Part IV – Modelling Spatio-Temporal Dynamics of Crime

This last part of the thesis addresses the spatio-temporal dynamics of crime. The spatio-temporal dynamics of crime are one of the main research interests within Environmental Criminology. Relevant questions within this area concern the movement and interaction of three types of agents, namely passers-by, criminals and guardians.

The main theory used as background in this part is the Routine Activity Theory (RAT) [2]. This theory states that a crime will occur when a motivated offender meets a suitable target and no capable guardian is present. Based on this theory we developed computational models that distinguish three types of agents (namely passers-by (potential victims), (formal) guardians and criminals (potential offenders)). The interaction between these types of agents in space and time is the main focus of investigation in all papers presented in this part (although their behaviour differs in the different papers). In this part we take a couple of assumptions underlying the RAT as a basis and investigate what the consequences of these assumptions are with respect to crime patterns under different circumstances. For example, how does crime shift over a city when (formal) guardians use a particular surveillance strategy?

An important concept in this area is the so called hot spot. A criminal hot spot is a location where many crimes occur [6]. These criminal hot spots tend to shift over time. This phenomenon brings up more questions. Why do hot spots emerge? And where do they emerge? How can the emergence of hot spots be prevented? In recent years, several researchers have applied different computational modelling approaches to help answer these questions (e.g. cellular automata [3, 4] or evolutionary computer techniques [5]).

These authors all share the aim of investigating crime dynamics, but differ in their underlying motivation. Some authors try to develop simulation models of crime dynamics in existing cities, which can be directly related to real world data (e.g., [4]), whereas others deliberately abstract from empirical information (e.g., [1]). Both these approaches have their pros and cons. A model that has been validated based on empirical data from existing cities could be beneficial because people can apply it to new real world situations. One can feed empirical data into the model and as a result is (hopefully) able to predict patterns of spatio-temporal dynamics of crime. However, obtaining useful empirical data is often difficult and time-consuming.

Another approach is to deliberately abstract from empirical information. In this case the model is used rather as an analytical tool. Such a model may be used by researchers to make a phenomenon more clear, and possibly discover interesting results that could be used by policy makers to improve existing policies. For example, to study the interaction of multiple agents (like for instance the inhabitants of a city), which is a process that cannot easily be studied by hand, simulation can be a very interesting option because one can adjust parameters in the model and see what happens in the simulated environment. It is an explorative process, without making many claims about the real world, to find out which factors play an important role in the spatio-temporal dynamics of crime. The downside of this approach is that the model does not take empirical information into consideration.

There are however also researchers that take an intermediate point of view. They initially build their simulation model to study the phenomenon per se, but define its basic concepts (e.g., locations, crime rates) in such a way that it can be directly
connected to empirical information, if this becomes available. Hence, these models in principle abstract from empirical information, but do not exclude that they can be filled with empirical information in the future. The research presented in this part also takes this intermediate perspective. Its main motivation is to develop an analytical tool to gain more insight in the spatio-temporal dynamics of crime dynamics. In this sense the developed model is just an abstract model as explained before. However we developed it in such a way that if empirical data were to become available we can use this in the model. For example, the concepts that were used as basic elements of the model were chosen such that they can be directly mapped to information that can be measured in the real world like crime rate or number of formal guardians.

In Chapter IV.1 we start with a relatively simple model. Here we distinguish the three types of agents mentioned before. In this case the targets are static (e.g., houses), whilst the guardians and criminals are dynamic. We modeled four different worlds in which the attractiveness of the targets differs. In one world the attractiveness of the targets is distributed randomly, while in the second world the most attractive targets are clustered. Further there is a world with two clusters of attractive targets separated by less attractive targets, and a world where all targets are equally attractive. In these worlds potential offenders move around with a high probability to move to the most attractive neighbor. When an offender encounters a target with a value higher than his personal ‘burglary threshold’ and no guardian is present, this would count as a burglary. Moreover, the guardians move around according to one out of three strategies, i.e., 1) randomly, 2) focused on hot spots (i.e., with a probability proportional to the amount of burglaries that took place in the past, or 3) hot spot focused but within a designated area. The results pointed out that the two hot spot focused strategies perform better than the random strategy. Moreover, which of the hot spots strategies performed best depended on the total amount of guardians. These findings provided some first evidence for the usefulness of simulation to study environmental dynamics of crime.

