribute the resources according to the payoff of each method and not the success rate of the method. This means that the resources should be distributed according to how successful a method was in the previous period while not taking into account how often it was used. This is important as otherwise methods that are not used much, automatically seem to be performing worse and therefore will get even a smaller part of the resources appointed each period until they are not used at all.

Another risk of modelling the updating rule in an agent-based model is that this updating rule should allow for methods that are not used much to be able to be used again when profitable. Otherwise, agent-based models will end up in a solution where both players only use one of their methods as can be seen in the results of the updating rule ’poker zero’. This is a big risk because when law enforcement agencies only implement one method while criminals might not, criminals can easily take advantage of the situation by only using a method that cannot be caught by the method used by law enforcement agencies. This can cause the success rate of law enforcement to become zero as can be seen in the graph of the success rate for the updating rule ’poker zero’.

This situation where one or more methods get a very small part of resources appointed causes multiple difficulties. This is because when resources are solely distributed according to the payoff, these methods will never reoccur causing previously mentioned risks. However, in order to ensure rational behaviour the updating rule should allow players to only use one method in a time period and it should also allow for players to not only one or more of their methods as in the Nash equilibrium not all methods are used. That is why this research has tested six different updating rules, from which none are able to overcome all difficulties. Next to the difficulty that the updating rule should allow for methods to not be used, the distribution of resources can also show false equilibria when it makes it difficult for a player to appoint a small part of resources to one or more methods, as seen in section D.3.

The last difficulty that this research encountered that should act as a warning for policymakers and agent-based modellers is that players might not react in the same way. In the case of this research, the game is a zero-sum game where the criminals want to minimise the chance of illegal goods being caught while law enforcement agencies want to increase it. To ensure that the same updating rule can be used for both players, the payoff of criminals is modelled as one minus the part of the containers using a method that is caught, so both players want to maximise their payoff. However, this causes criminals to not adapt as strongly each period when only a small part of illegal goods are intercepted.

This is because when only a small part of illegal containers is caught, for example, 3 out of 100 illegal containers, law enforcement agencies could have a method that caught 2 containers and a method that caught 1 container, making the first method twice as successful in that period. While criminals evaluate a method in which 48 out of 50 illegal containers were smuggled successfully and one method in which 49 out of 50 illegal containers were smuggled successfully making them around equally successful. Therefore in this example, criminals will appoint a similar part of their resources to each method while law enforcement agencies will appoint more to the method that caught 2 containers instead of 1. Another difficulty as to why both players do not adapt the same way is because in this research criminals have four smuggling methods while law enforcement agencies only have two methods.

7.3. Strengths and weaknesses of this research

Since this research is exploratory and because of the limited data available and the deep uncertainties, the results can not be seen as valid but this research can show the behaviour that can be expected. The most uncertain parameters are the accuracies of the methods of law enforcement agencies for each of the criminal smuggling methods. However, this research does provide both an agent-based model as well as a game-theoretical model which can be used to test the expected behaviour for other accuracies once further research is done on the reliability of these accuracies.

Since little data is known about the methods of law enforcement agencies, more general methods are chosen that combine smaller methods into two methods; scanning containers and surveillance for when criminal activity is visible. Next to the necessary simplifications to make the agent-based model, other simplifications were necessary to compare this agent-based model to the Nash equilibrium. This is because while criminals can choose a new smuggling method for each illegal container, law enforcement agencies do not choose a method per illegal container but can only choose how much of their resources they will appoint to each of their methods. Therefore, linearity needed to be assumed for the accuracy of the methods of law enforcement agencies so the payoffs could be calculated similarly to payoffs in game theory which was need to compare the agent-based model to the Nash equilibrium. In reality, it is more likely that to increase the capacity of the scan, a second scan might be needed. A big limitation of this research is that it is assumed that both criminals and law enforcement agencies only have these most used methods and will not use other methods or create new methods.

Despite these assumptions and simplifications, this research was able to capture the cat-and-mouse-like behaviour which is expected when law enforcement agencies and criminals respond to each other by adjusting their distribution of resources. It also shows that while the agent-based model can cycle around the Nash equilibrium when the agent-based model starts in this equilibrium it does not mean that using the same updating rule when starting the agent-based model by distributing the resources of a player equally among their methods, will result in ending up around the Nash equilibrium as well. By testing different updating rules this research acts as a warning for similar situations by showing multiple difficulties that can arise when comparing an agent-based model with game theory. This research also shows the importance of including game theory while evaluating the distribution of resources of law enforcement agencies in the Port of Rotterdam as it shows that without thinking about the Nash equilibrium law enforcement agencies could appoint all their resources to one method making them vulnerable to a low chance of catching illegal goods.

7.4. Recommendations

Recommendations that follow from this research, first of all, include the multiple difficulties when combining agent-based models with the Nash equilibrium as mentioned in this chapter, which should act as a warning for similar situations where an updating rule is desired. For law enforcement agencies this research has shown that even though one method might have a much higher accuracy, this does not mean that this is also the method that should be appointed most of the resources as criminals will most likely try to avoid often using smuggling methods that can be caught by this method. This research also shows the importance of updating the distribution of resources regularly because as seen in chapter 6 the success rate for law enforcement agencies can become zero when criminals do adapt while law enforcement agencies do not. Therefore it is recommended to update regularly, preferably as often as criminals update their methods. More research is needed into the updating behaviour of criminals. It is also recommended that when investments can be made in improving the accuracy of one of the methods from law enforcement agencies, game theory should be used to determine where this investment should be made because as seen in chapter 4 the expected payoff when investing in one of the methods depends on how the accuracy can be improved.

7.5. Further research

For further research, it would be interesting to test the six proposed updating rules with different parameter settings as this research shows that the behaviour of the agent-based model can differ a lot based on the parameter settings. Other research should also be done to see whether an updating rule (which only uses information on the distribution of resources in the last period and the payoff of each method) can be created that will always cause the agent-based model to end up in or around the Nash equilibrium. To expand the recommendations for law enforcement agencies, research could be done on how the behaviour changes when there is a delay while updating the distribution of resources for one player or when players do not update in the same way or not as frequently as each other.

Furthermore, because of the deep uncertainty in this topic and therefore also in the agent-based model, more research is needed to fill the gaps of the limited data, most importantly for the accuracy of the law-enforcing methods against the criminal methods. Since this data is not easily obtainable it would be difficult to research these accuracies, further research could include deep uncertainty analyses to explore the behaviour of different uncertain parameters including the accuracies. This research also provides interesting research opportunities to see how the behaviour of the agent-based model will differ when certain complexities are added to the agent-based model. These complexities can include implementing different behaviour for days and nights or removing the linearity assumption of the methods of law enforcement agencies. Comparing this more complex agent-based model to the Nash equilibrium would provide insights into the possibility of only using game theory without building a labour-expensive agent-based model.

8 Conclusion

This research has provided more insights into the criminal supply chain in the Port of Rotterdam by investigating the most used smuggling methods and methods that are used to catch illegal goods and by using an agent-based model in combination with game theory and testing different updating rules to redistribute resources for both law enforcement agencies and criminals. Criminals have four methods which are the pincode fraud method, the switch and pincode fraud method, the extraction method and the empty depot method. Law enforcement agencies have a scan and a surveillance method which can both catch different smuggling methods and both have a chance to catch illegal goods smuggled with the empty depot method.

Possible updating rules include a ’poker’ variant and a ’constant’ variant that both appoint the part of resources that will be redistributed to the methods of a player according to the payoff of each method. Where the ’poker’ variant will appoint a smaller part of the resources to methods that were not used much in the previous round, the ’constant’ variant will solely appoint the part of resources that will be redistributed based on the payoffs of the method and will always redistribute the same part of the resources for a player. For the situations where a method of a player gets appointed a small part of resources, three variants are tested for both the ’poker’ variant and the ’constant’ variant, namely ’zero’ where it is possible to appoint no resources to a method, ’non zero’ where this is not possible and ’back zero’ where it is possible to appoint no resources to a method but where it is also possible for this method to reoccur.

When comparing the agent-based model using these six updating rules to the Nash equilibrium calculated for this situation, this research shows that different updating rules show different behaviour and that when an updating rule will cause cyclic behaviour around the Nash equilibrium when the agent-based model starts off in this equilibrium, it does not mean that the agent-based model will also end up around the Nash equilibrium when it starts off by distributing the resources of a player equally among their methods. Ending up around the Nash equilibrium is also not guaranteed when changing the parameter settings for an updating rule that with certain parameter values can cause the agent-based model to end up around the Nash equilibrium. Next to ending up around the Nash equilibrium, different updating rules can cause the agent-based model to either end up in a state where each player appoints all of their resources to one method or in equilibria that should not exist as the payoffs of the methods are not equal to each other, meaning that this player rationally should continue redistributing its resources.

Therefore, it can be concluded that in order to use an agent-based model for the situation between law enforcement agencies and criminals the knowledge about Nash equilibria should be considered while creating the model. This will not happen automatically as seen by the multiple difficulties this research showed. Furthermore, it can be concluded that the updating rule, which determines how law enforcement agencies redistribute their resources among their methods to catch illegal goods, has a big influence on the behaviour and a big influence on whether or not the law enforcement agencies and criminals will end up around this Nash equilibrium. This research also shows that updating the distribution of resources by law enforcement agencies is important as they risk not having a chance to catch any illegal goods when criminals adapt, while they would not.

For law enforcement agencies, it is recommended to update the distribution of resources when it is expected that criminals will adapt as well, as this has a big effect on the success rate of law enforcement agencies. Furthermore, it is recommended to consider the Nash equilibrium while updating the distribution of resources and to carefully observe the distribution of resources of criminals when appointing all resources to only one method to not risk a chance of catching illegal goods of zero.

A big limitation of this research is that there is only a limited number of methods included and players can not learn new methods, while it is reasonable to expect this in the real world. Due to the limited data about methods that can be used by law enforcement agencies and deep uncertainty in model parameters, especially for the accuracies of the methods, these results are not entirely valid and should only be used to analyse expected behaviour. Further research is needed to validate the accuracy of the methods, perform a deep uncertainty analysis on uncertain parameters and further research is needed to test more updating rules, as this research does not provide an updating rule that will ensure that an agent-based model will always end up distributing the resources of each player according to the Nash equilibrium.

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A
Assumptions

This appendix is not publicly available.

B

Agent-based model specifics

Input variables
Cutoff distributions setup
Reoccur distribution setup
Distribution space law enforcement
Distribution space criminals
Chance of origin being America
Chance of being transported by a truck
Chance of needing cooling per container
Chance of big ship per ship
Chance of medium ship per ship
Chance of a risky container being scanned
Chance of scanning a risky container at full scan capacity
Accuracy scan
Chance of catching illegal goods at full surveillance capacity
Day night difference surveillance accuracy
Chance of getting seen day
Chance of getting seen night
Percentage of export containers empty
Minimal hours in terminal for containers
Average hours in terminal for import containers
Time a spot in the port needs between ships arriving
Part surveillance in use at the start
Part scan in use at the start
Chance pincode fraud at the start
Chance switch and pincode fraud at the start
Chance extracting at the start
Chance empty depot at the start

Table B.1: Input variables of agent-based model

Output variables
Part surveillance in use
Part scan in use
Chance pincode fraud
Chance switch and pincode fraud
Chance extracting
Chance empty depot
Payoff scan
Payoff surveillance
Payoff pincode fraud
Payoff switch and pincode fraud
Payoff extracting
Payoff empty depot
Successrate scan
Successrate surveillance
Successrate pincode fraud
Successrate switch and pincode fraud
Successrate extracting
Successrate empty depot

Table B.2: Output variables of agent-based model

Agent type	Variables per agent type
Ship	Status Origin Size Number of import containers Number of export containers Waiting time before arrival
Import container	Status Origin Means of transportation Started as illegal? Illegal? Illegal goods taken by Smuggle method Will be scanned? Belonging to ship unloading time throughput time Time to check scan results Digitally blocked? Cooling needed? People inside?
Export container	Status Origin Illegal? Started as illegal? Illegal goods taken by Belonging to ship Loading time Throughput time Smuggle method Full? Time till arrival People inside?
Employee	Status Caught? Container in need of connection Illegal container
Criminal	Status Trojan container Illegal container Safe container Caught?
Repairman	Status Illegal container Caught?

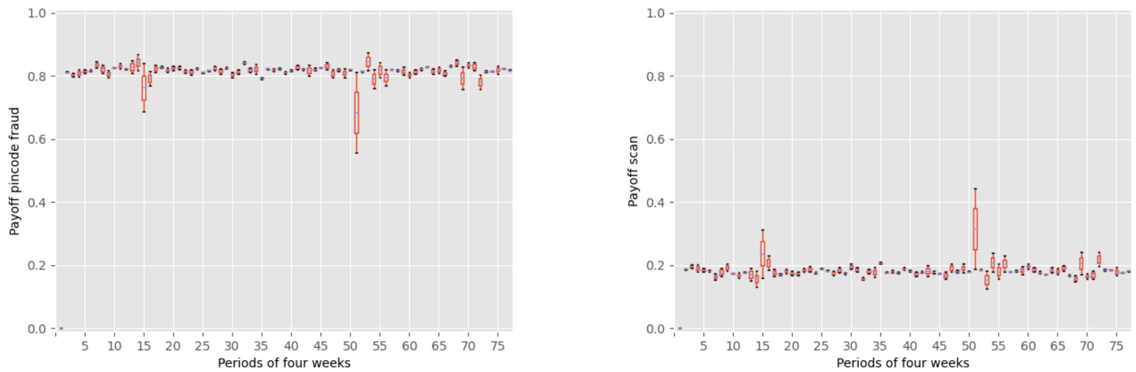
Table B.3: Agent types of agent-based model

C

Verification

This appendix shows the payoffs when single methods are tested against each other. This means that the distribution of the methods shown in the figures is always 1 during the whole runtime and that the distributions of the other methods from that same player are always zero. Therefore no updating rules are used in these runs. The figures are plotted using boxplots, when certain methods from law enforcement agencies are not capable of catching anything this means that the payoff of that method is zero whilst the payoff of the criminal method is 1. Two plots in one figure are always the opposite of each other, as what the law enforcement agencies catch criminals lose. The boxplot shows the outcome of the model for each period for all replications and shows the median and the interquartile range of the data. This means that the box represents 50% of the data points, and the whiskers show the minimum and maximum data points, without including outliers. A data point is considered an outlier when it is outside of lower than the first quantile minus 1.5 * the interquartile range or higher than the third quantile plus 1.5 * the interquartile range. The graphs in this appendix represent 2 replications. The graphs in this appendix show that the model doing what it is supposed to do as the payoffs are the same as seen in the matrix of chapter 4.

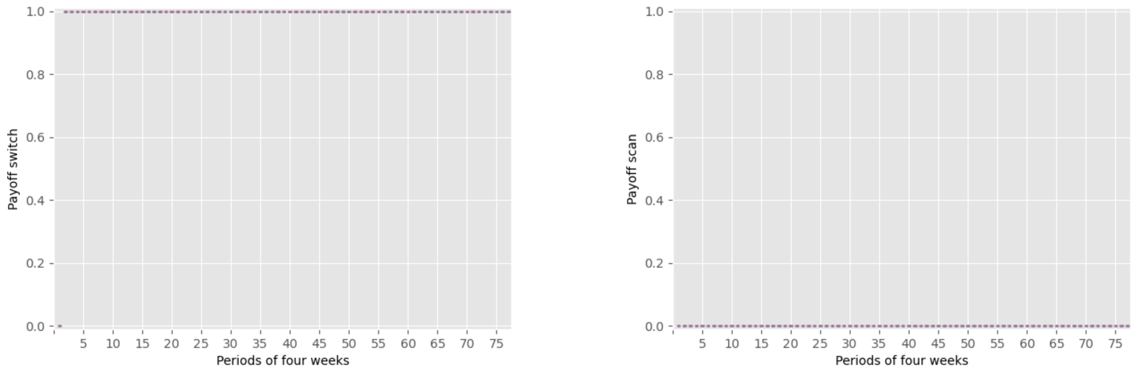
C.1. Criminal methods against the scan method



(a) Payoff pincode fraud

(b) Payoff scan

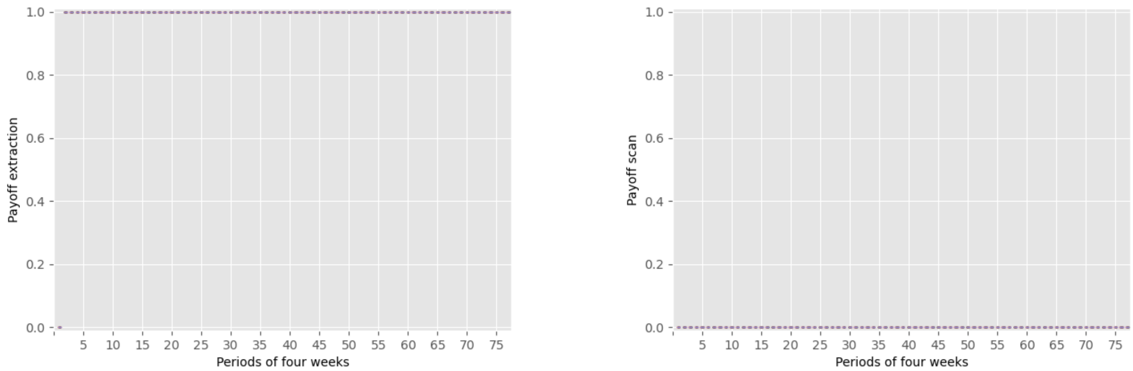
Figure C.1: Payoffs pincode fraud combined with scan



(a) Payoff switch

(b) Payoff scan

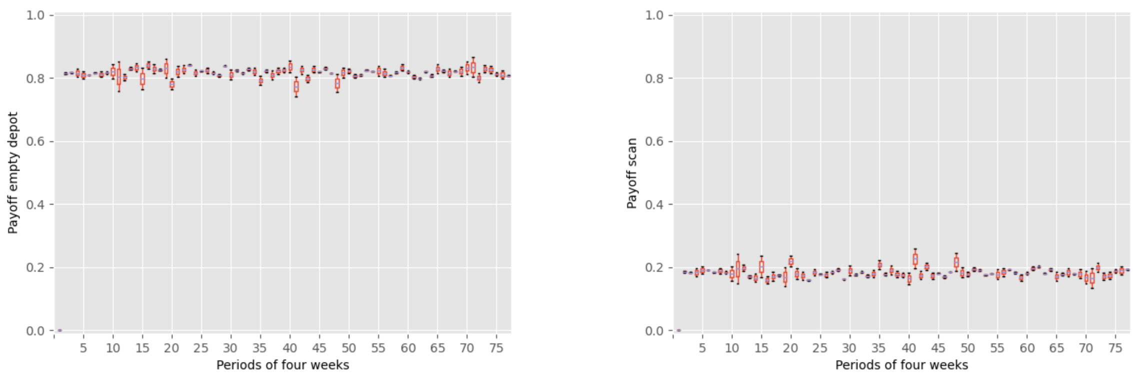
Figure C.2: Payoffs switch combined with scan



(a) Payoff extraction

(b) Payoff scan

Figure C.3: Payoffs extraction combined with scan

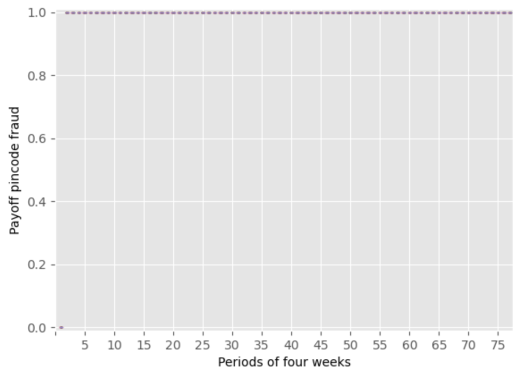


(a) Payoff empty depot

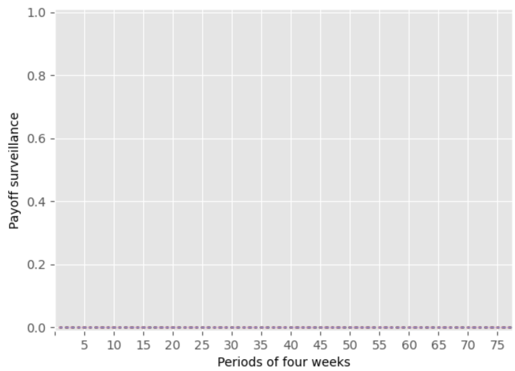
(b) Payoff scan

Figure C.4: Payoffs empty depot combined with scan

C.2. Criminal methods against the surveillance method

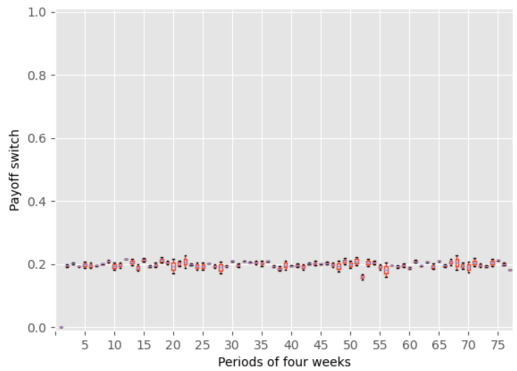


(a) Payoff pincode fraud

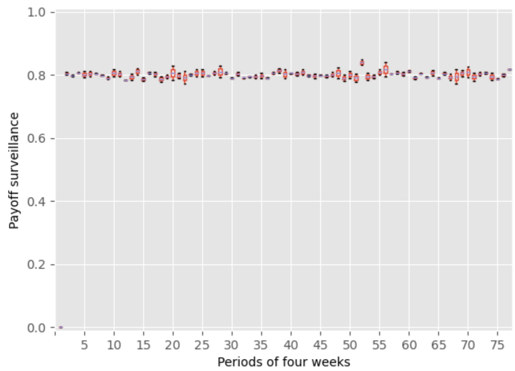


(b) Payoff surveillance

Figure C.5: Payoffs pincode fraud combined with surveillance

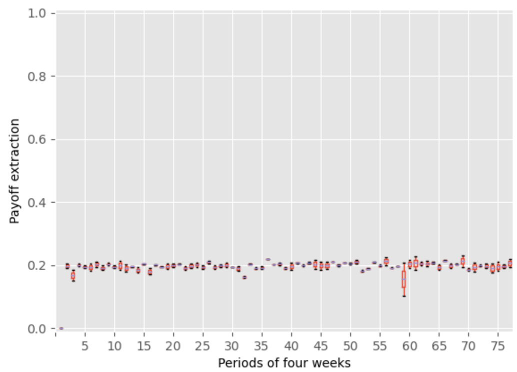


(a) Payoff switch

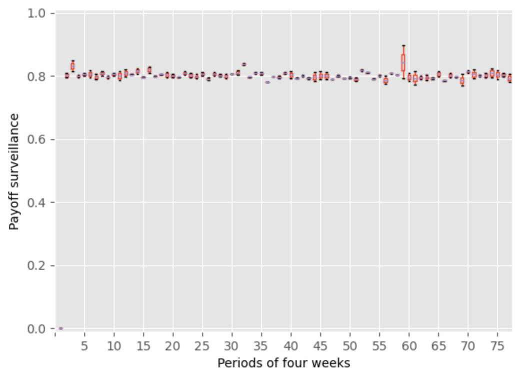


(b) Payoff surveillance

Figure C.6: Payoffs switch combined with surveillance

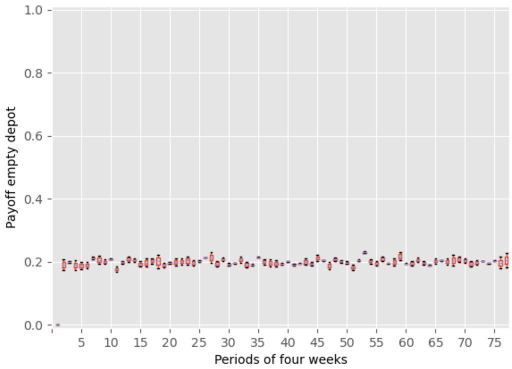


(a) Payoff extraction

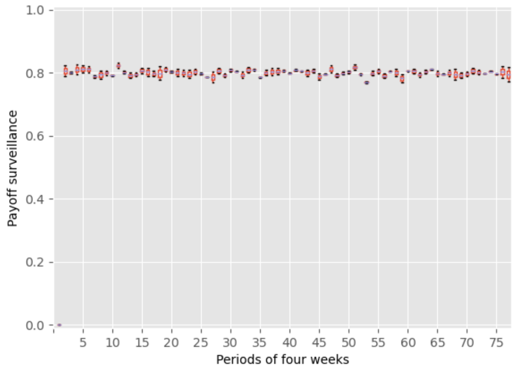


(b) Payoff surveillance

Figure C.7: Payoffs extraction combined with surveillance



(a) Payoff empty depot



(b) Payoff surveillance

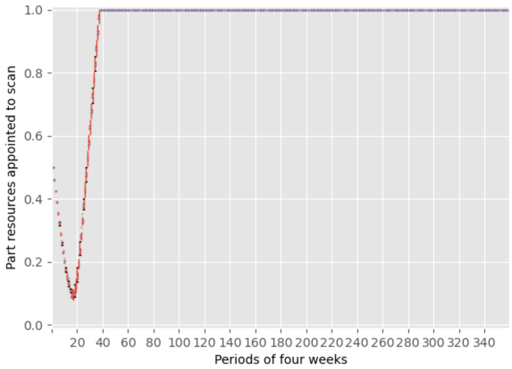
Figure C.8: Payoffs empty depot combined with surveillance