Chapter IV.2 also contributes an agent based model of crime dynamics, but in this case the targets are dynamic instead of static as in the previous paper (from now on we do not focus on burglary anymore but instead we focus on crimes that are performed on the streets against passers by, like pick pocketing). This model specifically focuses on the interplay between hot spots and reputation. Each location in the model has a reputation with respect to the amount of assaults and arrests that take place at that location. This reputation has a different impact on each type of agent. For instance, criminals are attracted by a location with a high assault rate, since they believe this increases their chances to assault someone but they are not attracted to locations with a high arrest reputation since they do not like to run the risk of getting caught. Based on the model, a large number of simulation runs have been performed, of which the results have been formally analysed (to see whether they satisfy certain expected properties such as cyclic patterns). Also this study provided evidence that agent-based modelling is a useful approach to answer questions on the interplay between hot spots and reputation. In this chapter, it was decided to equip the guardians with a reactive strategy; this means that the guardians move towards a location after the assault reputation has increased. An extended model, including other types of strategies is presented in a later paper (i.e. see the description about chapter IV.4 below).

In Chapter IV.3 we make a shift in modelling approach. In this paper we compare an agent-based model of the spatio-temporal dynamics of crime with a population-based model (again focused on crimes on the street against passers by) and on the interaction between potential victims, formal guardians and potential offenders. The difference
between agent-based modelling and population-based modelling is that the first type is based on models of the behaviour of individual agents and the second type is based on models in which groups of agents of the same type are represented by a numerical value, indicating their density (for an example and more details, see the main introduction). The simulation results for the agent-based model using the same parameter settings show an identical trend to the population-based model, except for some minor deviations. These findings were also as confirmed by a formal evaluation. Moreover, the computation time of the population-based model was shown to be much lower than the computation time of the agent-based model. Based on these results we used a population-based model in the following papers.

In Chapter IV.4 we extended the population-based model mentioned in the third paper. Here we added a number of different strategies to govern the behaviour of the guardians. More specifically, the guardians are not only able to move after an assault has been performed but they can also anticipate on expected future assaults. We compared ten different strategies (a baseline strategy, four reactive strategies, three anticipatory strategies and two hybrid strategies) and tested these on five scenarios. The goal of the guardians involved was to distribute in such a way over the different locations that the crime rates were kept as low as possible. Simulation experiments indicate that the best results are produced by the strategy where the guardians move to new locations based on the expected amount of passers by (potential victims) in the near future. Further, we compared all strategies in terms of their effectiveness and costs. The results suggest that a hybrid strategy is most effective, but that purely anticipatory strategies are more cost-efficient. These types of findings can be very useful input for policy makers, in order to elaborate their thoughts about efficient strategies.

The chapters mentioned in this part are based on the following publications:

Chapter IV.1 is available as:


Chapter IV.2 will appear as:


This article is also based on:


Chapter IV.3 appeared as:

Bosse, T., Gerritsen, C., Hoogendoorn, M., Jaffry, S.W., and Treur, J., Comparison of Agent-Based and Population-Based Simulations of Displacement of Crime. In:

This article is also based on:


Chapter IV.4 will appear as:


This article is also based on:


References


Simulating the dynamical interaction of offenders, targets and guardians

Tibor Bosse, Henk Elffers and Charlotte Gerritsen

1. Routine activity modelling

Within the routine activity paradigm [6, 10], it is argued that crime takes place when a motivated offender finds an insufficiently guarded attractive target. The beauty of this well corroborated theory lies in its clarity and simplicity on a sufficiently abstract level [9]. However, its simplicity seems to vanish as soon as we zoom in from an abstract level towards concrete questions on underlying processes. What governs whether a motivated offender will find an attractive target? The answer is clearly dependent on the movement of offenders and the whereabouts of targets. For instance, the likelihood of such meetings will be dependent on the distribution of targets’ attraction levels, their positions in space, whether they move or not, and whether their attraction levels are constant over time or not, and if not, what is governing their change. Likewise, the occurrence of a meeting between an offender and a target will be influenced by the movement pattern of motivated offenders, may be dependent on their knowledge of target availability or on other business the offender has on his agenda, on their preferences for certain attraction levels, and on whether these characteristics are influenced by having successfully or unsuccessfully attacked a target previously.

Targets may have a movement pattern, based both on their perception of criminal risk as well as of parameters governing their non-crime related behaviour (e.g., the route they take to go to work), which will also be influenced by experiencing crime. Moreover, the third routine activity factor, availability of suitable guardians, has to be taken into account as well. Are we talking about formal guardians, such as police officers and security personnel, or are we discussing informal or natural guardians, such as inhabitants and passers-by? How do guardians move around, are they aware of targets and target values, of the whereabouts of particular offenders, what about their suitability (i.e. their willingness and capability for exercising their crime hampering actions), is that constant over time, how do they react when they are or are not successful in preventing a crime from happening? It is clear that the temporal and spatial dynamics of such offender, target and guardian processes is paramount for the occurrence of crime within a routine activity context. That being so, we are faced with a considerable problem in any real life situation, as it seems rather optimistic to hope that all of the above mentioned processes can be specified, estimated and analyzed: measurement problems as well as analytical problems will be formidable.

The standard way out in such an overly complex case is simplifying the problem, by holding constant as many parameters in the processes as is feasible. E.g. we can try and compare pick pocketing rates in two neighborhoods close to each other, having a comparable population composition, but the one having houses with small windows is deemed to have low natural guardianship levels, while the other neighborhood having buildings with large windows will have a better guardianship structure. In so far as we dare to assume that offender routine patterns and target routine patterns are alike in both neighborhoods, comparing them is a fit method to investigate the effect of natural guardianship.
The second way out is experimenting, e.g. varying police surveillance intensity (as one of the guardianship parameters) over time periods in a given neighborhood. This research approach is, of course, also only feasible when many other parameters are held constant.

Dynamical aspects of the routine-activity-models are particularly devious to research in such designs, as the designs actually exploit the 'ceteris paribus' of all other parameters than the one under scrutiny, and hence implies an incentive on static processes, thus defying investigation of dynamics.

In the current paper, however, we intend to look into dynamical routine activity processes, by means of simulation methods, in which some routine activity processes are built into an artificial society of offenders, targets and guardians, and investigate what is happening if offenders, targets, or guardians react on what is happening, by increasing or decreasing parameters of their preferences, and by choosing the direction in which they move as a function of what is happening around them.

2. Simulation as an analytical tool

Simulation should be seen here as an analytical tool that makes it possible to investigate what is happening, given a set of rules whose mutual interactions are too complex to see through by traditional methods. Simulation is – in such an application – not an empirical, but a theoretical method, which uses computer generated instances of realizations of processes. It is meant for those cases where complexity outsmarts our capability for theoretical or mathematical analysis. Simulation departs from a given theory (in our case: routine activity theory) and looks into the dynamical interplay of various processes as specified by that theory. As such, simulation is not testing the theory from which it departs, but, on the contrary, it is explaining it, bringing forward implications of the assumptions of the theory that were not straightforward and clear before. The resulting outcomes of a set of simulation runs should then be studied and are meant to generate a deeper insight in the process that, implicitly, has been specified by the simulation model. Observing and analyzing a number of realizations of the dynamical development of resulting crime processes will enhance our understanding of the dynamics of routine activity in a given context. This usually takes the form of an input-output analysis: if we specify the parameters of the process to be simulated to be such-and-such, we observe that the outcomes end to be so-and-so. Applications of the use of simulation as an analytical tool for understanding can be found in various criminological fields. E.g. [1] has applied it for studying perceptual deterrence, while [2, 4] have used it for studying psychological processes that trigger violent behavior. Moreover, [3] apply it for studying social learning of delinquent behavior in adolescents.

Simulation may be called an ungrateful task: it usually generates tons of input-output relations, from which the researcher should make sense, either by insight or through systematic statistical analysis of the input-output connections. A very real danger is that researchers will drown in their results. It is therefore wise for researchers to restrain themselves and start with very simple simulation models. Experience shows that interpreting and understanding input – output relations is even in simple models often quite a task. A stepwise approach starts with a simple simulation model that can be made more complex only after having thoroughly understood the output of the original simple case.