D
Results

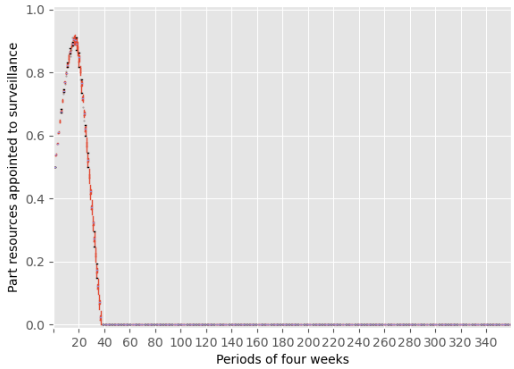
This appendix will show results that are not mentioned in the text. This chapter starts with showing all graphs as discussed in chapter 6. Following, this chapter will show all graphs for the updating rules when the agent-based model would start in the Nash equilibrium. Lastly, this model will show graphs for the three constant updating rules with a different parameter setting as these graphs show very different behaviour from the first ones as mentioned in chapter 6. These last graphs will show that this constant updating rules can get stuck in equilibria that according to game theory should not exist. The figures are made using a box plot showing the results for each period of four weeks. The boxplot shows the outcome of the model for each period for all replications and shows the median and the interquartile range of the data. This means that the box represents 50% of the data points, and the whiskers show the minimum and maximum data points, without including outliers. A data point is considered an outlier when it is lower than the first quantile minus 1.5 * the interquartile range or higher than the third quantile plus 1.5 * the interquartile range.

D.1. Updating rules starting with an equal part of resources

This section shows the output for all six tested updating rules. The values used in these updating rules for the output graphs are a cutoff of 0.01 for rules that are not allowed to have any methods go to zero and a reoccur value of 0.05 for the methods that come back from zero. Every period law enforcement reappoint 0.1 part of their resources and criminals reappoint 0.2 of their resources every period. This section shows 8 replications. It first shows the distribution of resources for each updating rule and then the payoff for each method which explains how the distribution of resources is modelled.

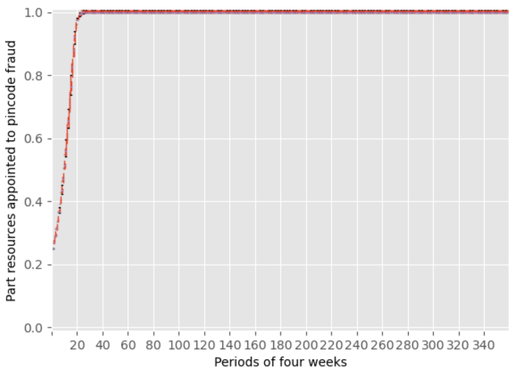


(a) Part resources appointed to scan

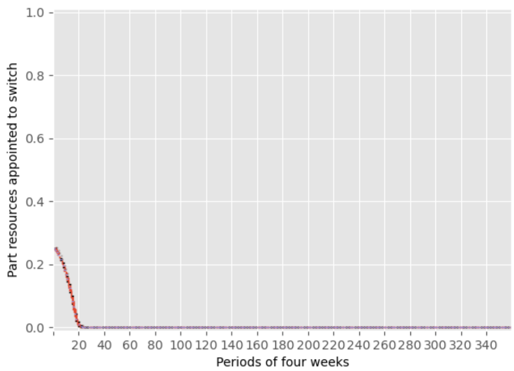


(b) Part resources appointed to surveillance

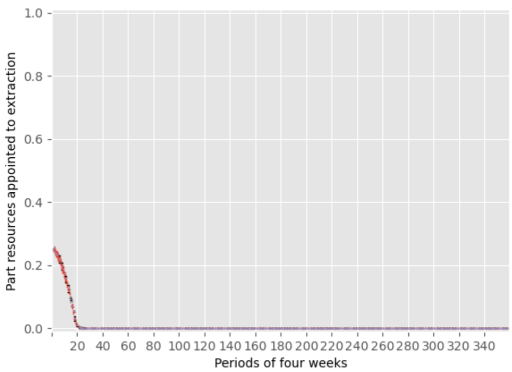
Figure D.1: Distribution law enforcement agencies methods with poker zero equal



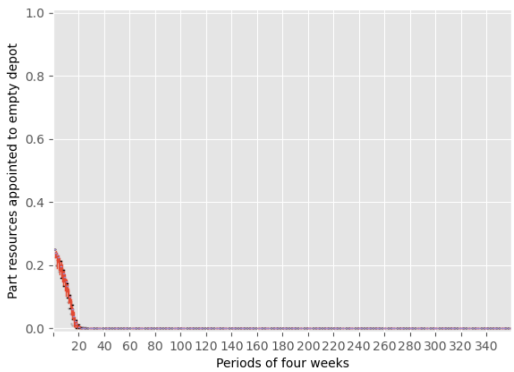
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

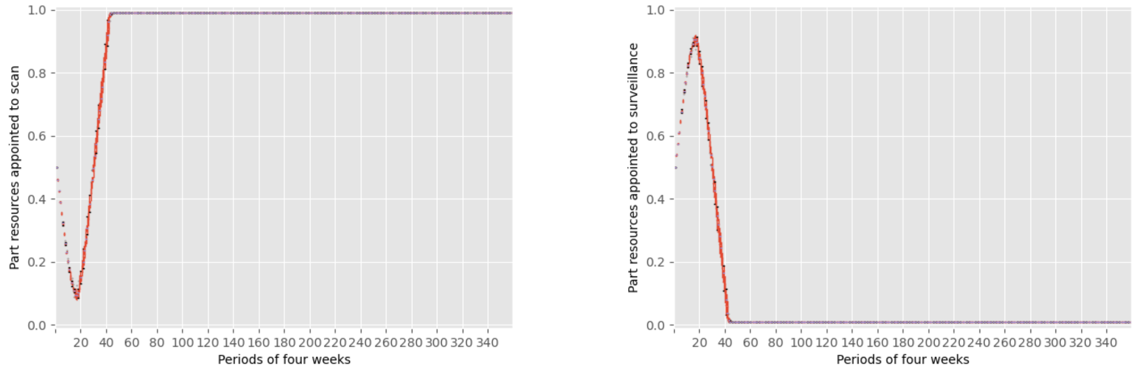


(c) Part resources appointed to extracting



(d) Part resources appointed to empty depot

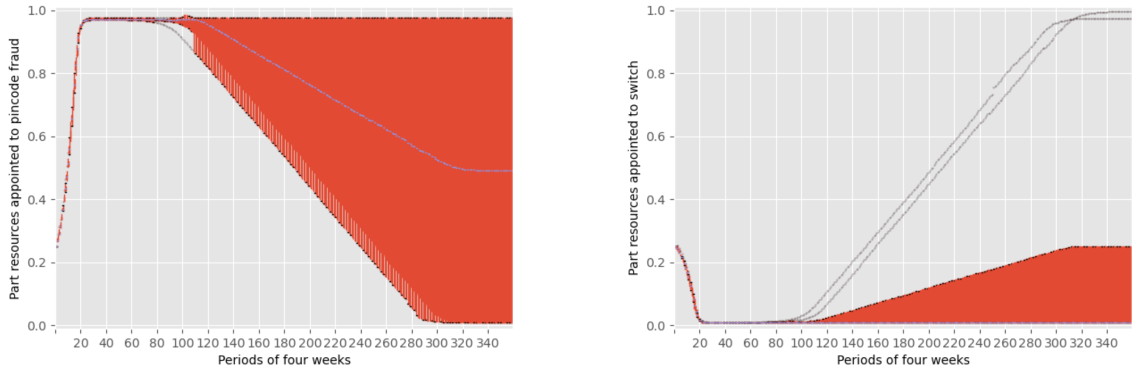
Figure D.2: Distribution criminal poker zero equal



(a) Part resources appointed to scan

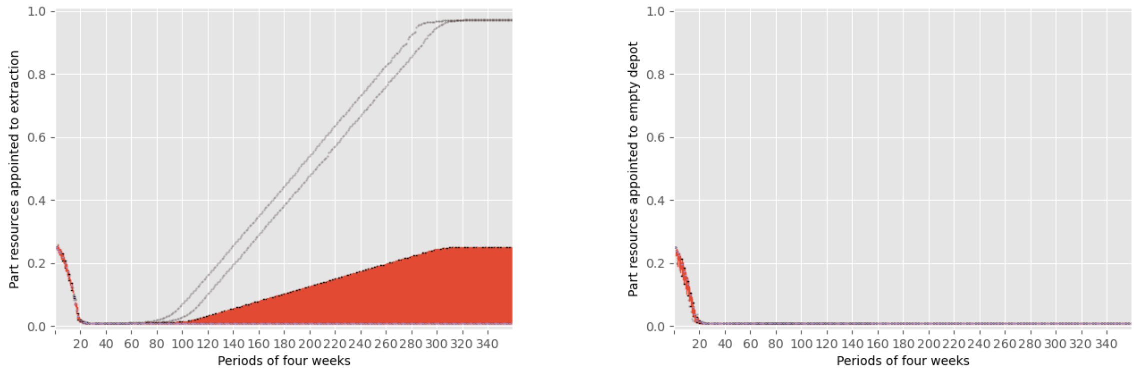
(b) Part resources appointed to surveillance

Figure D.3: Distribution law enforcement agencies methods poker non zero equal



(a) Part resources appointed to pincode fraud

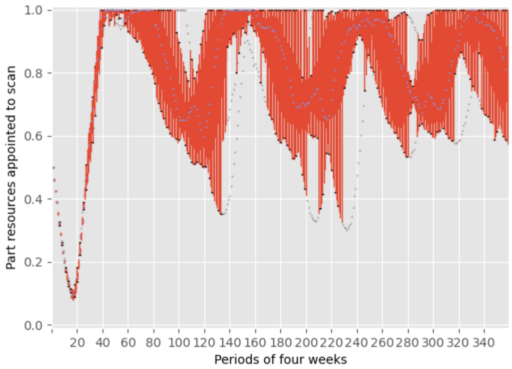
(b) Part resources appointed to switch and pincode fraud



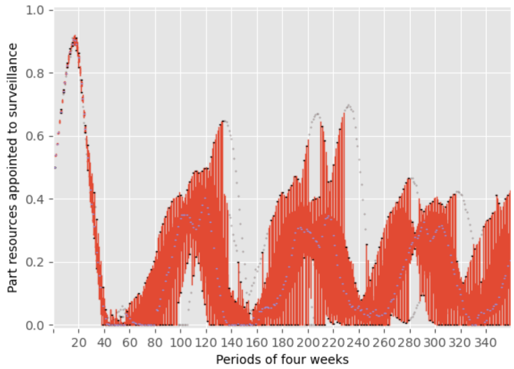
(c) Part resources appointed to extracting

(d) Part resources appointed to empty depot

Figure D.4: Distribution criminal methods poker non zero equal

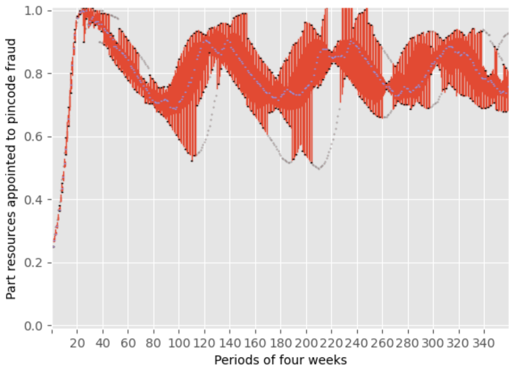


(a) Part resources appointed to scan

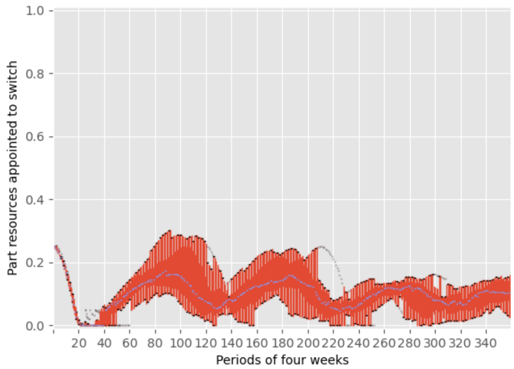


(b) Part resources appointed to surveillance

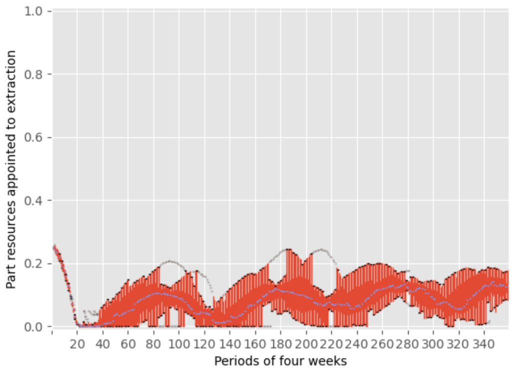
Figure D.5: Distribution law enforcement agencies methods with poker back zero equal



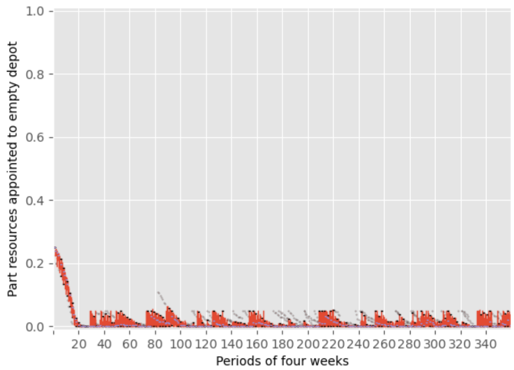
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

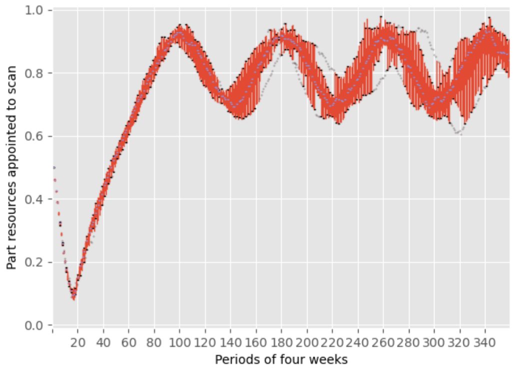


(c) Part resources appointed to extracting

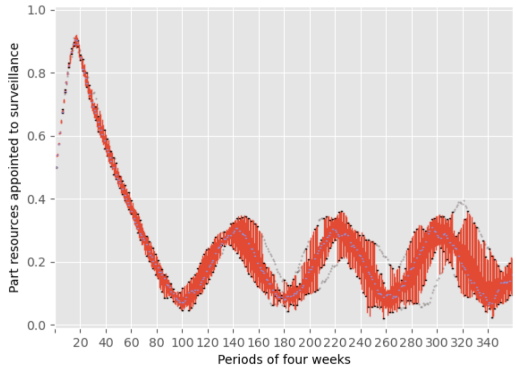


(d) Part resources appointed to empty depot

Figure D.6: Distribution criminal poker back zero equal

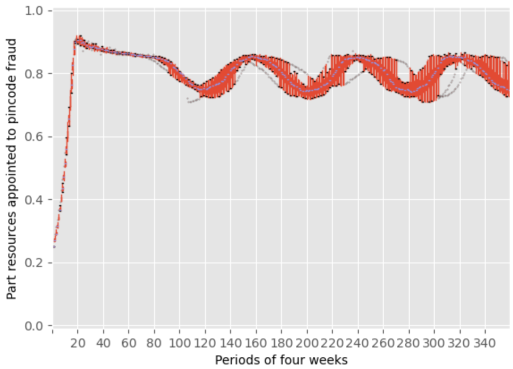


(a) Part resources appointed to scan

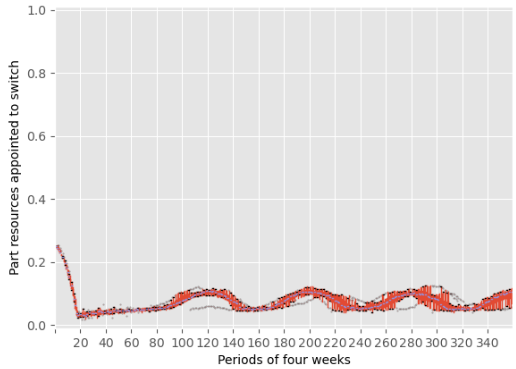


(b) Part resources appointed to surveillance

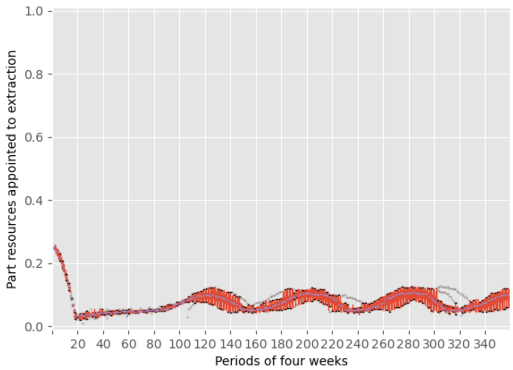
Figure D.7: Distribution law enforcement agencies methods with constant zero equal



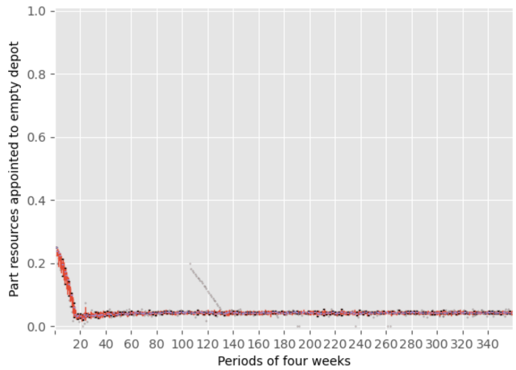
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