It seems worthwhile to stress explicitly that simulation models in the above sense are not yet meant as theories of reality: we do know beforehand that they are too gross
simplifications of reality for that matter, indeed that is their unique selling point. By rigorous simplification we optimize the conditions for understanding the complex interplay between various parts and rules in the model. Only after having understood a relatively simple model thoroughly, we may try to go a step further and build complex models of reality, using as building blocks what we have learned from the simple simulations. Notice that this modest view on simulation research rules out the testing of model results against empirical data, which indeed would be superfluous as we already know that the models do not fit reality.

Of course, other uses of the term ‘simulation research’ and other visions on the usefulness of simulation may be found in the literature (cf. [12]) and may be useful for their own purposes as well. Indeed, many researchers propose their simulation models already as fair approximations of reality. It is our conviction that at least in the field that we are studying in this paper, the dynamics of routine activity models, that stage has not been reached [8].

3. A simple routine activity model, global description

In the present project, we will study a small society of immobile targets (‘houses that can be targeted for burglary’), located in geographical space (‘town’), with standard characteristics as ‘neighboring relations’, ‘distance to each other’, and having a certain given distribution of attraction levels over space (‘spatial autocorrelation of wealth’). Moreover, the targets have a time dependent ‘reputation’, which is high when a property has been burglarized in the recent past, and erodes again when nothing untoward is happening for some time. Through that society a number of motivated burglars move around. They take one step every period (‘day’), and have a preference to moving to more attractive targets. However, they are rather short-sighted, and can ‘see’ only targets one step away from their previous position. They chose a move with a certain probability proportional to attraction levels of targets in sight. Offenders (burglars) have a characteristic of ‘choosiness’, i.e. every offender has a certain minimal attraction threshold, different for different offenders. When arriving at a target, an offender intends to burgle it, if and only if it is worthwhile for him, which is the case if the attraction level of the prospective target is surpassing the minimal attraction threshold of that offender, cf. [5, 7]. Notice therefore that a target that is eligible for burbling to one offender may be passed over by another offender.

The last element in the model is that of the guardians, also moving around through the town. Guardians, just as offenders, walk around one step at a time, and see only targets one step away. Guardians either have no preferences, i.e. they move around randomly (‘random policing’), or have a preference for moving to targets with high reputations (‘vulnerable targets’), to which they move probabilistically with probabilities proportional to reputations being visible from the present position. This last state of affairs is called: hot spot preferences or hot spot policing. If a guardian is present at a target, he completely precludes a burglary taking place. So if an offender intending to burgle a house (because its attraction level is surpassing his threshold) meets a guardian at the spot, he refrains from executing his intentions. Of course, burglars that had judged a target as not worthwhile, will not be affected by guardians; they go on behaving themselves at that moment. Notice that our guardians are what has been called formal guardians, that is agents having an official guardian task (such as police officers or security personnel), as opposed to informal guardians, who may be
present on the spot for other reasons (inhabitants, passers-by) and then nevertheless can preclude crime from happening [11].

4. Research questions

Within the framework of the model specified, we intend to investigate the effectiveness in crime prevention of various guardianship policies (output variable, operationalized as 1 – crime rate, in which the crime rate is the observed number of crimes per spatio-temporal unit), in various circumstances as specified by the spatial attraction patterns of the targets, the number of offenders and guardians and the distribution of the attraction thresholds of the offenders (input variables).

Guardian policies to be investigated here are: random policing; hot spot policing; area (or beat) hot spot policing. The last of those policies is a hot spot policing scheme but with mutually exclusive zones allotted to the guardians, zones that they may not leave.

Circumstances we vary are: number of guardians and distribution of target attraction values. Concerning the former, we are interested in investigating to what extent the effectiveness in crime prevention is influenced by the amount of guardians that are present in the model. To this end, the number of guardians will be varied between very few (e.g., only 2 guardians) to very many, (e.g., almost one guardian at every location). The other circumstance to be varied over the different simulations is the distribution of target attraction values. This choice was based on the hypothesis that differences in geographical makeup between areas may result in very different burglary patterns (e.g., the burglary patterns in an area where all expensive houses are clustered will be different from those in an area where all expensive houses are spread. Therefore, the distribution of attraction levels of houses over space will be varied (see Section 6).

Other parameters of the model were the number of offenders present in the simulation, and the distribution of threshold values of the offenders (i.e., the individual attractiveness levels of the offenders that a certain target should surpass in order to be judged sufficiently attractive to burglarize). However, these two parameters are kept constant over the different simulation runs.

Notice that our research question can, in principle, be investigated without simulating many instances of the process under investigation, if we would have the capability to analyze the complex interactions of the various elements in our set-up. However, as we see no way forward here, we use studying input-output relations in simulated outcomes instead. We hold that it is not clear at the outset how the various parameter settings influence the overall crime level over time.

5. Simulation model, in detail

In this section, the simulation model used within the present project is introduced in detail. The main component of the model is a virtual environment, a world which is represented mathematically by a matrix of m*n elements (and can be visualized as a grid of m*n adjacent locations). Thus, each location has maximally 4 neighbors (in case of central locations) and minimally 2 neighbors (in case of corner locations). In addition, each location (or house) has a level of attractiveness attached, which is modeled by a natural number between 1 and 10. This number is assumed to represent the attractiveness of that particular location to burglars (e.g., a high number may stand for an expensive house without surveillance cameras). Finally, each location has a
reputation attached, which is modeled by a real number \( \geq 1 \), and is assumed to represent the reputation of that location with respect to burglary (i.e., a high number stands for a house where many burglaries have taken place). Initially, the reputation of each location is set to the value 1. Reputation increases by 1 after a burglary takes place at that location, and decreases by 0.5 when no burglary takes place.

Within a given simulation run, the world is populated by artificial agents. Two types of agents are distinguished, namely offenders (i.e., potential burglars) and guardians. Each offender has an individual burglary threshold, modeled by a natural number between 0 and 10, which represents the threshold above which the agent considers a house sufficiently attractive to burgle it (i.e., a high number denotes a person that will only select very attractive targets). Offenders move randomly through the environment. However, to be able to compare different surveillance strategies, the guardians exist in three different types:

- **type 1 guardians** follow a random strategy: they move randomly through the environment.
- **type 2 guardians** follow a hot spot strategy: they select adjacent locations with a probability that is proportional to the reputations of those locations.
- **type 3 guardians** follow an area hot spot strategy: they select adjacent locations with a probability that is proportional to their reputation, but only within their individually assigned surveillance area. This means that each guardian of type 3 has a number of locations assigned (an area), which it is not allowed to leave.

In order to generate a simulation run, the following algorithm is performed (denoted in pseudo-code):

1. Initialize the simulation (either randomly or according to some setting defined by the user) according to the following steps:
   a. Determine the size of the world.
   b. For all locations, set the initial reputation to 1, and assign attractiveness levels to them.
   c. Determine the amount of agents of the different types.
   d. Assign burglary thresholds to all offenders.
   e. Assign personal areas to all type 3 guardians.
   f. Place all agents at their start locations.
2. For each time step until the end of the simulation, repeat the following cycle:
   a. For each location, if it contains at least 1 motivated offender (in the sense that its individual burglary threshold is lower than the attractiveness of the location) and no guardians of any type, then count a burglary for that location.
   b. Increase the reputation of each location that is burglarized with 1.
   c. Decrease the reputation of each location that is not burglarized with 0.5.
   d. For each offender, move to one of the adjacent locations (including the current location) with a probability that is proportional to its attractiveness. For example, suppose an offender is at a (corner) location A with two neighbors, B and C, and that the attractiveness of A, B, and C is 3, 5, and 7, respectively. Then, the probability that the agent will stay at location A is \( 3/(3+5+7) = 0.2 \). Similarly, the probability that it will go to location B is 0.33, and the probability that it will go to C is 0.47.
   e. For each type 1 guardian, move randomly to one of the adjacent locations (including the current location). For example, in case
a guardian is at a central location, it may go north, south, west, or east, or stay at its current location, each with a probability of 0.2.

f. For each type 2 guardian, move to one of the adjacent locations (including the current location) with a probability that is proportional to its reputation. For example, suppose a guardian is at a (corner) location A with two neighbors, B and C, and that the reputations of A, B, and C are 4.5, 7.5, and 2.0, respectively. Then, the probability that the agent will stay at location A is \( \frac{4.5}{4.5+7.5+2.0} = 0.32 \). Similarly, the probability that it will go to location B is 0.54, and the probability that it will go to C is 0.14.

g. For each type 3 guardian, move to one of the adjacent locations (including the current location) within its own area with a probability that is proportional to its reputation.