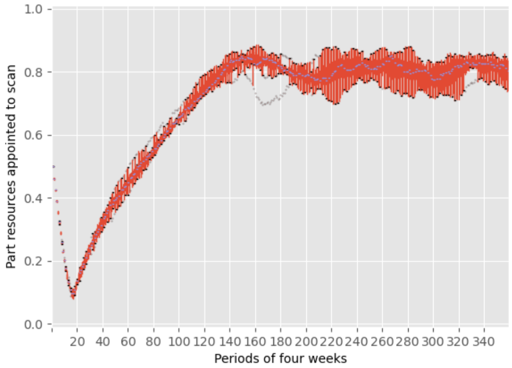


(c) Part resources appointed to extracting

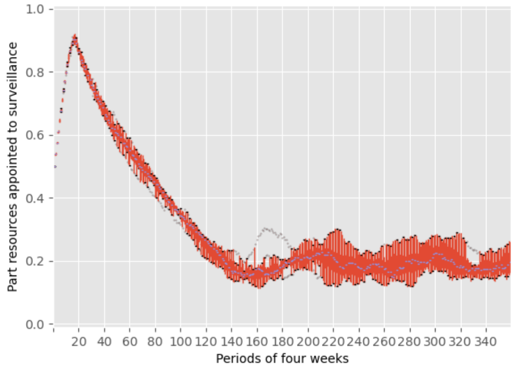


(d) Part resources appointed to empty depot

Figure D.8: Distribution criminal constant zero equal

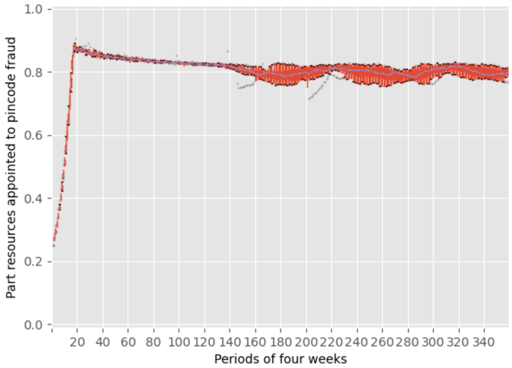


(a) Part resources appointed to scan

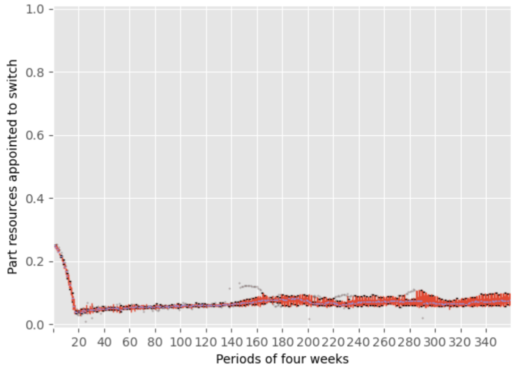


(b) Part resources appointed to surveillance

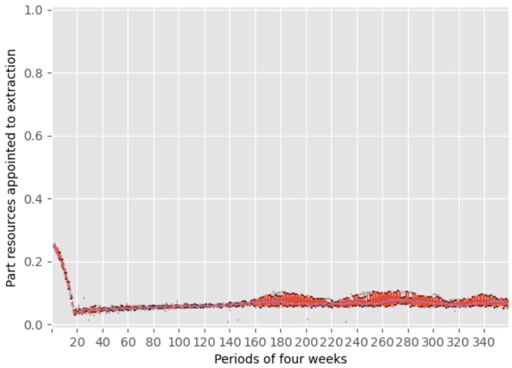
Figure D.9: Distribution law enforcement agencies methods constant non zero equal



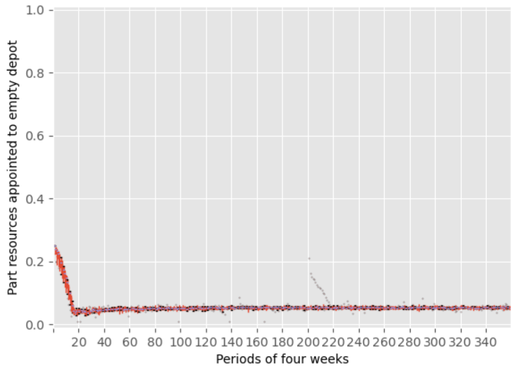
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

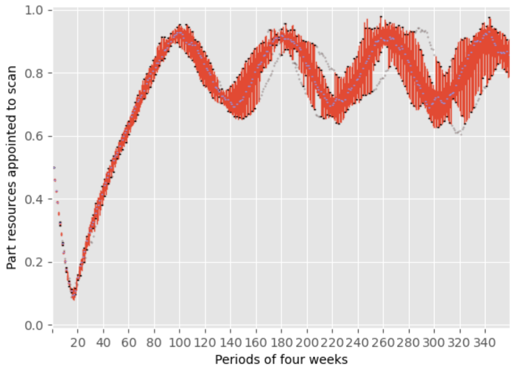


(c) Part resources appointed to extracting

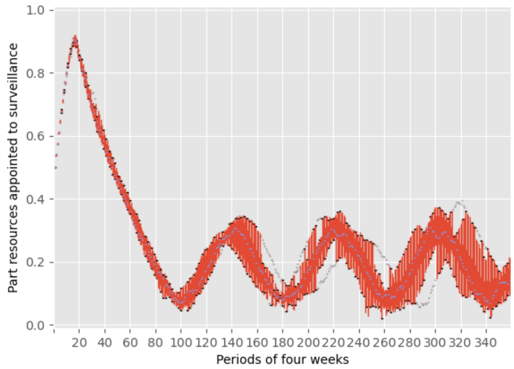


(d) Part resources appointed to empty depot

Figure D.10: Distribution criminal methods constant non zero equal

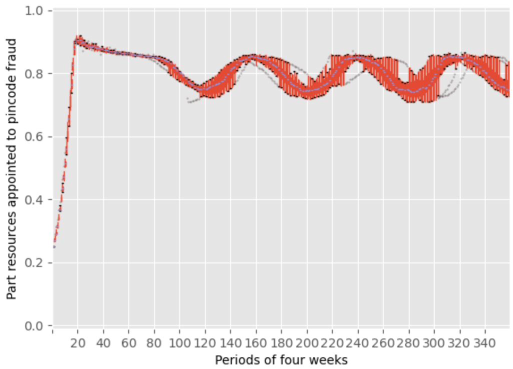


(a) Part resources appointed to scan

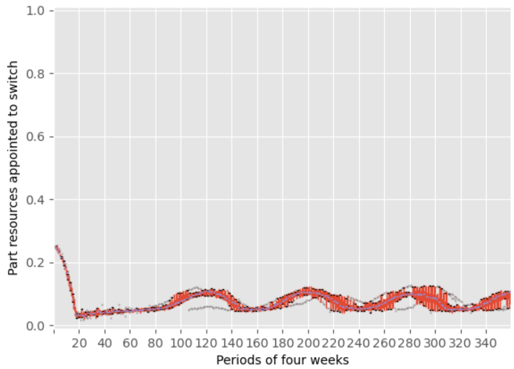


(b) Part resources appointed to surveillance

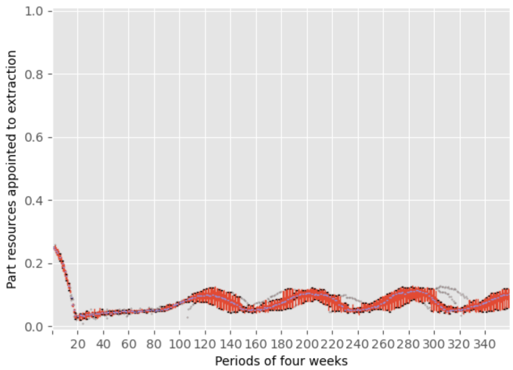
Figure D.11: Distribution law enforcement agencies methods with constant back zero equal



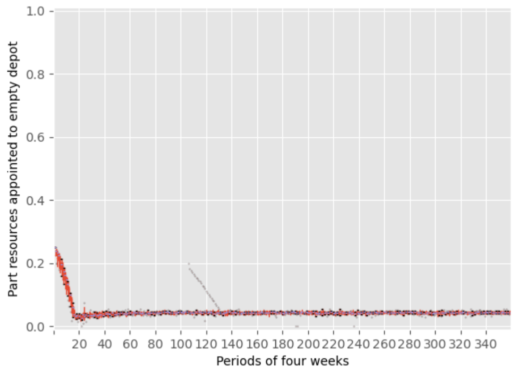
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

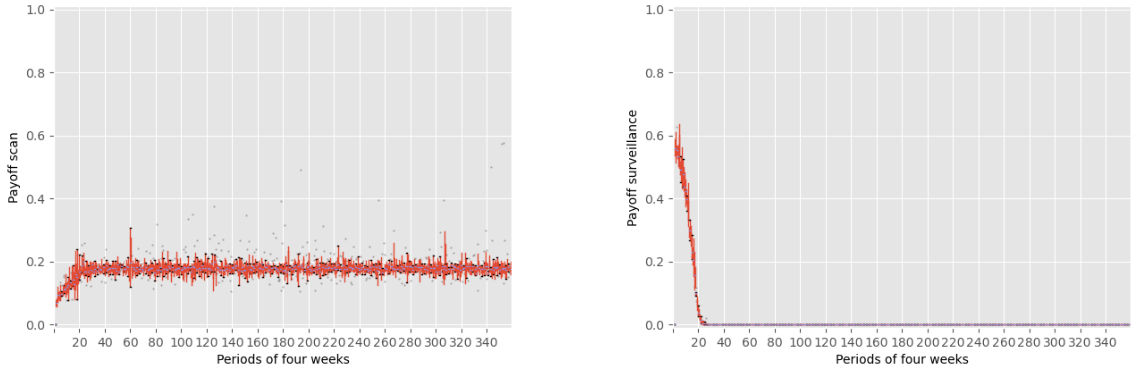


(c) Part resources appointed to extracting



(d) Part resources appointed to empty depot

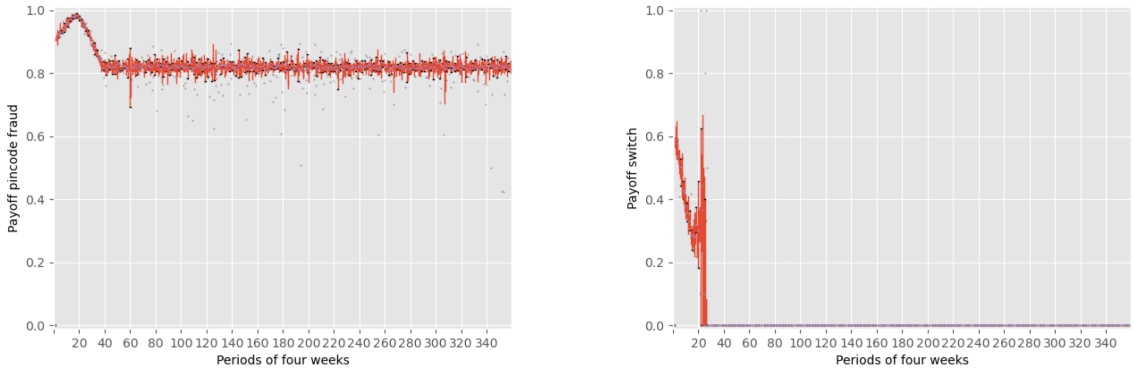
Figure D.12: Distribution criminal constant back zero equal



(a) Payoff scan

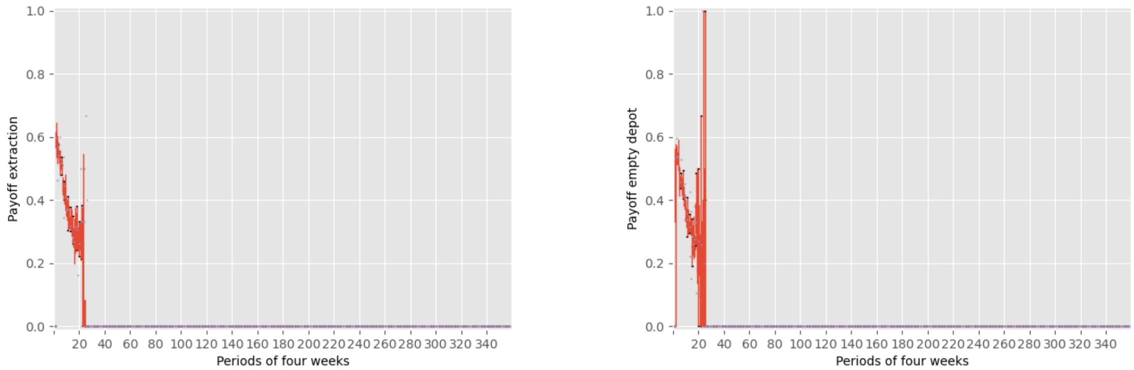
(b) Payoff surveillance

Figure D.13: Payoff law enforcement agencies methods with poker zero equal



(a) Payoff pincode fraud

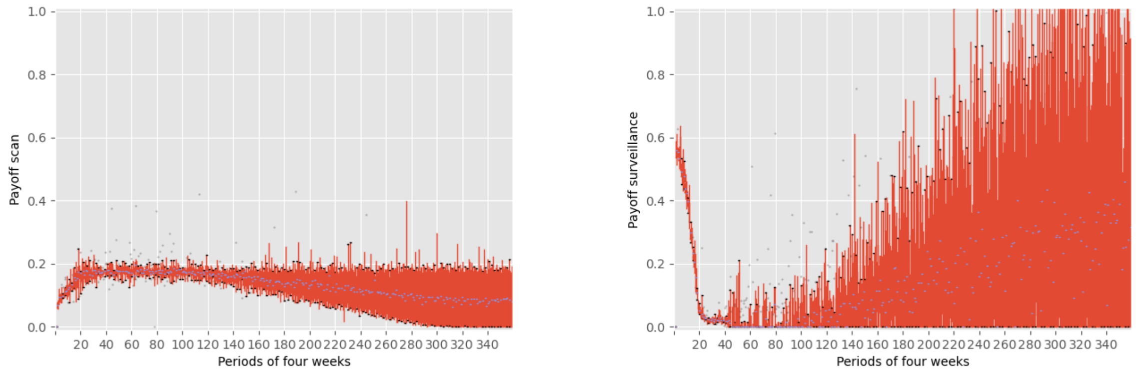
(b) Payoff switch and pincode fraud



(c) Payoff extracting

(d) Payoff empty depot

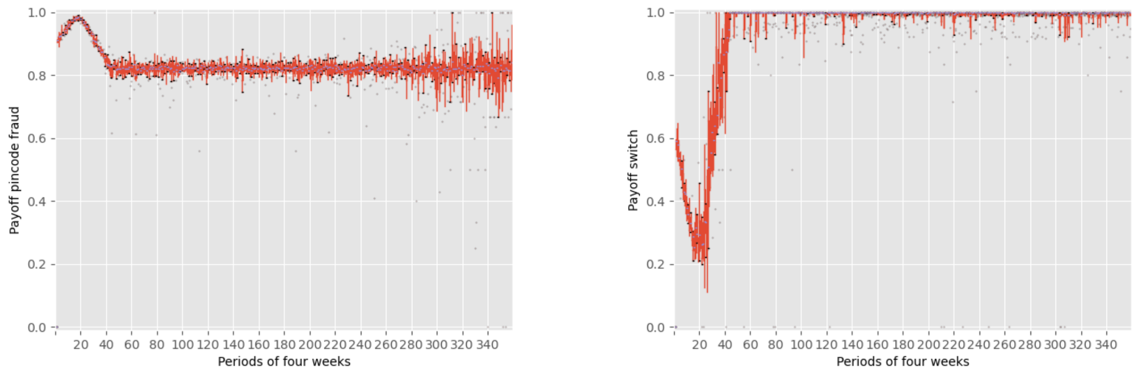
Figure D.14: Payoff criminal poker zero equal



(a) Payoff scan

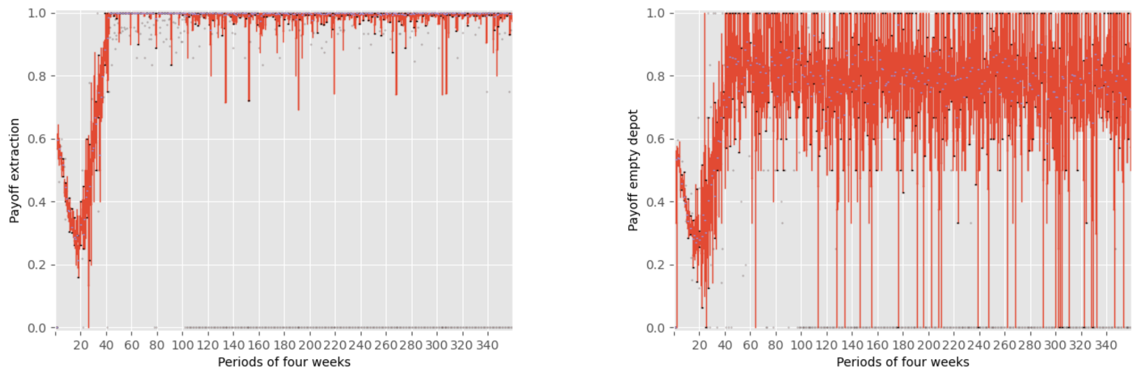
(b) Payoff surveillance

Figure D.15: Payoff law enforcement agencies methods poker non zero equal



(a) Payoff pincode fraud

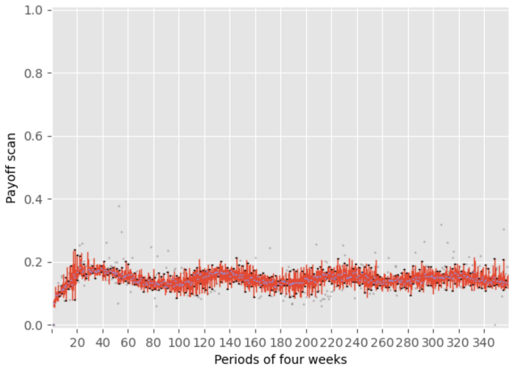
(b) Payoff switch and pincode fraud



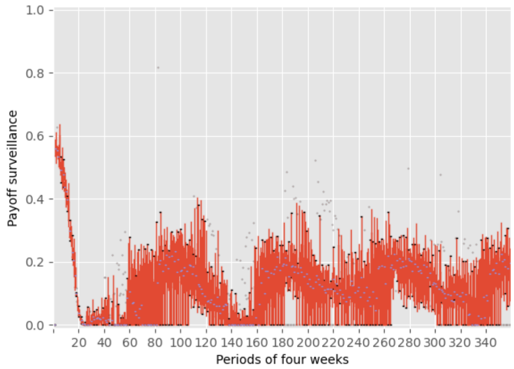
(c) Payoff extracting

(d) Payoff empty depot

Figure D.16: Payoff criminal methods poker non zero equal

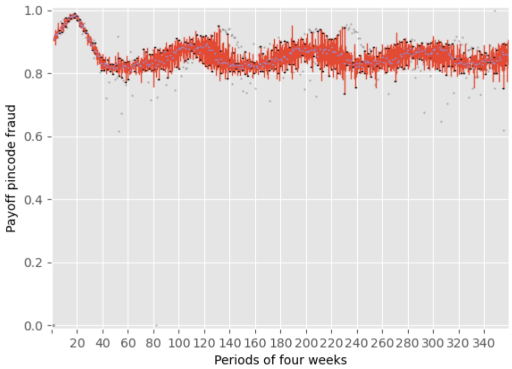


(a) Payoff scan

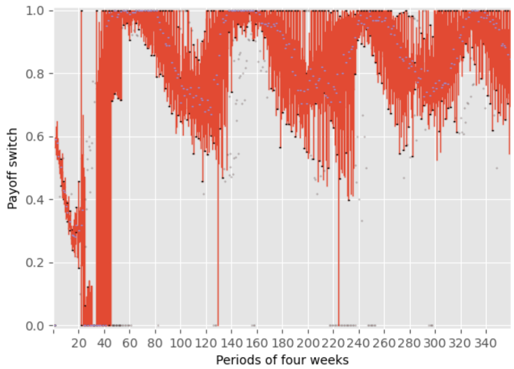


(b) Payoff surveillance

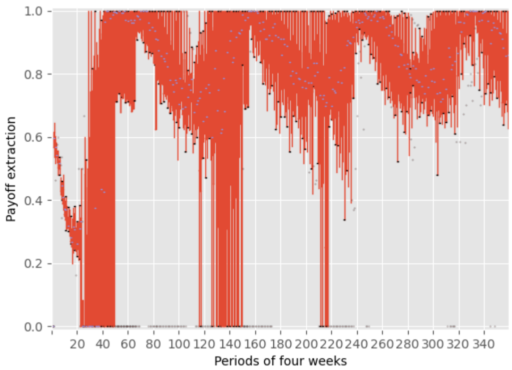
Figure D.17: Payoff law enforcement agencies methods with poker back zero equal



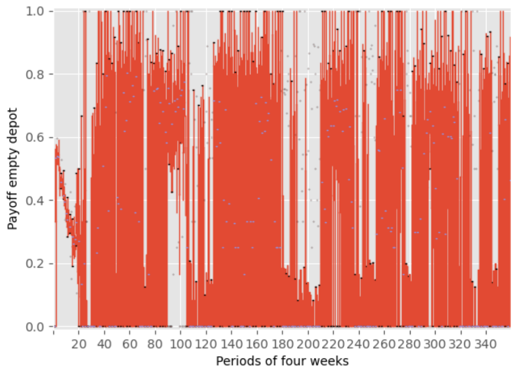
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

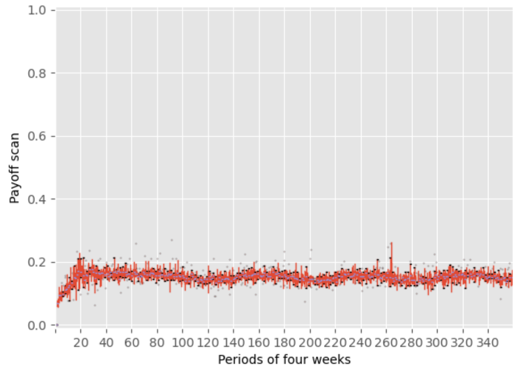


(c) Payoff extracting

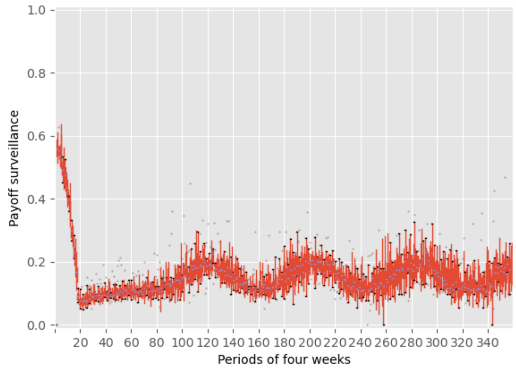


(d) Payoff empty depot

Figure D.18: Payoff criminal poker back zero equal

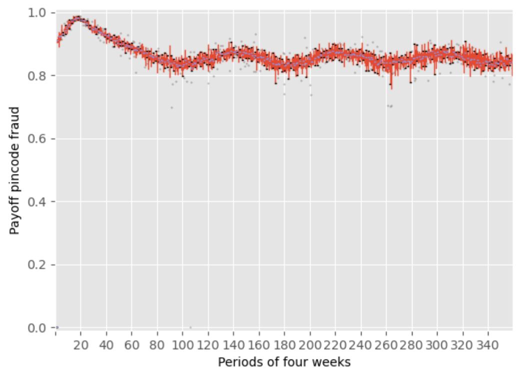


(a) Payoff scan

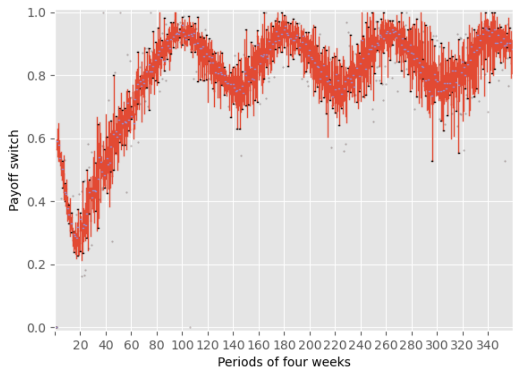


(b) Payoff surveillance

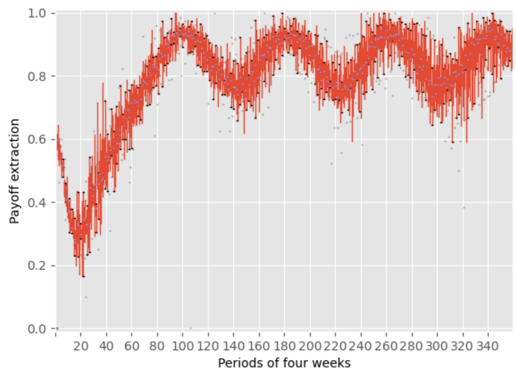
Figure D.19: Payoff law enforcement agencies methods with constant zero equal



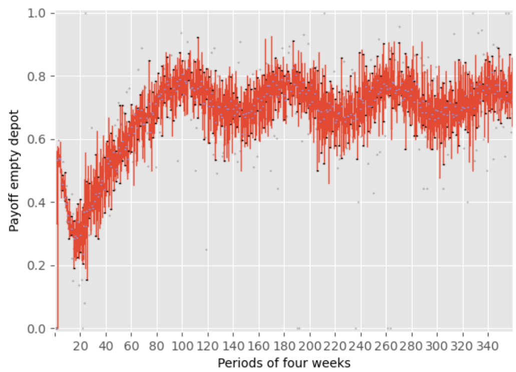
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

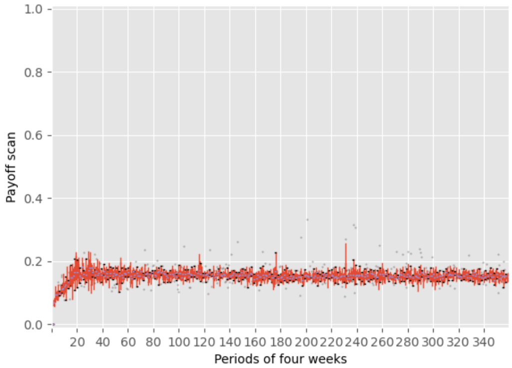


(c) Payoff extracting

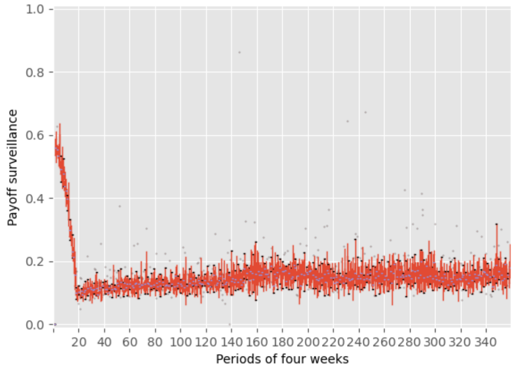


(d) Payoff empty depot

Figure D.20: Payoff criminal constant zero equal

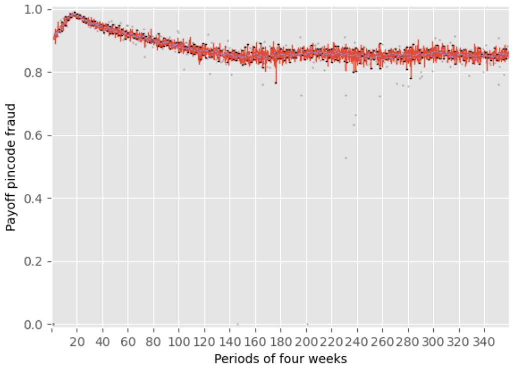


(a) Payoff scan

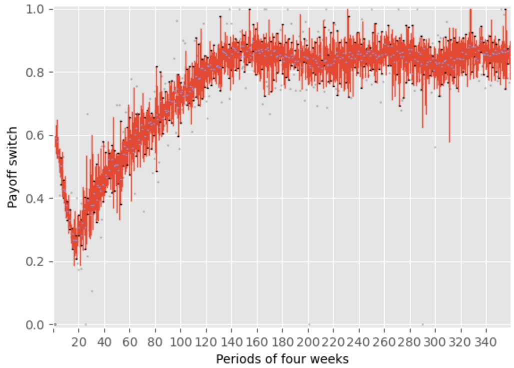


(b) Payoff surveillance

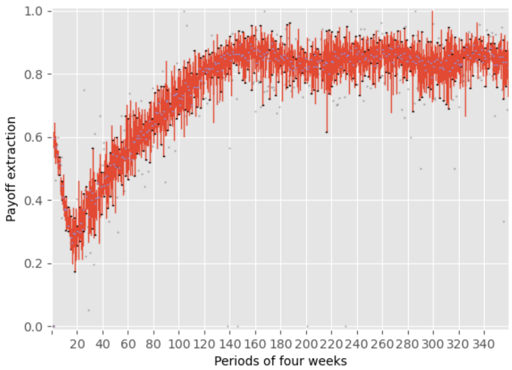
Figure D.21: Payoff law enforcement agencies methods constant non zero equal



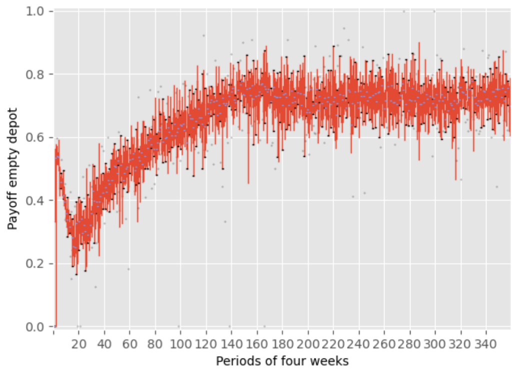
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

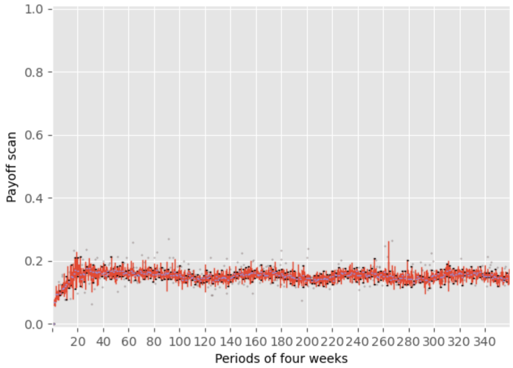


(c) Payoff extracting

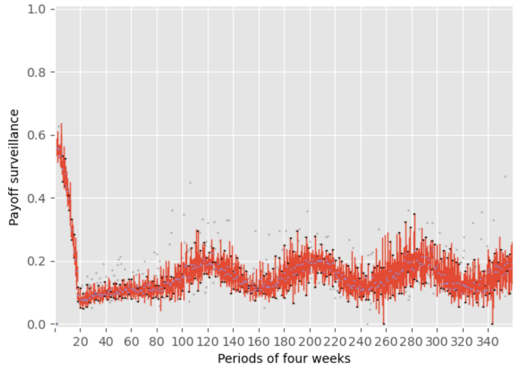


(d) Payoff empty depot

Figure D.22: Payoff criminal methods constant non zero equal

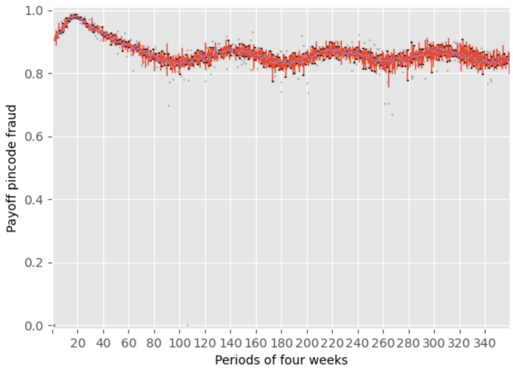


(a) Payoff scan

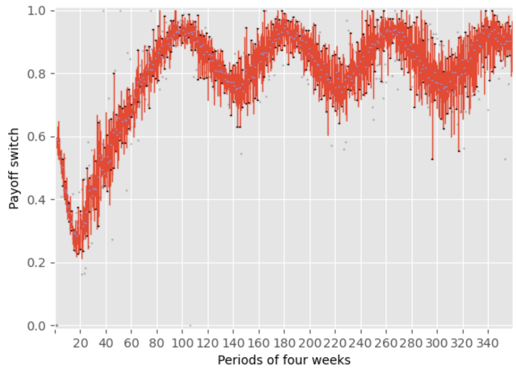


(b) Payoff surveillance

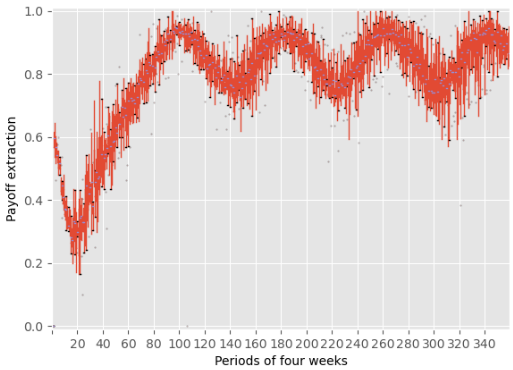
Figure D.23: Payoff law enforcement agencies methods with constant back zero equal



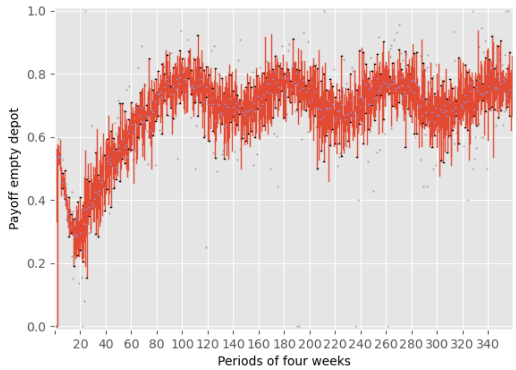
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud



(c) Payoff extracting



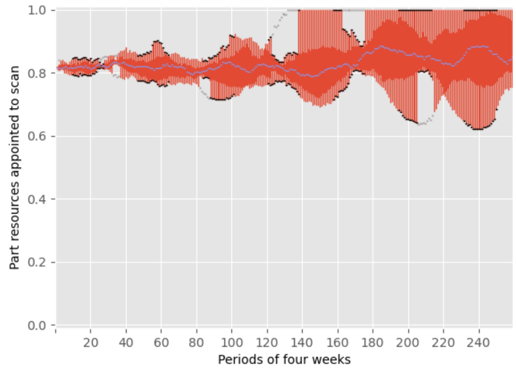
(d) Payoff empty depot

Figure D.24: Payoff criminal constant back zero equal

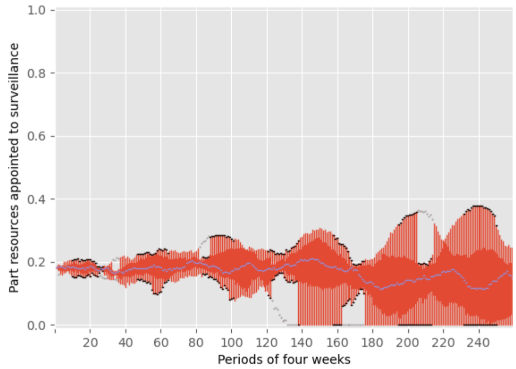
D.2. Updating rules starting in the Nash equilibrum

This section shows the output for all six tested updating rules. The values used in these updating rules for the output graphs are a cutoff of 0.01 for rules that are not allowed to have any methods go to zero and a reoccur value of 0.05 for the methods that come back from zero. Every period law enforcement reappoint 0.1 part of their resources and criminals reappoint 0.2 of their resources every period. This section shows 6 replications. It first shows the distribution of resources for each updating rule and then the payoff for each method which explains how the distribution of resources is modelled.

The figures in this section show that for each updating rule the behaviour of the graphs shows a cyclic pattern around the Nash equilibrium with a few exceptions when law enforcement agencies get stuck appointing (almost) all their resources to only one of their methods while criminals are not stuck and can adapt to this behaviour.

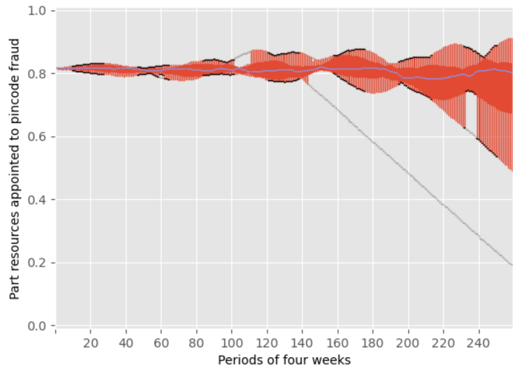


(a) Part resources appointed to scan

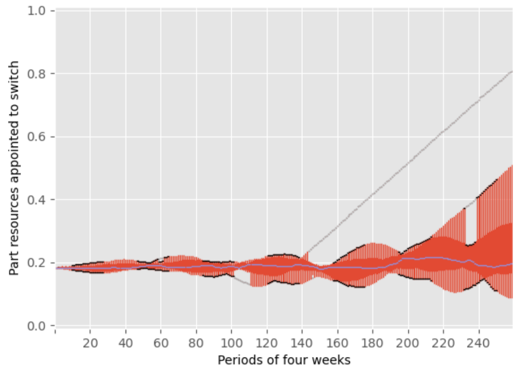


(b) Part resources appointed to surveillance

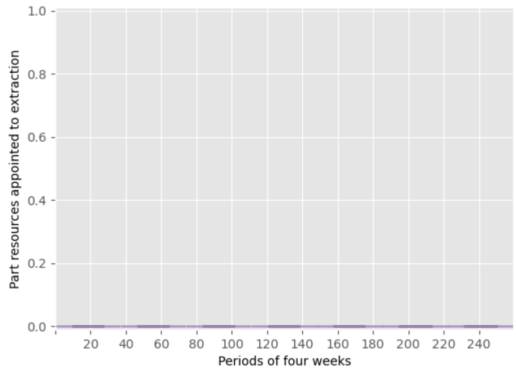
Figure D.25: Distribution law enforcement agencies methods with poker zero nash



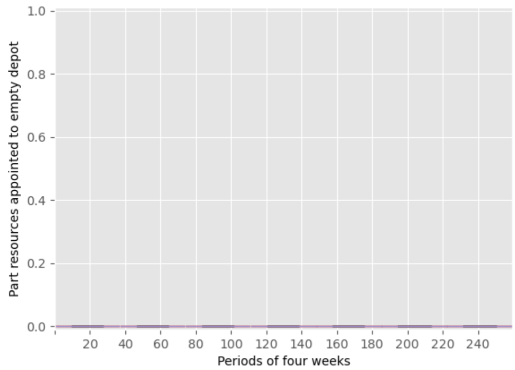
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

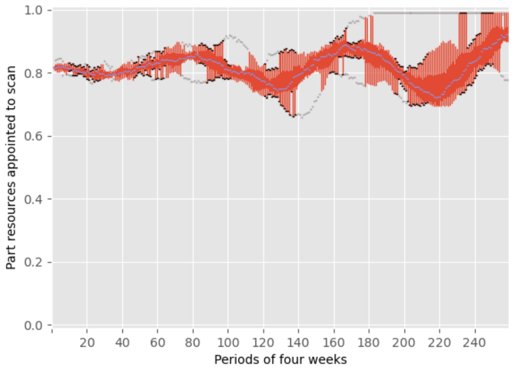


(c) Part resources appointed to extracting

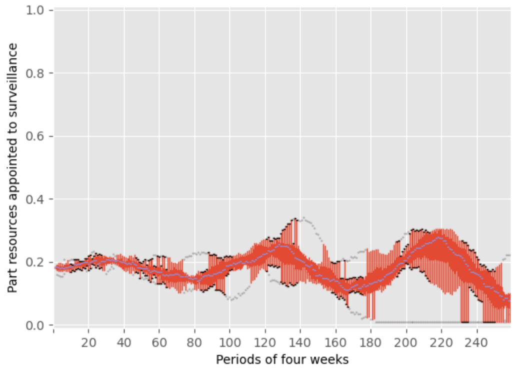


(d) Part resources appointed to empty depot

Figure D.26: Distribution criminal poker zero nash

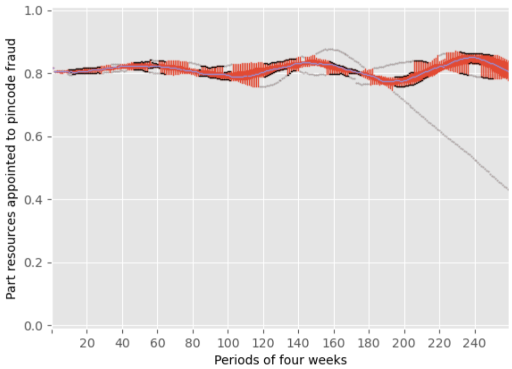


(a) Part resources appointed to scan

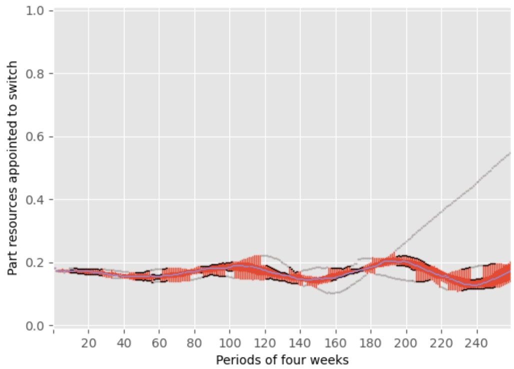


(b) Part resources appointed to surveillance

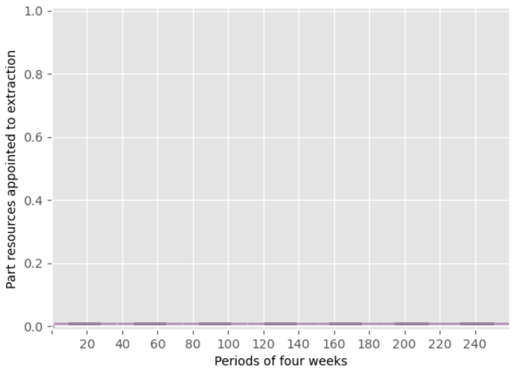
Figure D.27: Distribution law enforcement agencies methods poker non zero nash



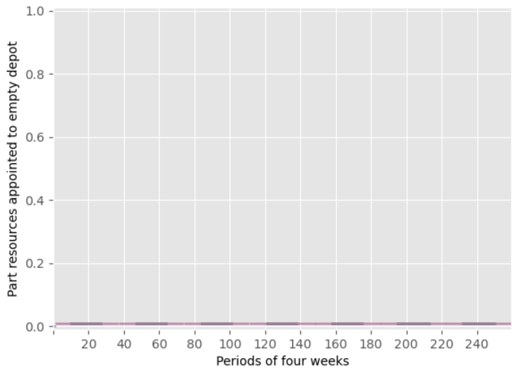
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

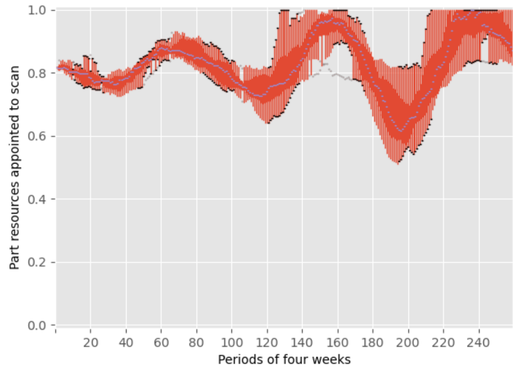


(c) Part resources appointed to extracting

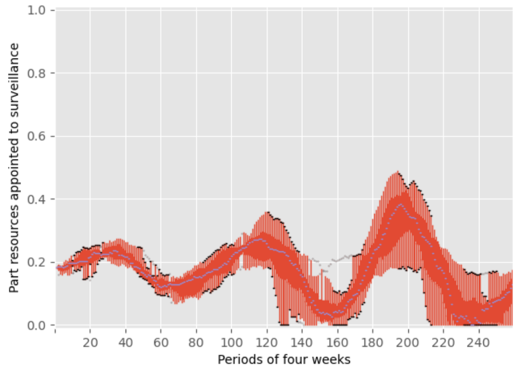


(d) Part resources appointed to empty depot

Figure D.28: Distribution criminal methods poker non zero nash

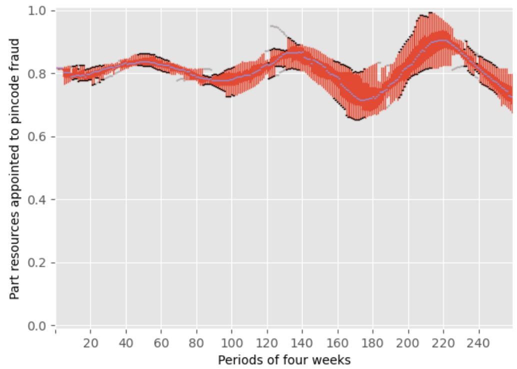


(a) Part resources appointed to scan

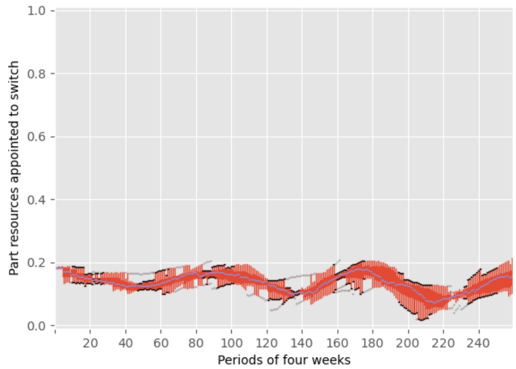


(b) Part resources appointed to surveillance

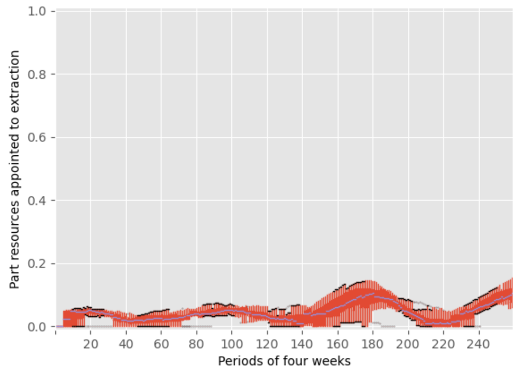
Figure D.29: Distribution law enforcement agencies methods with poker back zero nash