As can be seen in this pseudo-code, in principle it is possible to have guardians of different types in one and the same simulation. However, in the simulations that are discussed in this paper, this is not the case, i.e., per simulation run only one type of guardians is placed in the environment.

During a simulation, various types of relevant information are stored, such as the total number of burglaries, the amount of times that offenders encounter guardians (prevention rate), and the amount of times that 2 or more guardians are present at the same location (idleness rate). Since the model contains probabilistic elements, multiple runs will provide different results. Therefore, in order to obtain reliable results, the model is run many times, to generate a large number of simulated traces (i.e. developments of all dynamic parameters over time), of which the average is then taken.

The simulation model has been implemented in Matlab (www.mathworks.com). To provide the user more insight in the exact spatial dynamics of a simulation run, the implementation offers the possibility to visualize each simulation run in terms of an animation (which can be stored as an .mpg-file). In Figure 1, a screenshot of such an animation is shown.

![Figure 1. Screenshot of the simulation environment.](image-url)
Here, each intersection represents a location in a city. In the example addressed here, there are 25 locations in total that are connected through edges (according to a grid or ‘block’ structure). Furthermore, there are 4 offenders (represented by the red dots) and 2 guardians (the blue dots). The black dots represent the reputation of a certain location. The bigger the dot, the higher the ‘burglary reputation’ of that location. As an illustration, a number of animations (for different guardian strategies) can be found at: http://www.cs.vu.nl/~wai/crimesim/.

6. Input parameters that are varied over different runs

The model has been used to generate a large number of simulations under different settings (input parameters). First, we used different settings for the distribution of the attraction values of the targets. In this way, four types of worlds have been created. In the first world type, all targets have the same attraction value (“equal world”). In the second world type, the attraction values are distributed without structure over the community (“distributed world”). Actually, in the present set of simulations, we once and for all simulations manually distributed values between 1 and 10 in an unsystematic way over the society. In the third world type, the values are distributed according to a concentric ring structure (“ring world”), with the highest attraction value in the southwest corner of the world and attraction values decreasing linearly with the number of concentric ‘rings’ that have to be passed from that centre. This can be compared to a city where the most expensive houses are located close to each other, and the less attractive the houses are located further away from that wealthy centre. In the fourth world type, there are two distinct areas in which the expensive houses are located (“segregated world”), which are separated from each other by houses that are less attractive. In Figure 2 these worlds are shown.

<table>
<thead>
<tr>
<th>Equal world</th>
<th>Ring world</th>
</tr>
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<tbody>
<tr>
<td>5 5 5 5 5</td>
<td>2 2 2 2 2</td>
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<td>5 5 5 5 5</td>
<td>4 4 4 4 2</td>
</tr>
<tr>
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<td>5 5 5 5 5</td>
<td>8 8 6 4 2</td>
</tr>
<tr>
<td>5 5 5 5 5</td>
<td>10 8 6 4 2</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Distributed world</th>
<th>Segregated world</th>
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<tbody>
<tr>
<td>4 7 1 10 2</td>
<td>2 2 2 8 10</td>
</tr>
<tr>
<td>9 3 6 8 5</td>
<td>2 2 2 8 8</td>
</tr>
<tr>
<td>4 3 5 1 9</td>
<td>2 2 2 2 2</td>
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<tr>
<td>2 5 7 4 3</td>
<td>8 8 2 2 2</td>
</tr>
<tr>
<td>1 10 2 8 6</td>
<td>10 8 2 2 2</td>
</tr>
</tbody>
</table>

Figure 2. Different world types used in the simulation.

For each world, simulations have been performed with different numbers of guardians (i.e., 2, 3, 4, 5, 6, 10, 15 and 20 guardians), which were either all of type 1 (the random strategy), of type 2 (the hot spot strategy), or type 3 (the area hot spot strategy; all guardians in a given simulation get an area of approximately equal surface to survey). In each simulation, always 4 offenders were present, with burglary thresholds 4, 5, 6, and
7. Per setting, we ran 1000 simulations (of 200 time steps each). So in total we have performed 96000 simulations (= 4 worlds * 8 amounts of guardians * 3 guardian types * 1000 simulations). The most interesting results will be discussed below.

7. Simulation results

In this section, the results of the simulations will be discussed, with respect to total crime rates (Section 7.1), crime hot spot rate (Section 7.2), guardian hot spot rate (Section 7.3), guardian efficiency (Section 7.4), and the effect of larger geographical areas (Section 7.5).

7.1. Total amount of crime

In Figure 3, for the different worlds, the average crime rate is shown. In these graphs, the horizontal axis shows the different types of strategies, and the vertical axis shows the average amount of crimes per location, per time point. Note that the results for 4, 6, and 15 guardians have been left out, to improve readability.

Figure 3. Total crime rate - comparing different numbers of guardians within one world.
The different strategies seem to have the same effect in the segregated, ring and distributed society. In these societies, hot spot policing works better than random patrolling, and area hot spot surveillance works better than random patrolling. Furthermore, hot spot patrolling is better than area hot spot surveillance until you swamp society with guardians (>5). Only in the equal society, the type of guardian has hardly any influence. Overall, when there are more than 5 guardians, the guardians that patrol in an area hot spot based manner are more effective than the other types of guardians.

When we compare the crime rates in the different worlds (see Figure 4), it can be observed that they are the highest in the segregated community. In the ring and distributed society, the crime rates are about the same, and the equal society is the world with the lowest crime rate.

![Figure 4. Total crime rate - comparing different worlds for one number of guardians.](image)

**7.2. Crime hot spot rate**

In addition, for each location, we counted the amount of times that it was populated by 2 or more motivated offenders, per time point. Encounters between motivated offenders are independent of the amount and the type of guardians (since offenders move around in a random manner), therefore we do not show the results graphically as a function of the types of guardians. The motivated offenders encounter each other most often in the segregated world (0.017 times per location, per time point). The ring society is second (0.0095 times), the distributed society is third (0.0075), and the offenders have the least encounters in the equal society (0). There were no encounters between motivated offenders in the equal society, because in this society there was only one offender of which the burglary threshold was lower than the attractiveness of the houses.

**7.3. Guardian hot spot rate**

Next, we investigated the average amount of times per location that it was populated by 2 or more guardians, per time unit. The results (for the case of 2 guardians and the case of 20 guardians) are displayed in Figure 5. Our main finding is that guardians that use a hot spot strategy have more encounters than guardians that move randomly. Guardians that have an area hot spot strategy never meet each other because they are restricted to
certain areas. Although this cannot be seen in the figures (since all points overlap), the guardians encounter each other most often in the segregated world. The ring society is second, the distributed society third, and the guardians have the least encounters in the equal society. However, these differences are very small.

![Figure 5. Guardian hot spot rate.](image)

### 7.4. Guardian efficiency

The guardian efficiency is the average amount of times that a guardian meets at least one offender, per time point. The results of this are shown, for the different worlds, in Figure 6. In the segregated, ring and distributed world, hot spot patrolling is more efficient than random patrolling and hot spot patrolling is more efficient than area hot spot patrolling. Random patrolling and area hot spot patrolling are just as efficient in these worlds, at least for large amounts of guardians. However, when there are less than 10 guardians, area hot spot patrolling is more efficient than random patrolling. In the equal society, hot spot patrolling is slightly more efficient than random patrolling and area hot spot patrolling. Random surveillance and area hot spot surveillance are equally efficient. Overall, guardians are most efficient in the segregated society. Both the ring and the distributed society are second, and guardians in the equal society are least efficient.
7.5. Scaling up

The simulations mentioned above all were performed in a world of 5x5 (25 locations), with 4 offenders and 2 to 20 guardians. To test whether these results are independent of the size of the society, we scaled up the simulation. We created a larger world (10x10 = 100 locations), and also multiplied the number of guardians and offenders with 4. This yields a setting with 16 offenders and 8 to 80 guardians (for the time being we only considered the situation with 8 guardians). Further, we only made a comparison between the randomly patrolling guardian (type 1) and the hot spot patrolling guardian (type 2). The results are shown in Table 1 and 2. As can be seen, scaling up does not have a big impact on (normalized) findings.