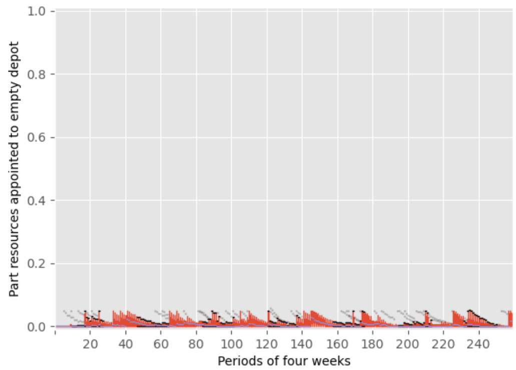
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

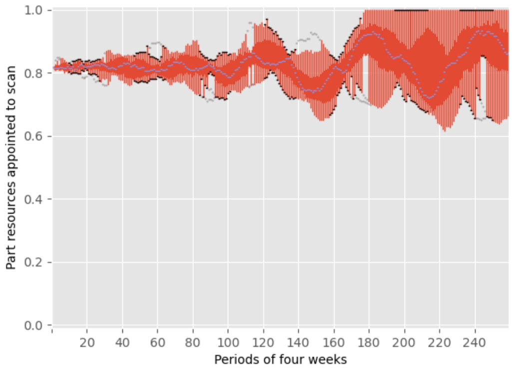


(c) Part resources appointed to extracting

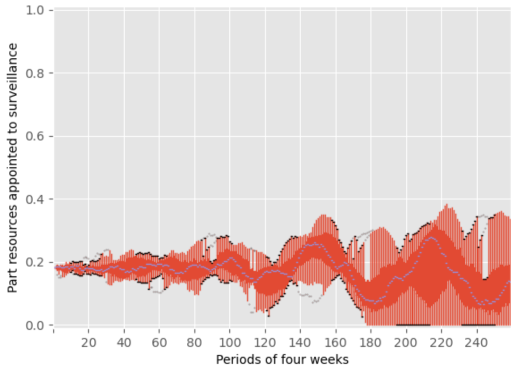


(d) Part resources appointed to empty depot

Figure D.30: Distribution criminal poker back zero nash

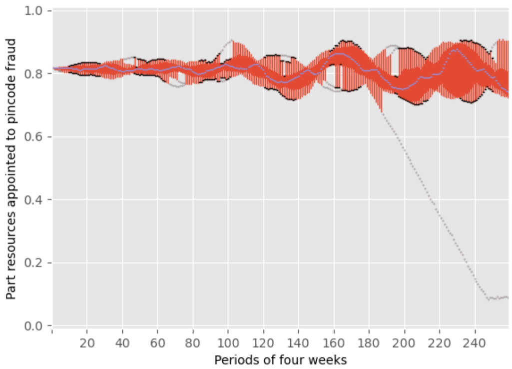


(a) Part resources appointed to scan

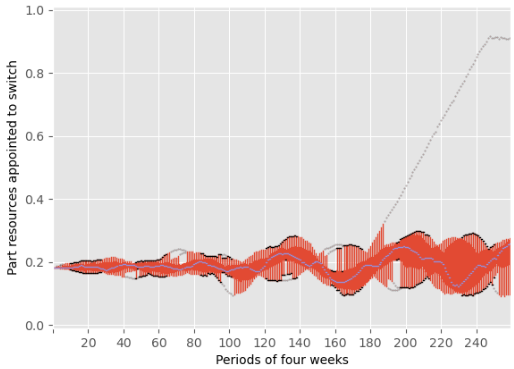


(b) Part resources appointed to surveillance

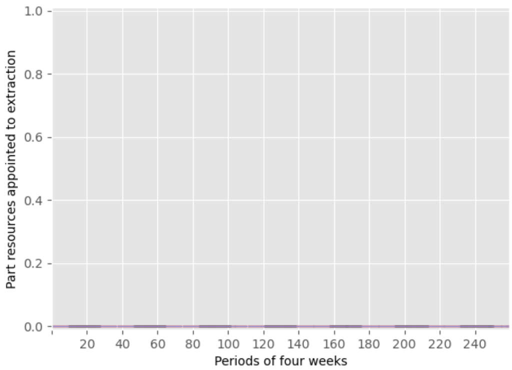
Figure D.31: Distribution law enforcement agencies methods with constant zero nash



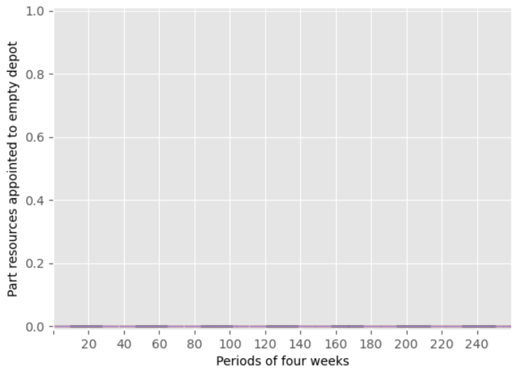
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

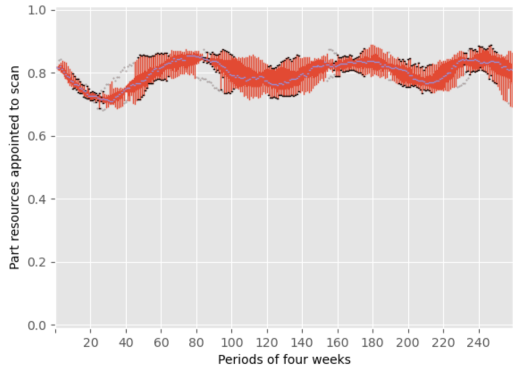


(c) Part resources appointed to extracting

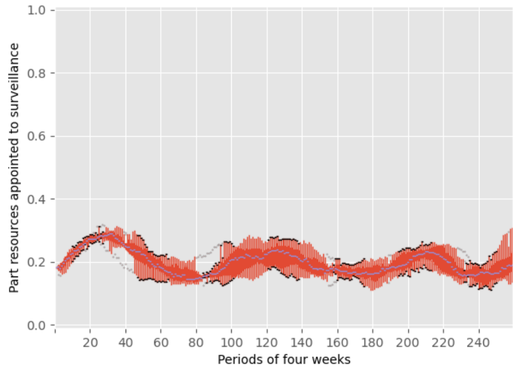


(d) Part resources appointed to empty depot

Figure D.32: Distribution criminal constant zero nash

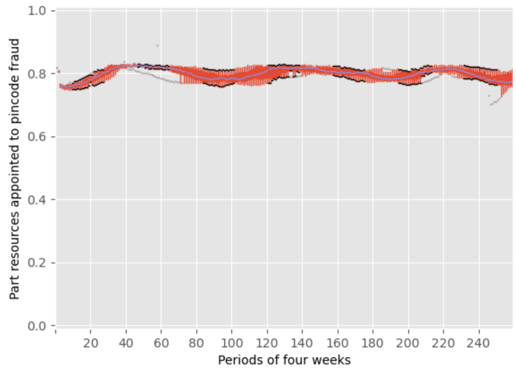


(a) Part resources appointed to scan

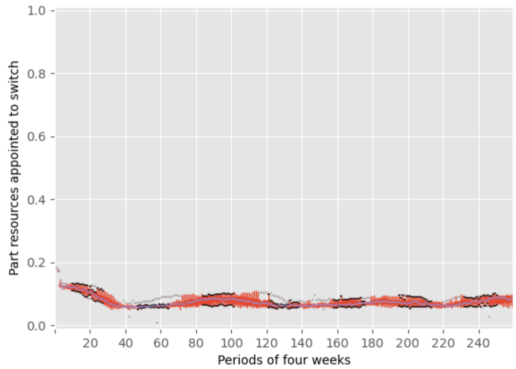


(b) Part resources appointed to surveillance

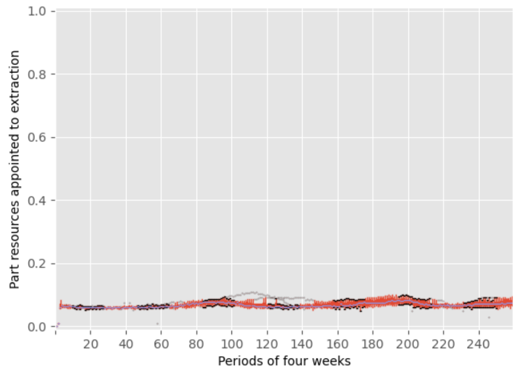
Figure D.33: Distribution law enforcement agencies methods constant non zero nash



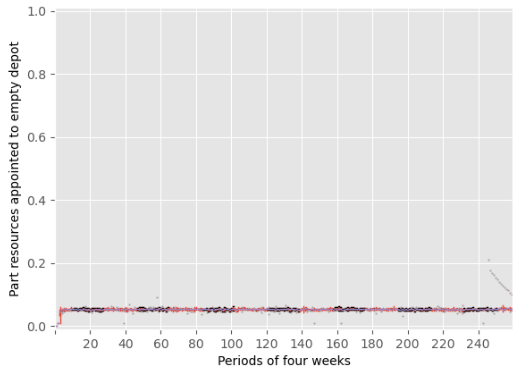
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

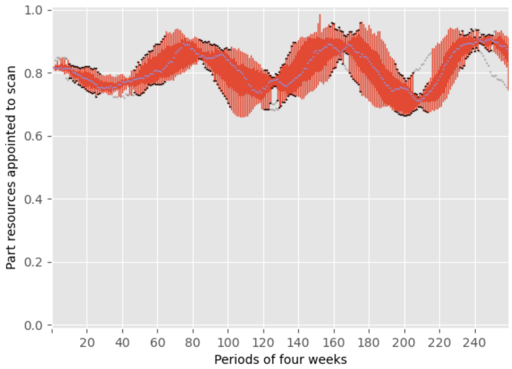


(c) Part resources appointed to extracting

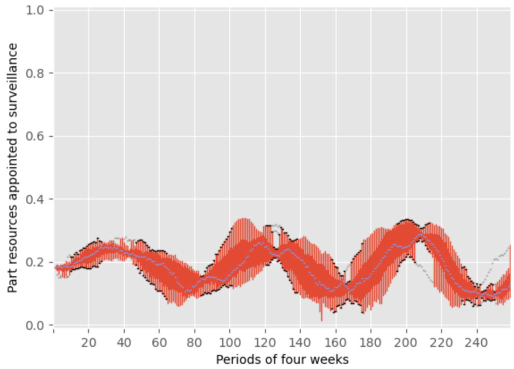


(d) Part resources appointed to empty depot

Figure D.34: Distribution criminal methods constant non zero nash

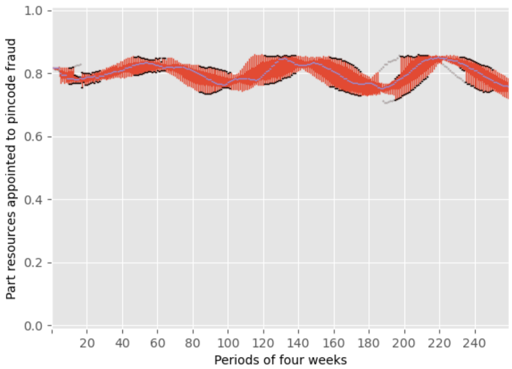


(a) Part resources appointed to scan

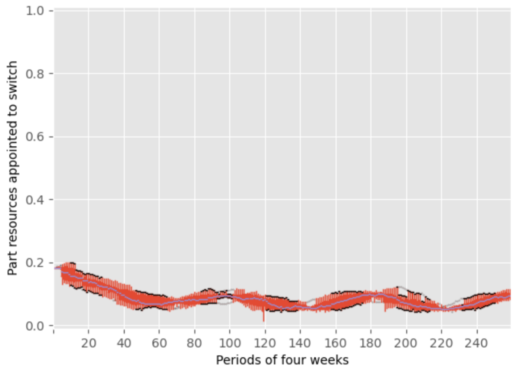


(b) Part resources appointed to surveillance

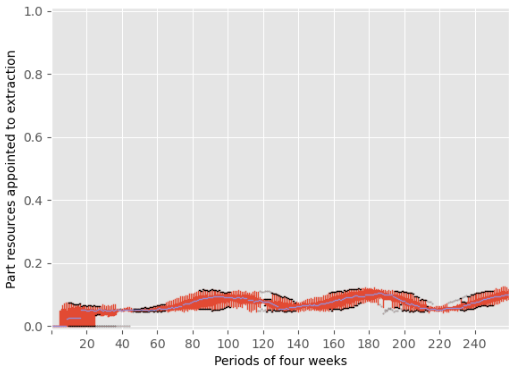
Figure D.35: Distribution law enforcement agencies methods with constant back zero nash



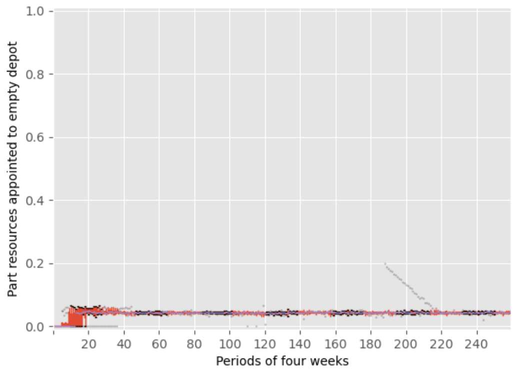
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

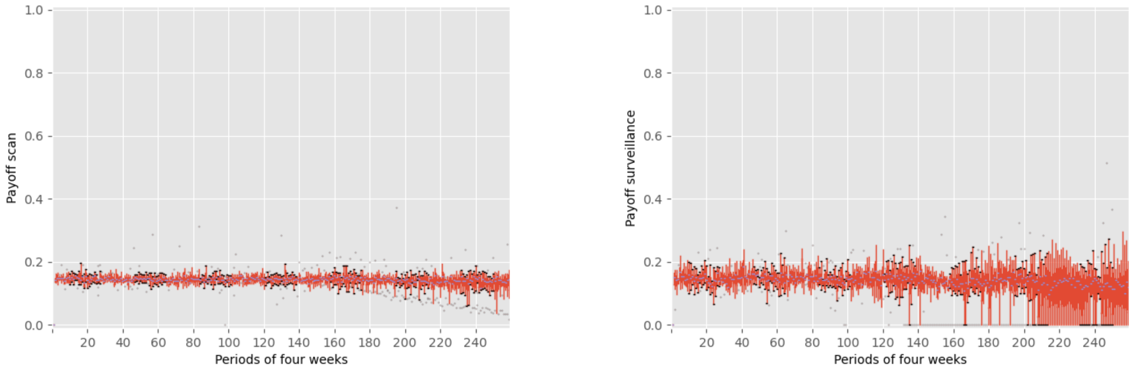


(c) Part resources appointed to extracting



(d) Part resources appointed to empty depot

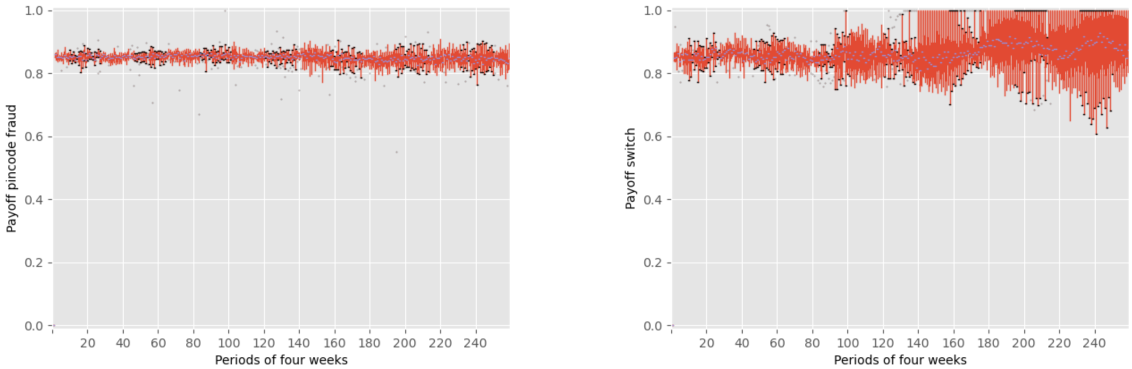
Figure D.36: Distribution criminal constant back zero nash



(a) Payoff scan

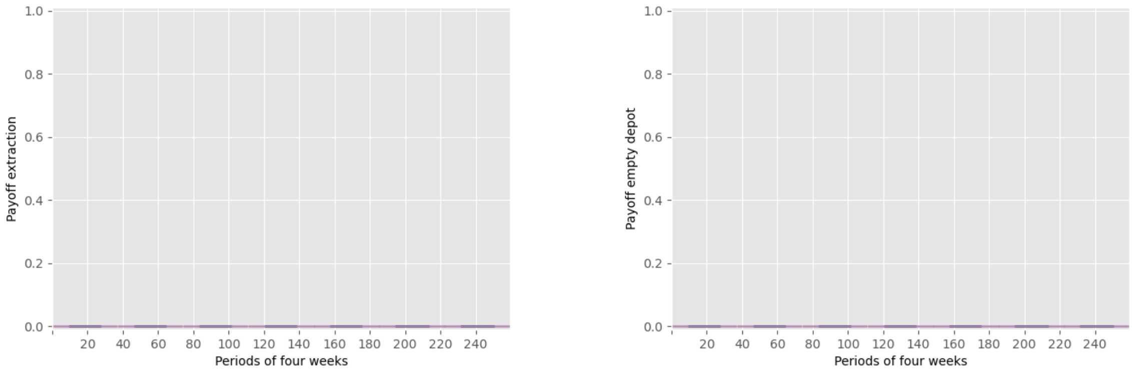
(b) Payoff surveillance

Figure D.37: Payoff law enforcement agencies methods with poker zero nash



(a) Payoff pincode fraud

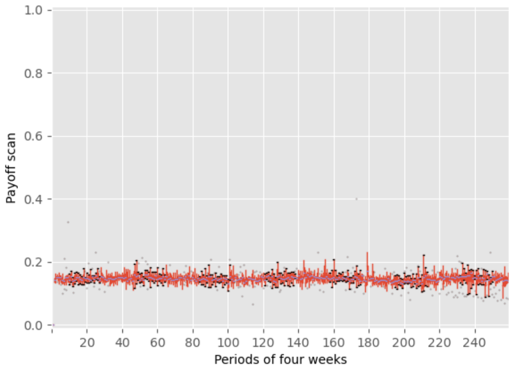
(b) Payoff switch and pincode fraud



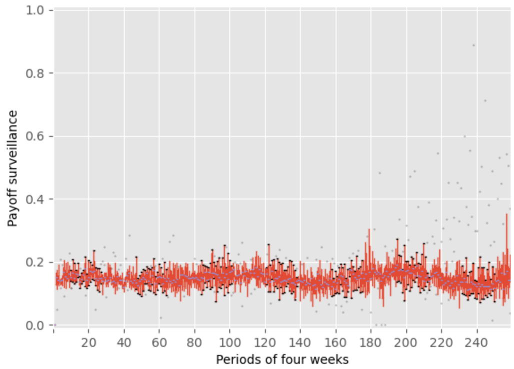
(c) Payoff extracting

(d) Payoff empty depot

Figure D.38: Payoff criminal poker zero nash

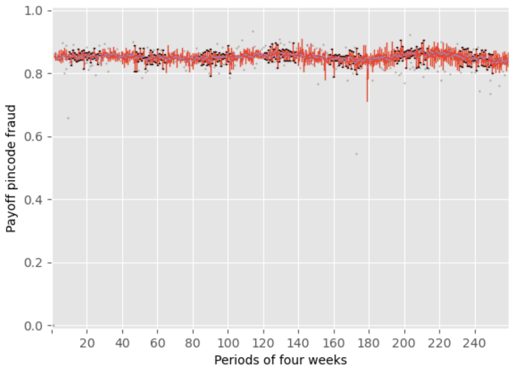


(a) Payoff scan

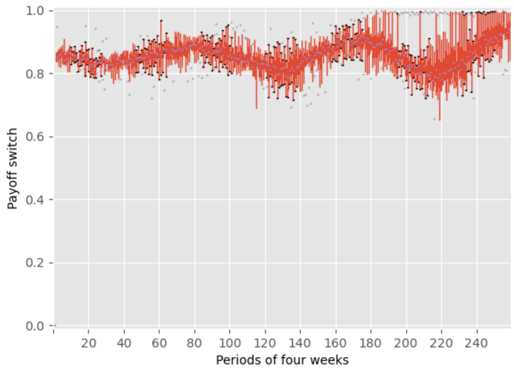


(b) Payoff surveillance

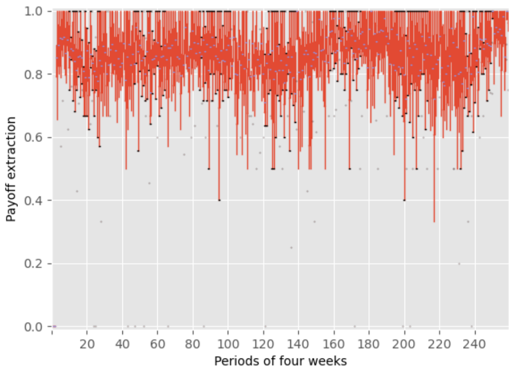
Figure D.39: Payoff law enforcement agencies methods poker non zero nash



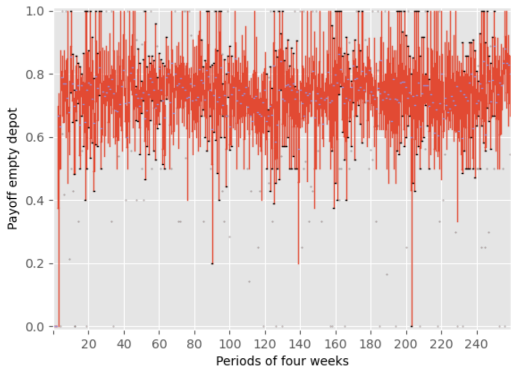
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