<table>
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<th>5x5</th>
<th>10x10</th>
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<tbody>
<tr>
<td>crime rate</td>
<td>0.0368</td>
<td>0.0369</td>
</tr>
<tr>
<td>offender hot spot rate</td>
<td>0</td>
<td>0.0006</td>
</tr>
<tr>
<td>guardian efficiency</td>
<td>0.0412</td>
<td>0.0399</td>
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<tr>
<td>guardian hot spot rate</td>
<td>0.0015</td>
<td>0.0026</td>
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</table>
Table 2. Comparing worlds with different sizes - type 2 guardians.

<table>
<thead>
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<th>3x5</th>
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</tr>
</thead>
<tbody>
<tr>
<td>crime rate</td>
<td>0.0357</td>
<td>0.0359</td>
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<tr>
<td>offender hot spot rate</td>
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<td>guardian efficiency</td>
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<td>0.0525</td>
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<tr>
<td>guardian hot spot rate</td>
<td>0.0017</td>
<td>0.0027</td>
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</table>

8. Discussion

The simulation experiments described above clearly illustrate the usefulness of simulation as an analytical tool to investigate consequences of criminological theories under certain assumptions. In this project, the Routine Activity Theory [6, 10] was taken as a point of departure, and a number of assumptions that form the basis of the theory were formalized in sufficient detail to be able to generate a simulation model. The simulation model was focused at the domain of burglary. It allowed us to create artificial societies, and define varying circumstances for these societies, such as different attractiveness distributions of targets, different numbers of guardians, and different guardian strategies. By executing the simulation model for these varying circumstances, various ‘thought experiments’ were performed that enabled us to oversee consequences of the theory (of course, still given certain assumptions) that we would not have been able to derive by means of traditional methods like common sense reasoning or empirical methods.

For example, a first finding was that in our simulations, hot spot surveillance and area hot spot surveillance turned out to work better than random patrolling, unless all targets were equally attractive. This makes sense, because in case all targets have the same attractiveness, probably no hot spots will occur at all. Moreover, hot spot surveillance turned out to usually work better than area hot spot surveillance, unless the amount of guardians was almost as big as the amount of locations. In such a situation, clearly, it pays off to distribute guardians over locations, to prevent that multiple guardians are guarding the same location and thereby ‘wasting resources’.

With respect to the different geographical makeups of the societies, our simulations suggested that the crime rates are highest in situations where there are specific locations with a high concentration of attractive targets (such as in our segregated or ring society).

Finally, the effect of scaling up the size of the society turned out to be small. Apparently, the (relative) crime rates do not increase much when a larger area is considered, as long as the number of offenders and guardians are increased proportionally.

Obviously, these results should be interpreted with care. As mentioned earlier, a simulation model is by definition a ‘not entirely correct’ representation of reality. Various simplifying assumptions have been made when developing the model, e.g., about the distances between targets, the movement of the agents involved, and, last but not least, the individual decision making processes of the agents. In addition, the experiments described were only performed for some particular sets of parameter settings. Therefore, the results found should not directly be generalized to the real world. Nevertheless, we hope to have convinced the reader that they shed some light on
interesting issues to be further investigated, such as the finding that area hot spot surveillance only works better than hot spot surveillance if the number of guardians is sufficiently large, to name a concrete example.

For future research, the current model can be extended in various directions. For instance, it would be interesting to investigate what happens if the offenders are made more intelligent, i.e., if they are able to ‘learn’ the behavior of the guardians. Similarly, the guardians can be made more intelligent, e.g., by having them anticipate on the expected movements of the offenders, instead of reacting to their actual movements. And finally, an interesting extension would be the addition of passers-by to the model (e.g., ordinary citizens that go to their work at 9 am and go back home at 5 pm, via some standard route), and study how the presence of these passers-by would influence the patterns found so far.

References