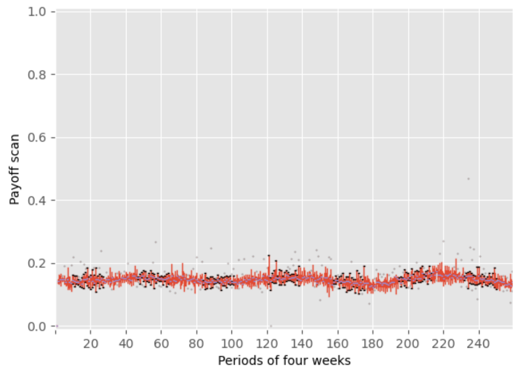


(c) Payoff extracting

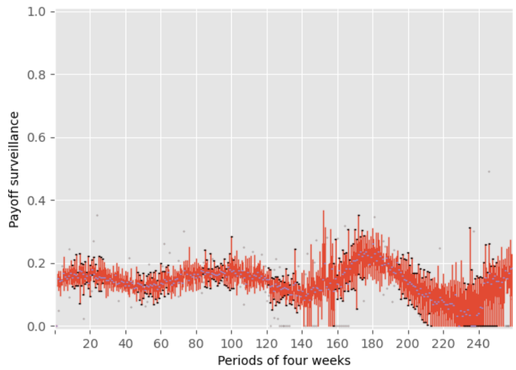


(d) Payoff empty depot

Figure D.40: Payoff criminal methods poker non zero nash

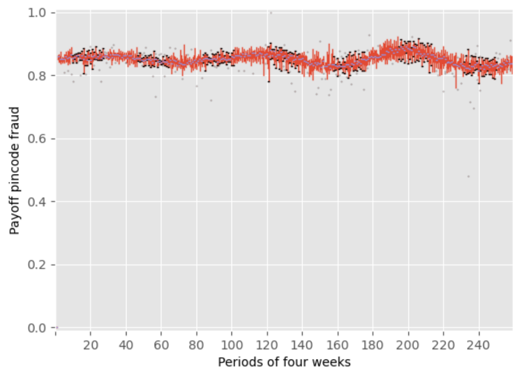


(a) Payoff scan

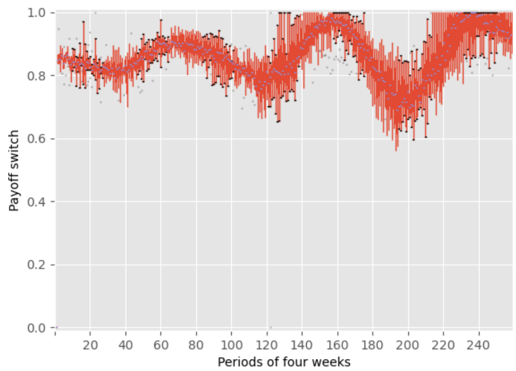


(b) Payoff surveillance

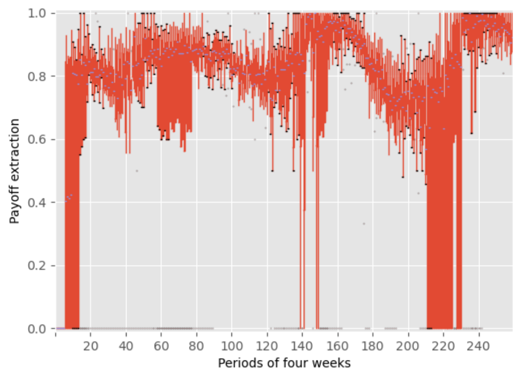
Figure D.41: Payoff law enforcement agencies methods with poker back zero nash



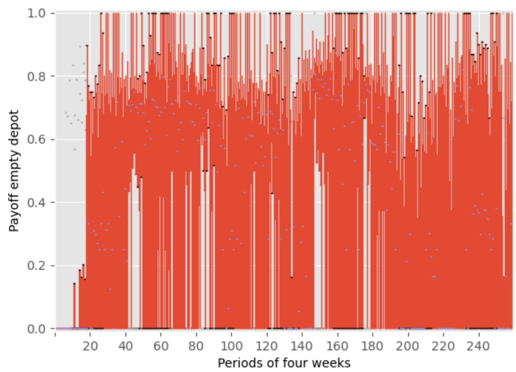
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

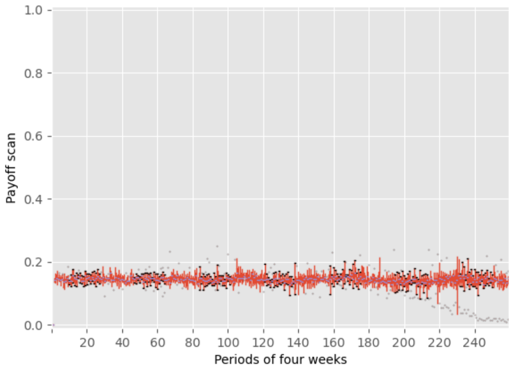


(c) Payoff extracting

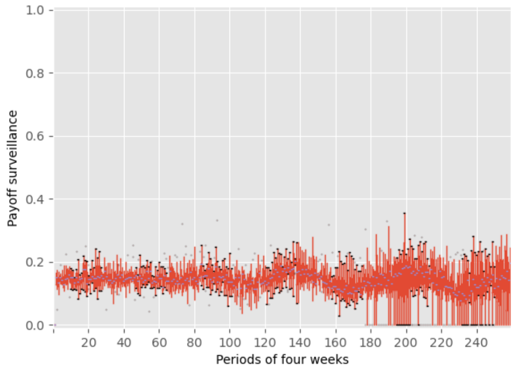


(d) Payoff empty depot

Figure D.42: Payoff criminal poker back zero nash

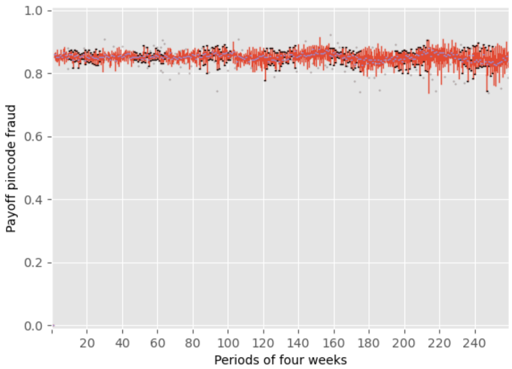


(a) Payoff scan

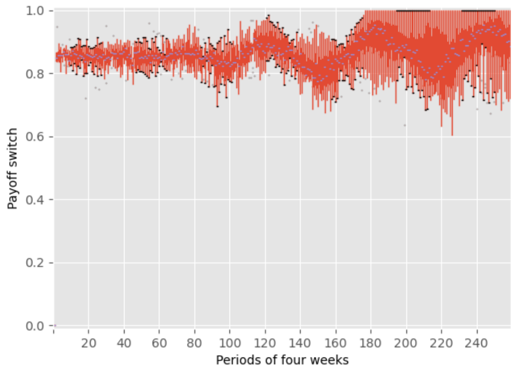


(b) Payoff surveillance

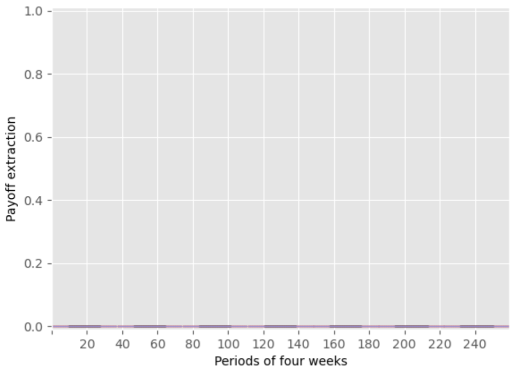
Figure D.43: Payoff law enforcement agencies methods with constant zero nash



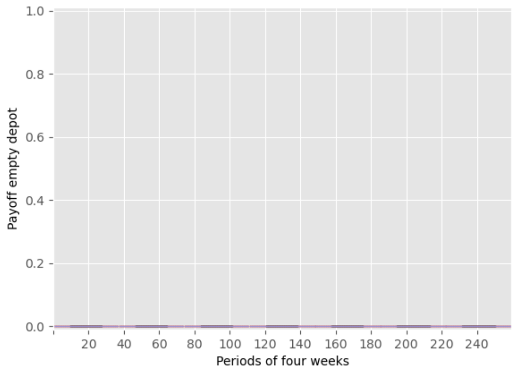
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

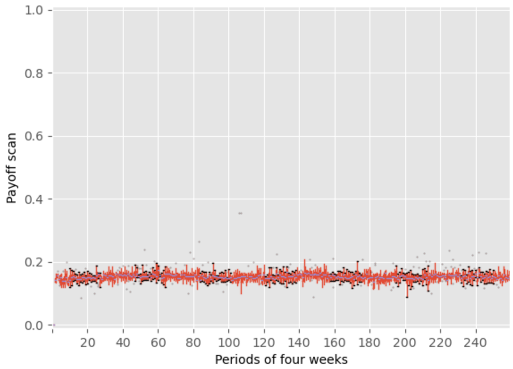


(c) Payoff extracting

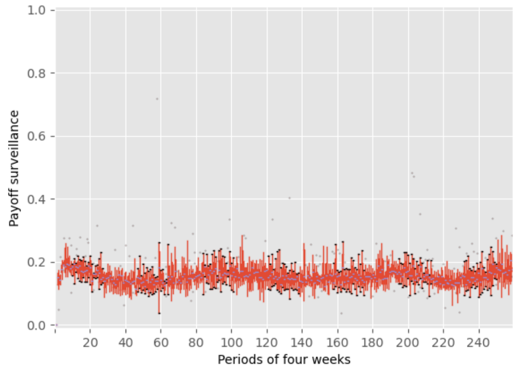


(d) Payoff empty depot

Figure D.44: Payoff criminal constant zero nash

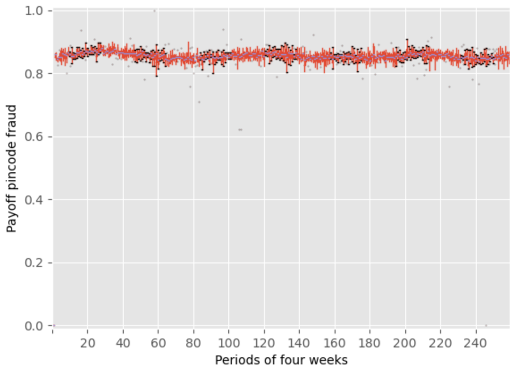


(a) Payoff scan

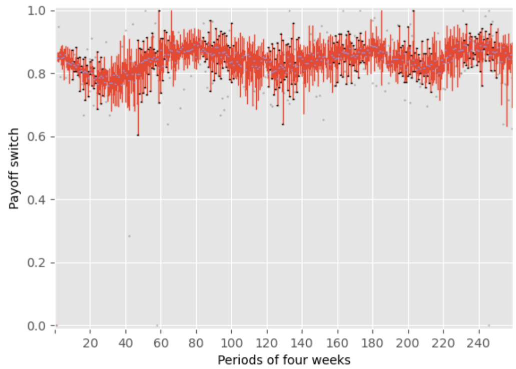


(b) Payoff surveillance

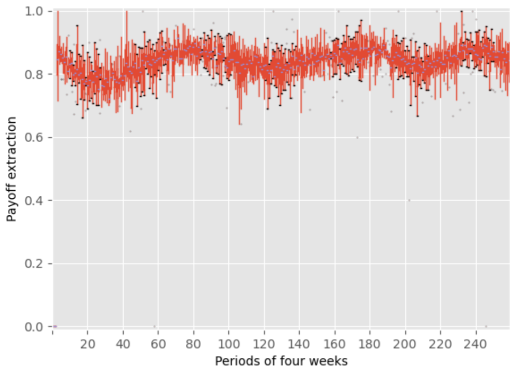
Figure D.45: Payoff law enforcement agencies methods constant non zero nash



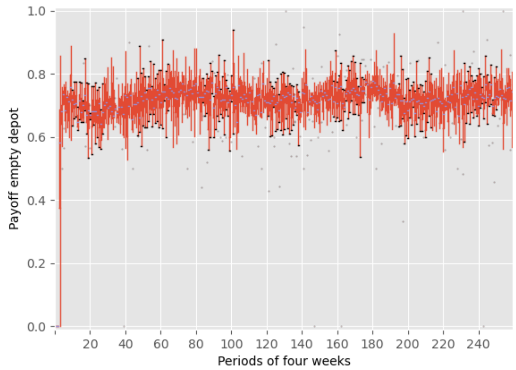
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

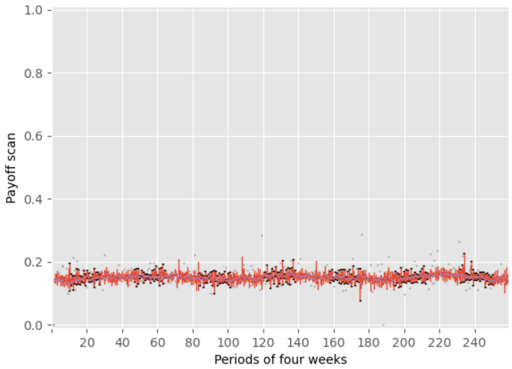


(c) Payoff extracting

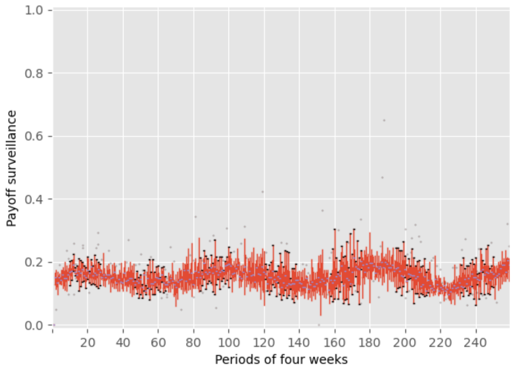


(d) Payoff empty depot

Figure D.46: Payoff criminal methods constant non zero nash

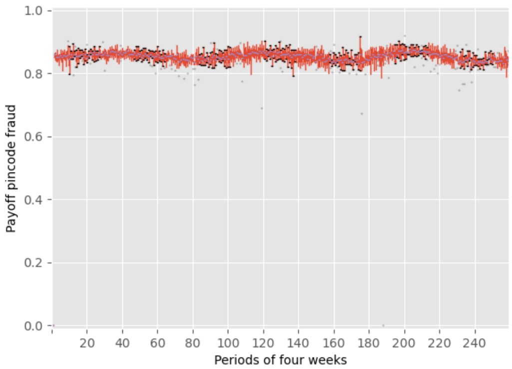


(a) Payoff scan

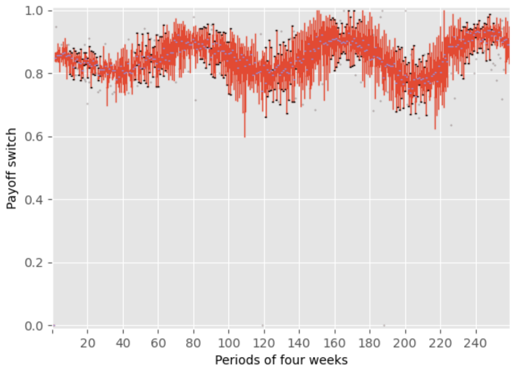


(b) Payoff surveillance

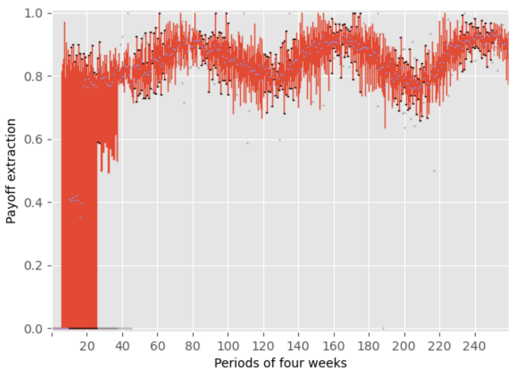
Figure D.47: Payoff law enforcement agencies methods with constant back zero nash



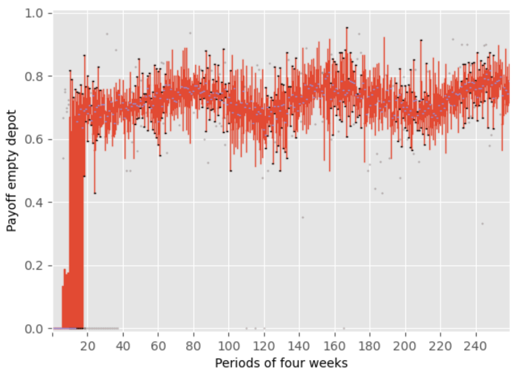
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud



(c) Payoff extracting



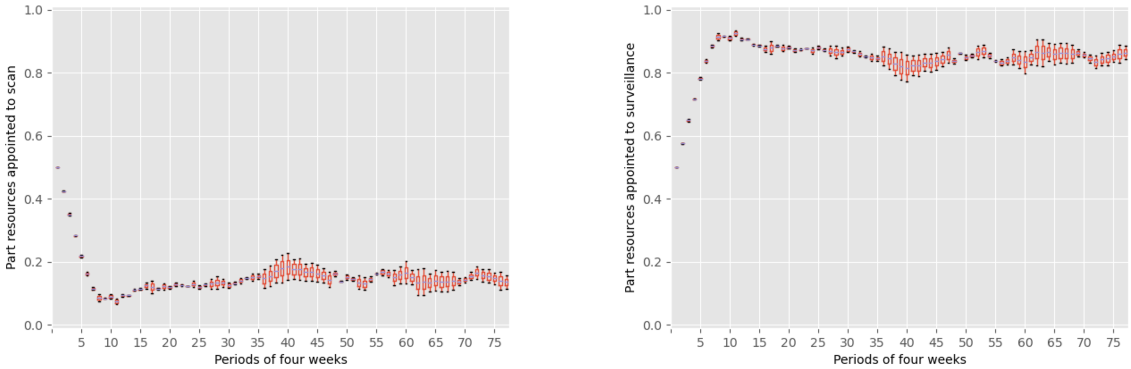
(d) Payoff empty depot

Figure D.48: Payoff criminal constant back zero nash

D.3. Constant updating rules starting with an equal part of resources for different parameters

This section shows the output for the three constant updating rules. The values used in these updating rules for the output graphs are a cutoff of 0.01 for rules that are not allowed to have any methods go to zero and a reoccur value of 0.05 for the methods that come back from zero. Every period law enforcement reappoint 0.2 part of their resources and criminals reappoint 0.4 of their resources every period. This section shows 3 replications. It first shows the distribution of resources for each updating rule and then the payoff for each method which explains how the distribution of resources is modelled. Notice that the next to the numbers of periods and the number of replications shown the only difference with the graphs in the first section is that the parameters of which part of the resources are reappointed for law enforcement agencies and criminals are doubled.

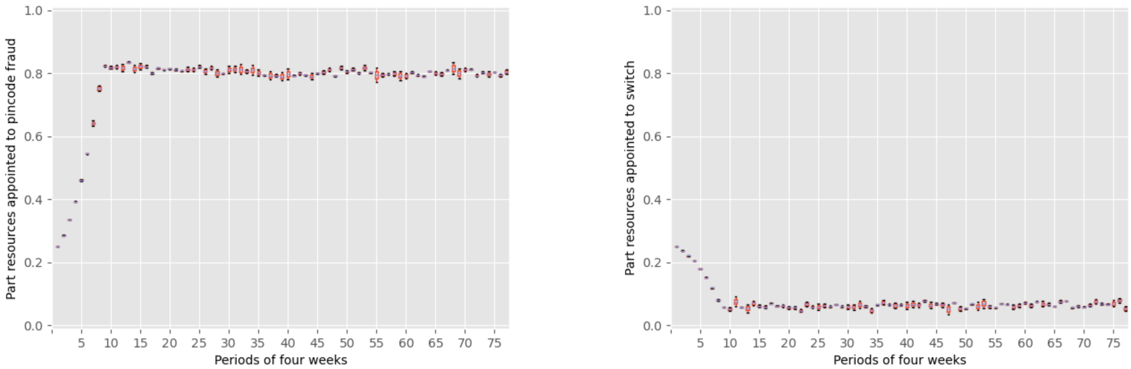
These graphs clearly show that, unlike the graphs in the first section, no cyclic pattern is achieved in distributing resources among methods. There is also no sign of the Nash equilibrium. In all three updating rules, this is caused by the new parameters since these parameters cause the pincode fraud method to get stable instead of rising which would lead to a cyclic pattern. The payoffs of pincode fraud show that based on the payoff this method should be appointed more resources which does not happen. The pincode fraud method gets stuck due to the other methods not being able to get any lower as this constant updating rule makes this impossible.



(a) Part resources appointed to scan

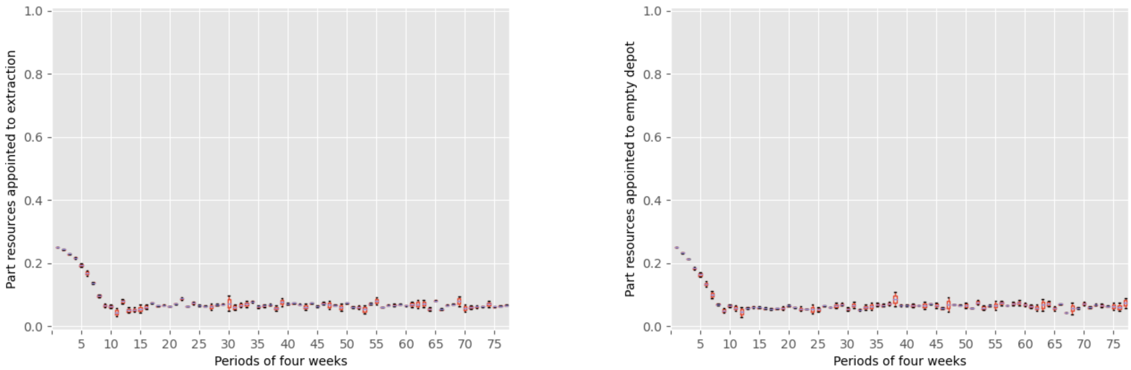
(b) Part resources appointed to surveillance

Figure D.49: Distribution law enforcement agencies methods with constant zero equal



(a) Part resources appointed to pincode fraud

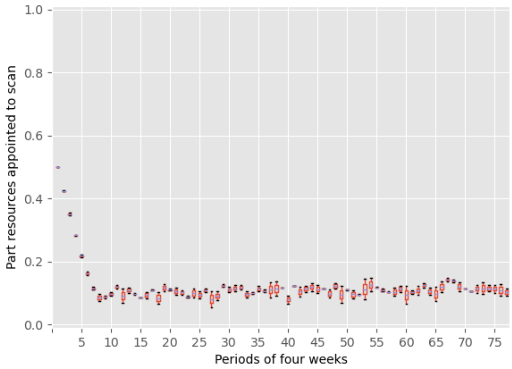
(b) Part resources appointed to switch and pincode fraud



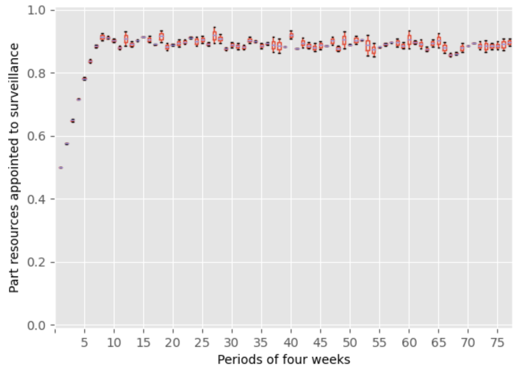
(c) Part resources appointed to extracting

(d) Part resources appointed to empty depot

Figure D.50: Distribution criminal constant zero equal

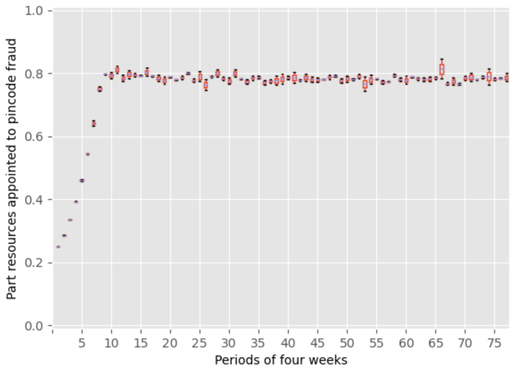


(a) Part resources appointed to scan

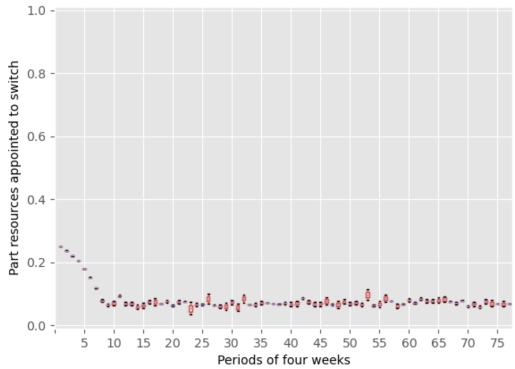


(b) Part resources appointed to surveillance

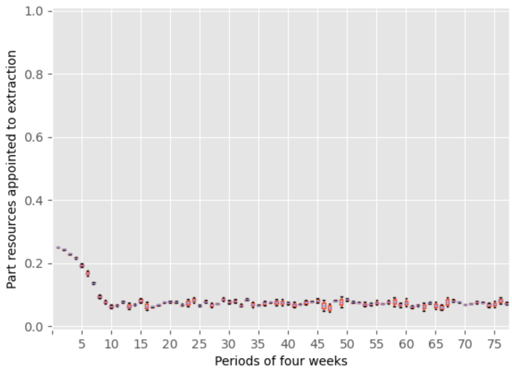
Figure D.51: Distribution law enforcement agencies methods constant non zero equal



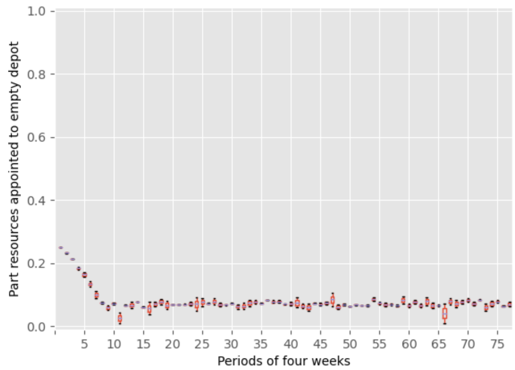
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

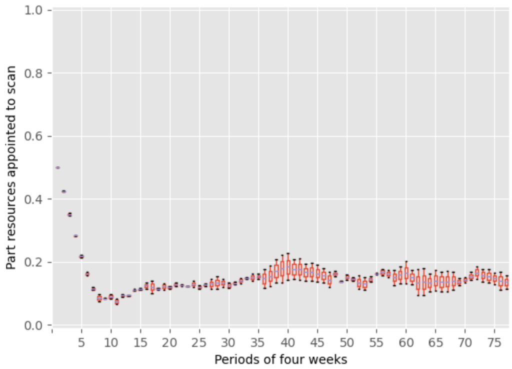


(c) Part resources appointed to extracting

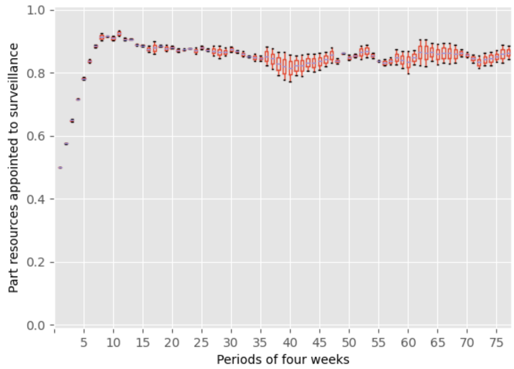


(d) Part resources appointed to empty depot

Figure D.52: Distribution criminal constant non zero equal

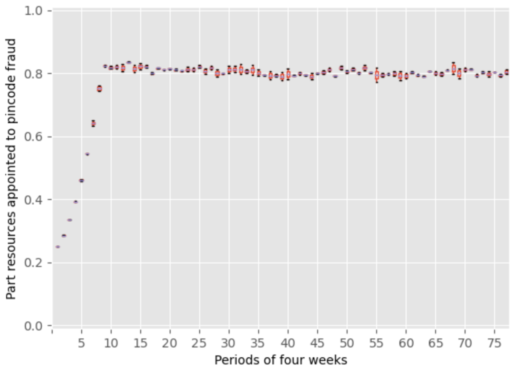


(a) Part resources appointed to scan

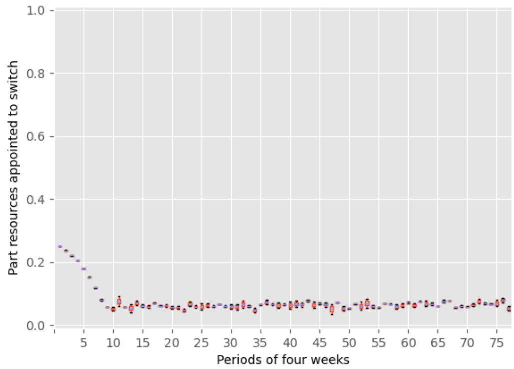


(b) Part resources appointed to surveillance

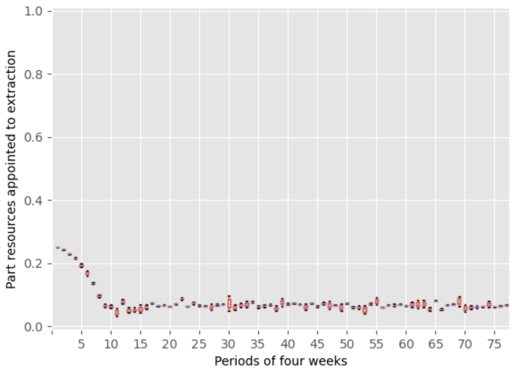
Figure D.53: Distribution law enforcement agencies methods with constant back zero equal



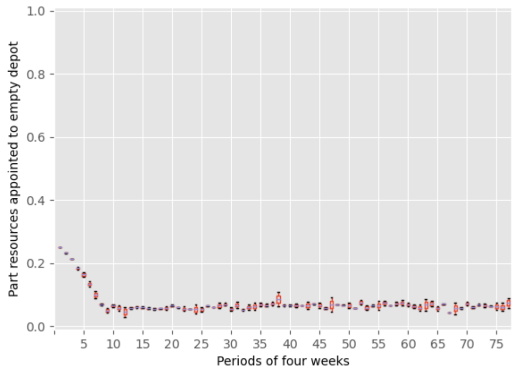
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

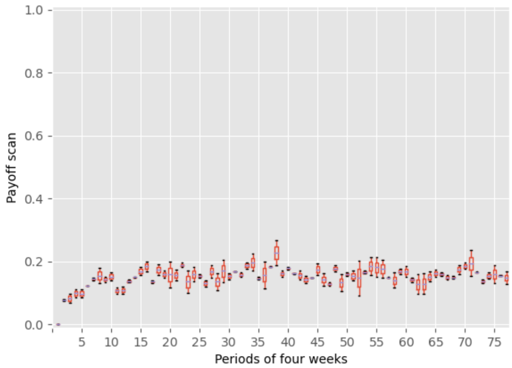


(c) Part resources appointed to extracting

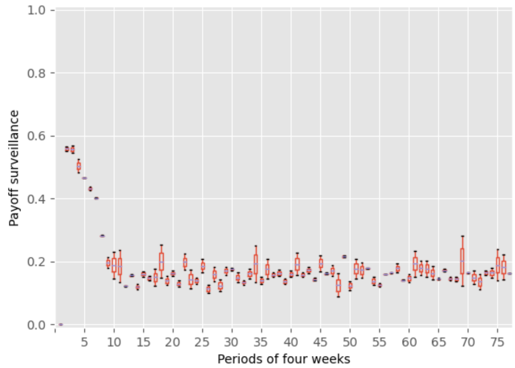


(d) Part resources appointed to empty depot

Figure D.54: Distribution criminal constant back zero equal

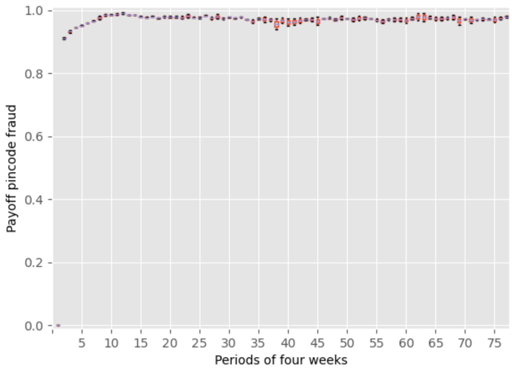


(a) Payoff scan

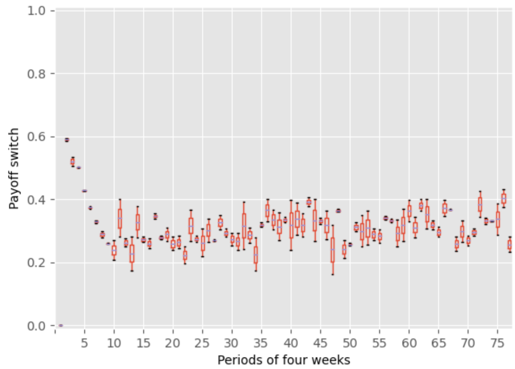


(b) Payoff surveillance

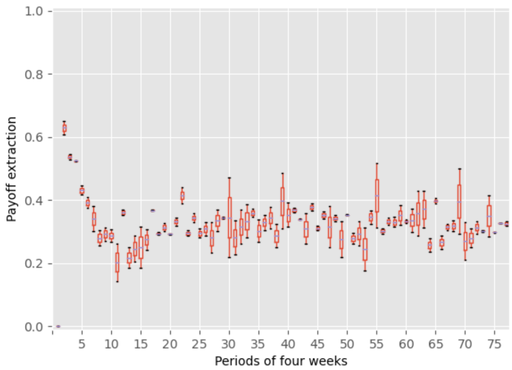
Figure D.55: Payoff law enforcement agencies methods with constant zero equal



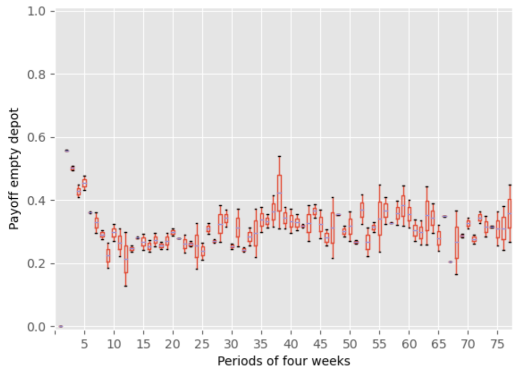
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

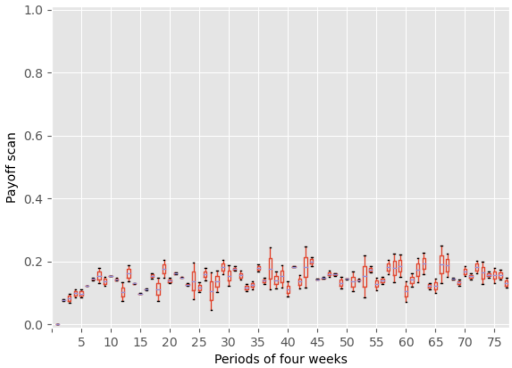


(c) Payoff extracting

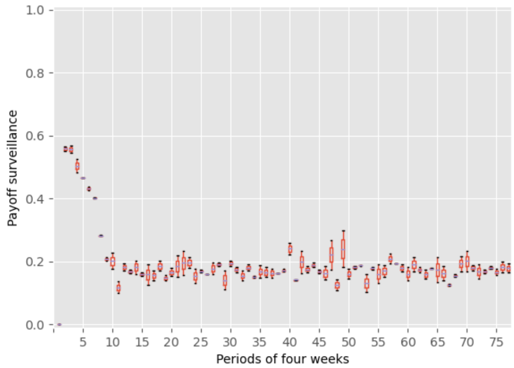


(d) Payoff empty depot

Figure D.56: Payoff criminal constant zero equal

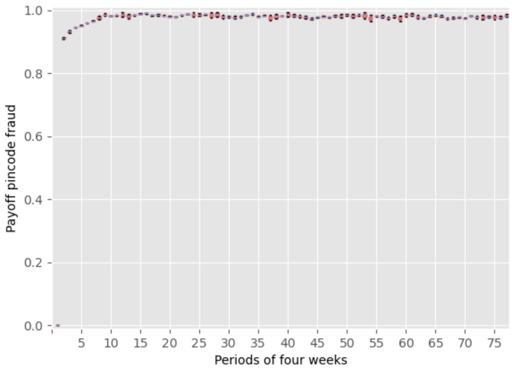


(a) Payoff scan

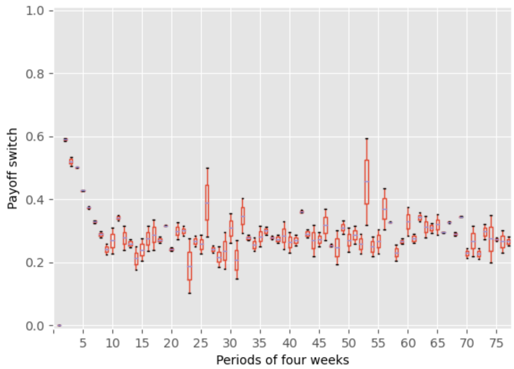


(b) Payoff surveillance

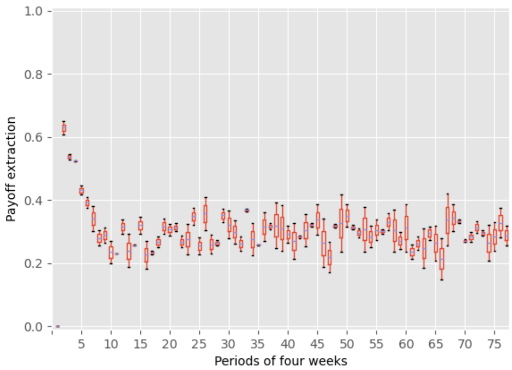
Figure D.57: Payoff law enforcement agencies methods constant non zero equal



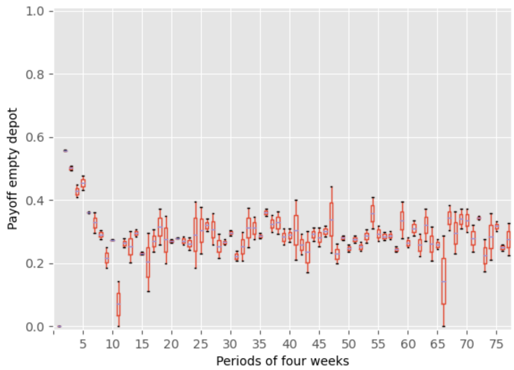
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

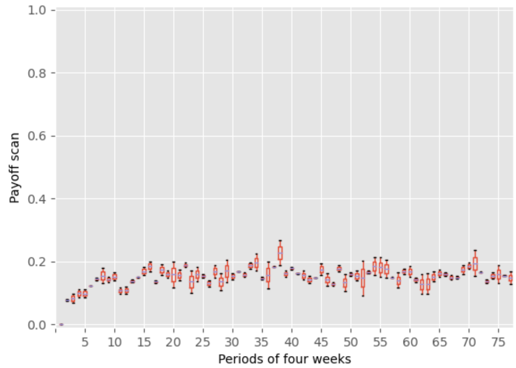


(c) Payoff extracting

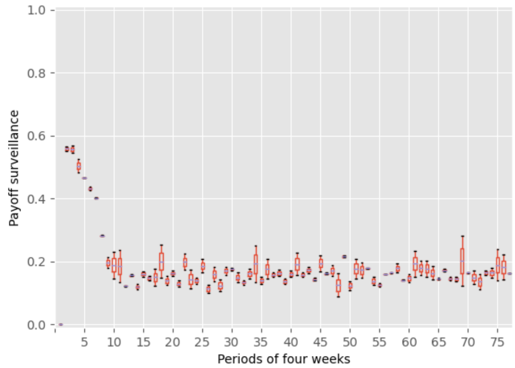


(d) Payoff empty depot

Figure D.58: Payoff criminal methods constant non zero equal

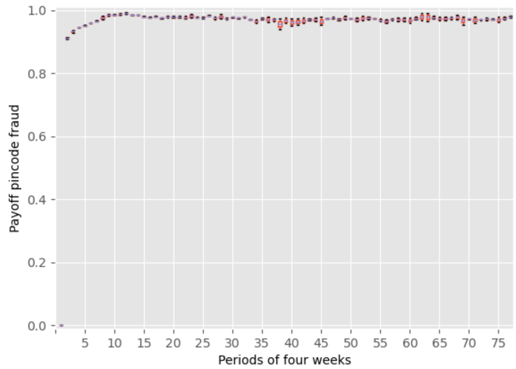


(a) Payoff scan

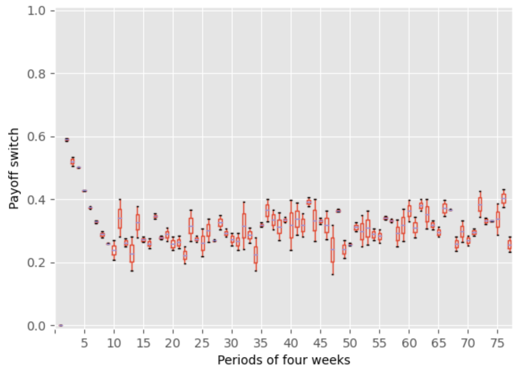


(b) Payoff surveillance

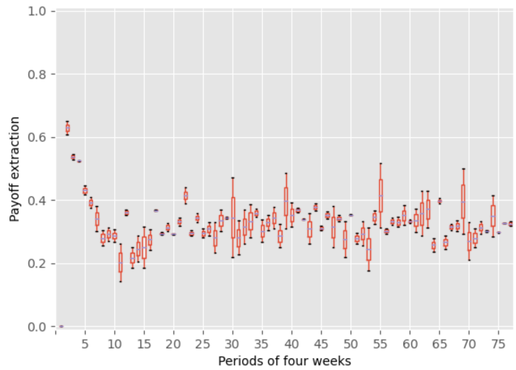
Figure D.59: Payoff law enforcement agencies methods with constant back zero equal



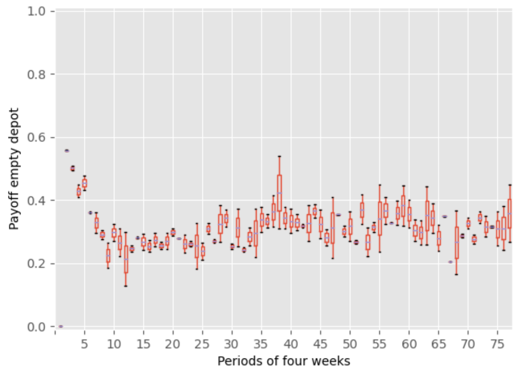
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud



(c) Payoff extracting

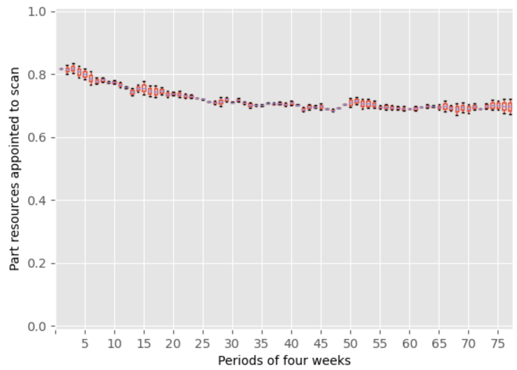


(d) Payoff empty depot

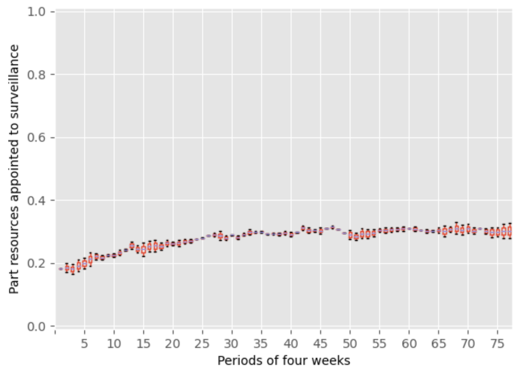
Figure D.60: Payoff criminal constant back zero equal

D.3.1. Starting the model in the Nash equilibrium

The following graphs show what happens to this model with these other parameters when the agent-based models starts distributing all resources according to the Nash equilibrium. These graphs show that even though the distribution of resouces of criminals seems very close to the distribution of resources from the Nash equilibrium as calculated in chapter 4, the behaviour of law enforcement agencies is not close to this equilibrium at all. This again, is due to the false equilibria where criminals get stuck. As long as criminals are not in the Nash equilibrium and do not respond rationally, law enforcement agencies can take advantage of this by also not distributing their resources according o the Nash equilibrium.

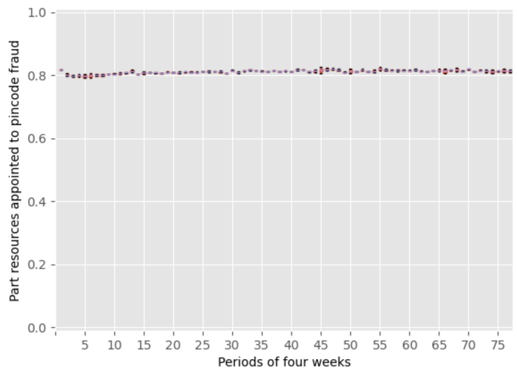


(a) Part resources appointed to scan

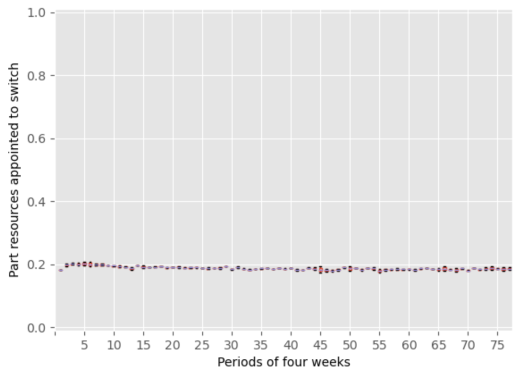


(b) Part resources appointed to surveillance

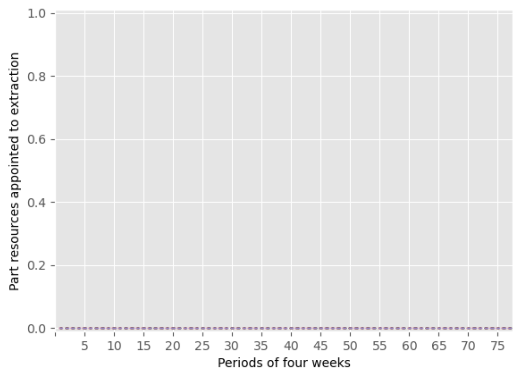
Figure D.61: Distribution law enforcement agencies methods with constant zero nash



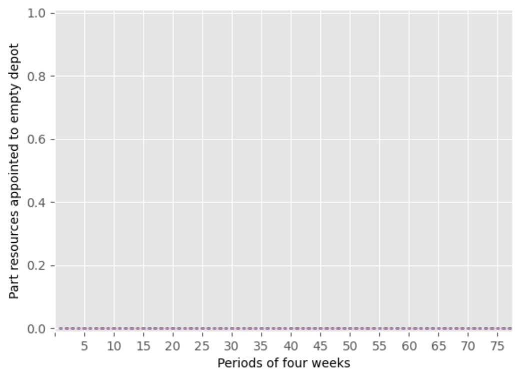
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

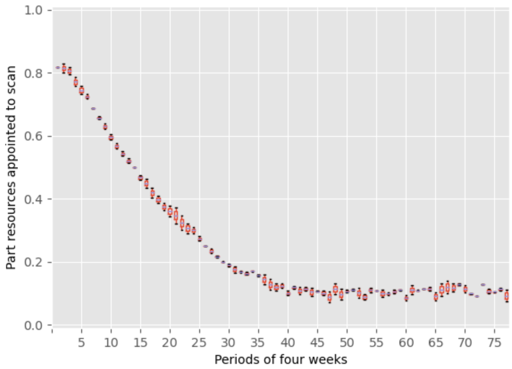


(c) Part resources appointed to extracting

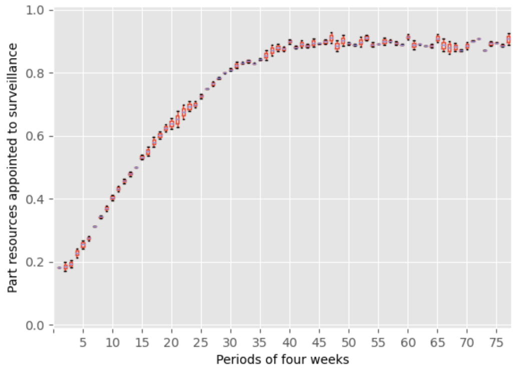


(d) Part resources appointed to empty depot

Figure D.62: Distribution criminal constant zero nash

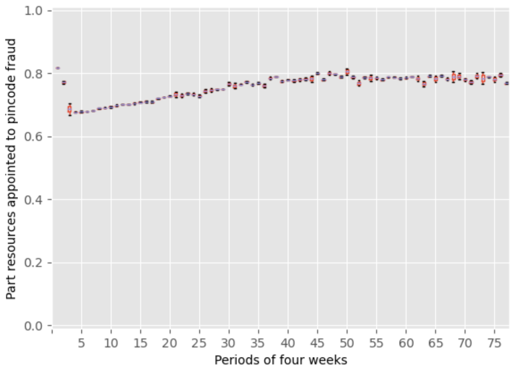


(a) Part resources appointed to scan

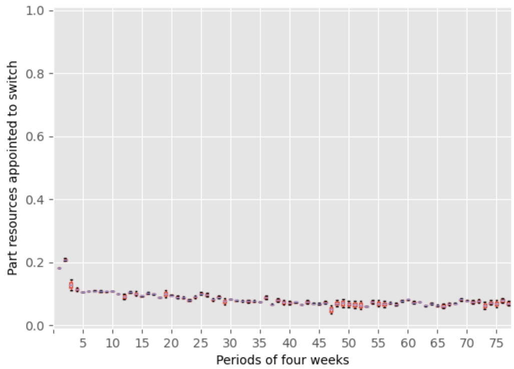


(b) Part resources appointed to surveillance

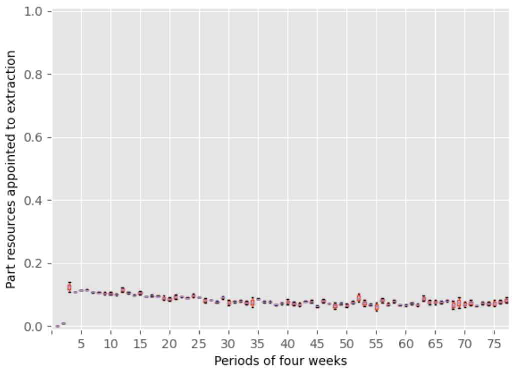
Figure D.63: Distribution law enforcement agencies methods constant non zero nash



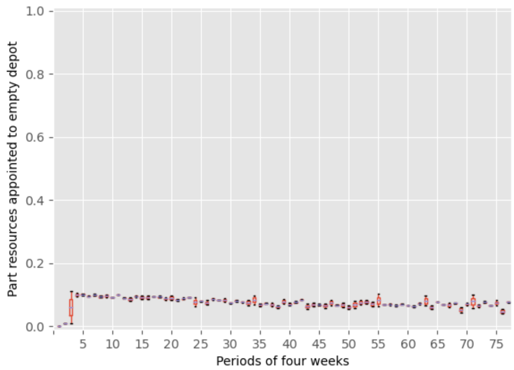
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud

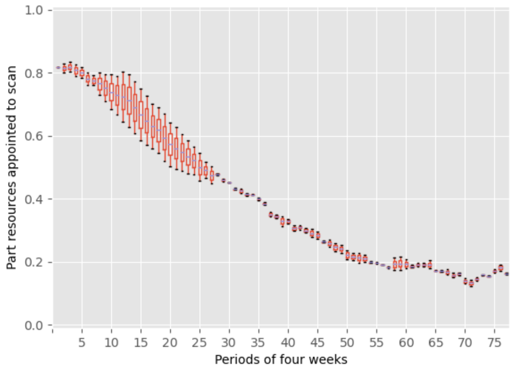


(c) Part resources appointed to extracting

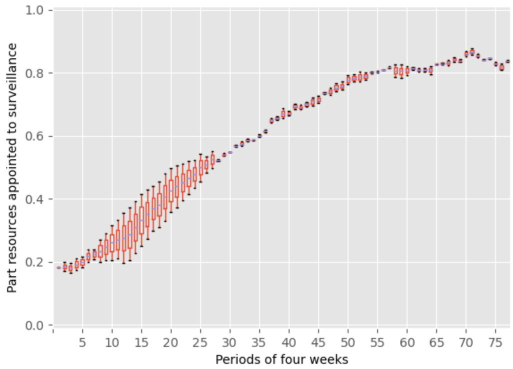


(d) Part resources appointed to empty depot

Figure D.64: Distribution criminal constant non zero nash

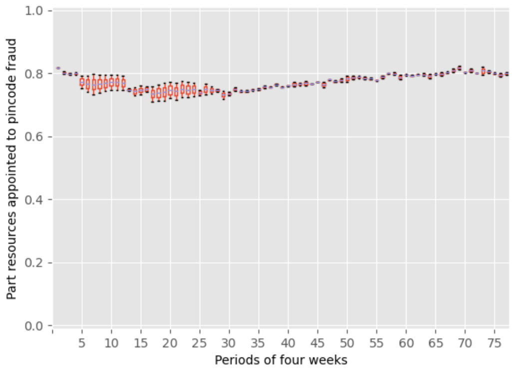


(a) Part resources appointed to scan

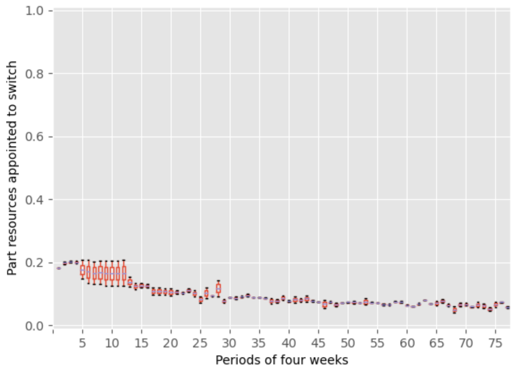


(b) Part resources appointed to surveillance

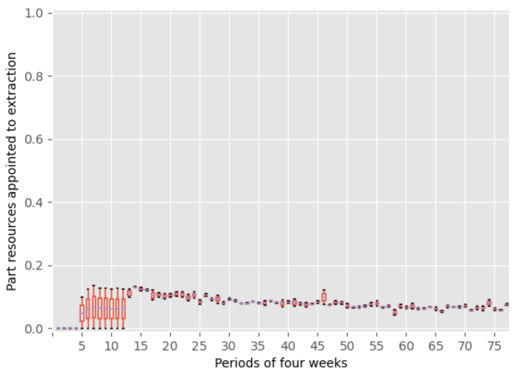
Figure D.65: Distribution law enforcement agencies methods with constant back zero nash



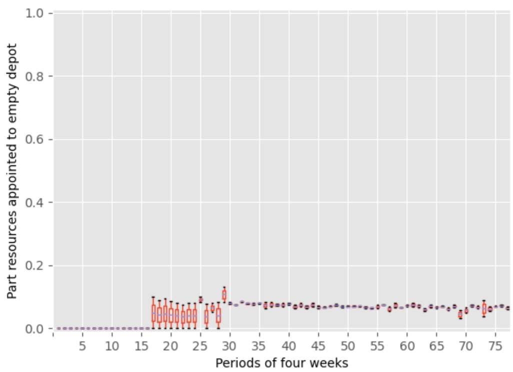
(a) Part resources appointed to pincode fraud



(b) Part resources appointed to switch and pincode fraud



(c) Part resources appointed to extracting



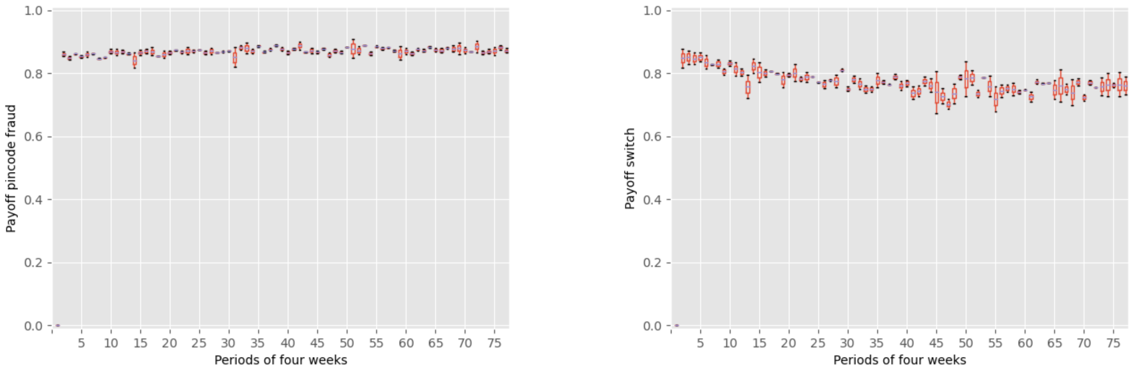
(d) Part resources appointed to empty depot

Figure D.66: Distribution criminal constant back zero nash

(a) Payoff scan

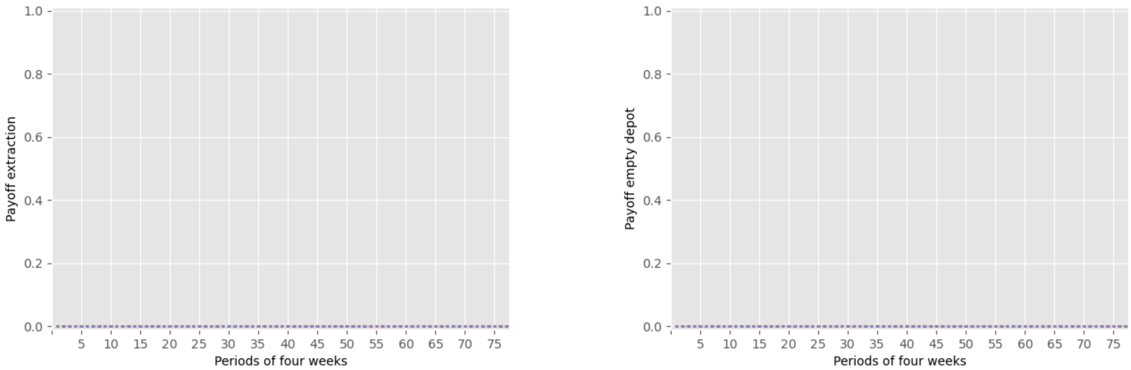
(b) Payoff surveillance

Figure D.67: Payoff law enforcement agencies methods with constant zero nash



(a) Payoff pincode fraud

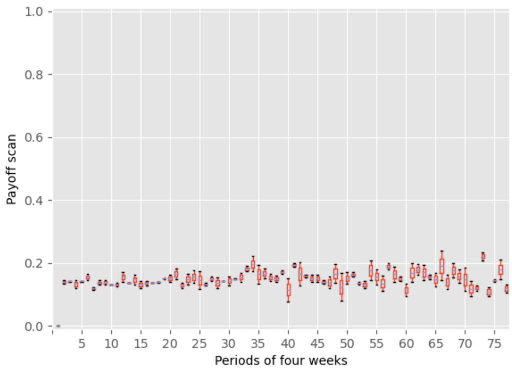
(b) Payoff switch and pincode fraud



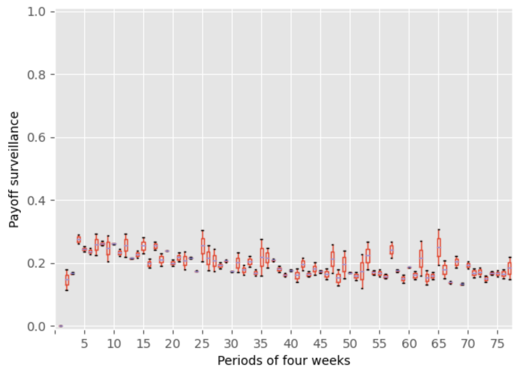
(c) Payoff extracting

(d) Payoff empty depot

Figure D.68: Payoff criminal constant zero nash

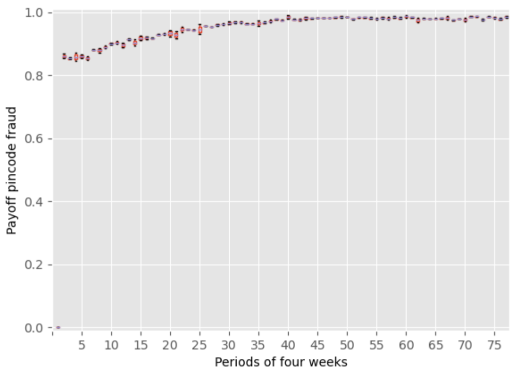


(a) Payoff scan

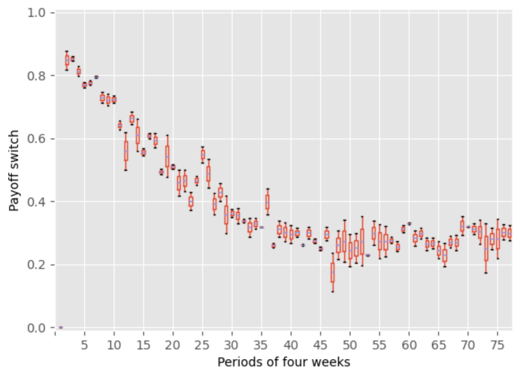


(b) Payoff surveillance

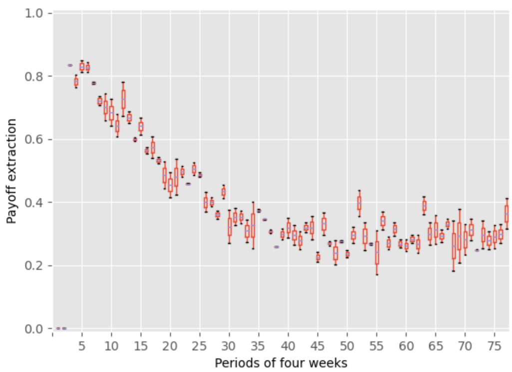
Figure D.69: Payoff law enforcement agencies methods constant non zero nash



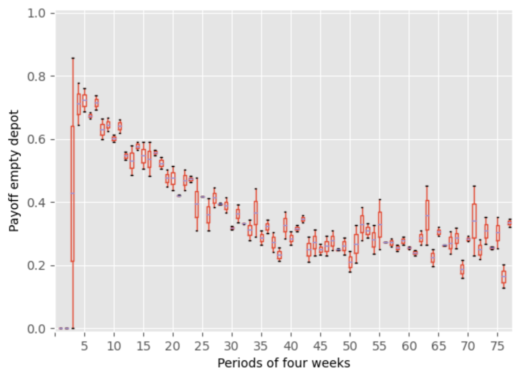
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud

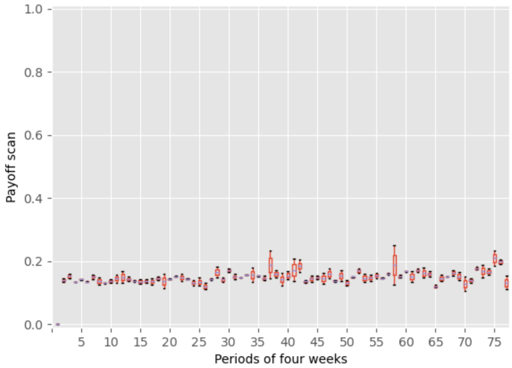


(c) Payoff extracting

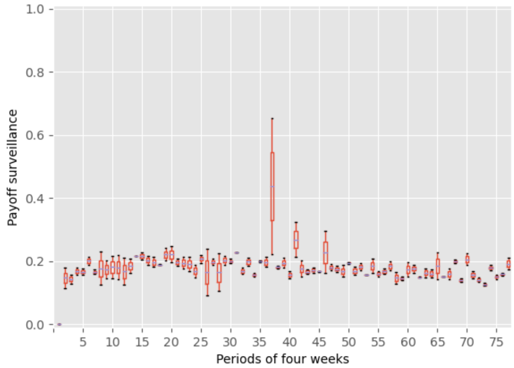


(d) Payoff empty depot

Figure D.70: Payoff criminal methods constant non zero nash

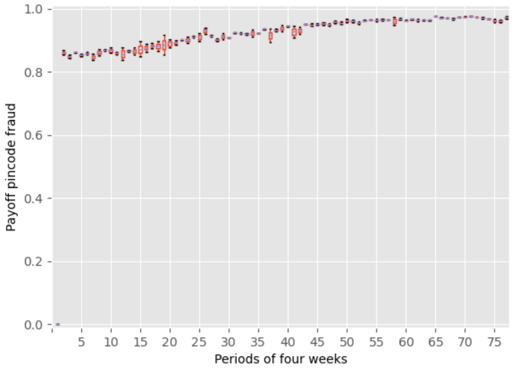


(a) Payoff scan

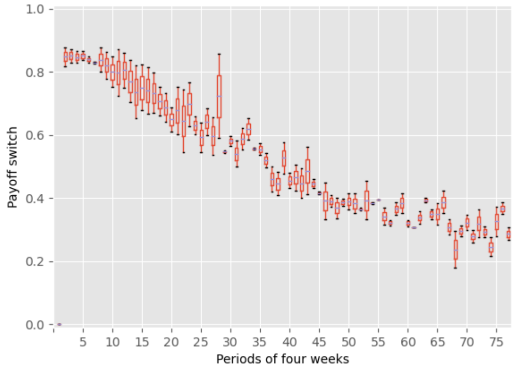


(b) Payoff surveillance

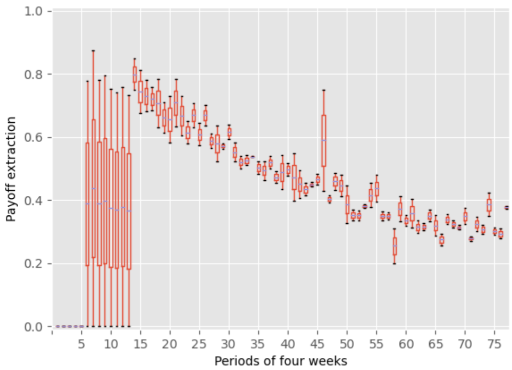
Figure D.71: Payoff law enforcement agencies methods with constant back zero nash



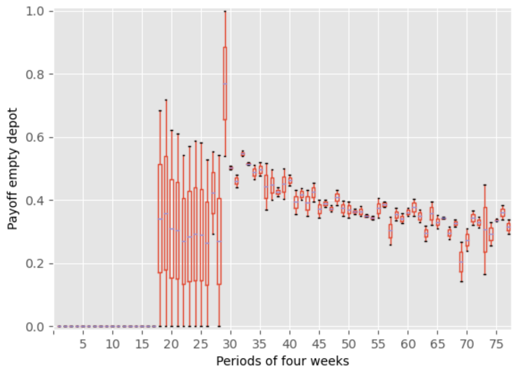
(a) Payoff pincode fraud



(b) Payoff switch and pincode fraud



(c) Payoff extracting



(d) Payoff empty depot

Figure D.72: Payoff criminal constant back zero nash