Part I –
Introduction

1. Background

Deviant behaviour or behaviour that violates social norms is an aspect of everyday life that has been important since the beginning of mankind. One could say that eating the forbidden fruit from the tree of knowledge of good and evil by Adam and Eva [16] was the first ‘deviant’ act performed by mankind. Since then, the world has changed in almost every possible way and the content of deviant behaviour has changed accordingly. In this thesis we focus on the legal aspect of deviant behaviour commonly know as crime. Crime can be defined as the violation of rules that, according to criminal law, would lead to conviction.

With time came also a changed interpretation of deviant behaviour. Countries were formed, the population increased and also the number of types of ‘criminal’ acts expanded and changed over time. This resulted in changes in (criminal) law, which could mean that acts that were punishable before suddenly were not punishable anymore, for example adultery. In addition, also acts that were not punishable earlier became punishable, like for instance insider trading. An important thing to note here is that crime is something that is socially constituted and can differ between different countries. Something that is prohibited is one country (for instance bigamy) is considered a normal way of life in other countries.

The reaction on crime has also changed over time. The era of burning witches or torture of thieves is luckily long gone in most parts of the world. After a period in which these brutal methods were normal (not only to punish but also as means to get a statement or a confession), an era started in which the investigation and treatment of different causes of crime became more prominent. There was a period when Lombroso [18] defended his theory that criminality is caused by someone’s biological makeup and that this was visible in someone appearance (e.g. large nose, thick eyebrows). In response to this, others like Lacassagne instead claimed that the social environment was the main factor to contribute to criminal behaviour [30].

Nowadays it is more accepted that anyone can be an offender, and that crime may have biological, psychological, and social causes. It is important to note here that crime is usually the result of an interaction of the different aspects. Someone may temporarily have a high level of testosterone which can cause aggressive behaviour (biological component), however there also has to be an opportunity to act (social component). Or a person can have a desire for material needs (a psychological component) but will only act on this desire (by for instance stealing) when after weighing the pros and cons (s)he has an opportunity that is too good to pass on (social component). Thus, to be able to understand, explain and possibly predict deviant behaviour, one needs to gain more insight in both biological, psychological, and social aspects of human behaviour.

Fortunately, over the last decades, there have been rapid developments in various scientific disciplines related to these human aspects. For instance, the area of neurological research has quickly developed during the last couple of years. The possibility to perform brain scans and observe what happens in the brain under different circumstances and the possibility to acknowledge deviations in the brain are part of recent accomplishments, and may be useful in understanding (deviant) behaviour.
Another example is the development of DNA databases. This is an area under development which can be very beneficial while identifying offenders.

In line with these developments, in this thesis we will also make use of new scientific research methods to help gain greater insights in crimes and offenders. Increasing the insight in why and when certain crimes are performed by certain people is very important to help develop approaches and measurements to prevent criminal actions. Instead of using more traditional research methods we are applying techniques from the area of Artificial Intelligence (AI) to realise this goal. The last couple of years there has been a growing interest in the question how social processes (such as crime) can be studied by means of computational methods, as for instance from AI. In my thesis we will use such techniques (like mathematical modelling, agent-based and population-based modelling, simulation and formal verification) and we will show that applying them to study criminological theories may be very beneficial to the understanding of the occurrence and dynamics of crime and how crime in some cases can be predicted, prevented or decreased.

This introduction is organised as follows. First, in Section 2, we will briefly introduce the research goal of this thesis. Next, in Section 3, we will discuss the areas within Artificial Intelligence that were important in my research. In Section 4 the methodology will be discussed, and the modelling approach will be presented in Section 5. Finally in Section 6 a short overview of the chapters to come is provided.

2. Research Goal

The main research goal of this thesis is to explore whether techniques from the area of Artificial Intelligence can increase insight into different aspects within the field of Criminology. Thus, the main research question of this thesis is defined as follows:

How can techniques from the area of Artificial Intelligence enhance the understanding of criminological phenomena?

Obviously, in criminology, already many theories exist about various (biological, psychological, and social) aspects of deviant behaviour. However, such theories in the criminological domain are often informal, i.e., not in a computational format. This is not a problem when one wants to understand what is happening on an abstract level. However, when detailed dynamics are studied, it is important to take the influence of all aspects (and their interaction) involved into account. This can still be done using an informal theory, but when the number of aspects increases it will be more difficult to oversee all dynamical patterns that result from the interaction between these aspects. Thus, when the numbers increase, it can be very helpful to represent the theories in a computational format, in such a way that they can be used to perform simulation. This will make it possible to perform automated (pseudo-)experiments, in order to gain more insight in a phenomenon, and possibly refine the original theory. This is exactly what is meant with enhancing the insight as mentioned in the main research question. This approach leads to another research (sub-)question namely:

How can theories from criminology be represented as computational models?
Using such computational models, the researcher can investigate different dynamical aspects of the process without changing anything in the real world. Moreover, when something changes in the real world (for instance when a new railway station is opened providing opportunity for offenders, or a new drug comes on the market that changes biological states within a person), one can easily alter the model accordingly. It should be noted that these models usually are not a representation of the entire world but only of relevant aspects. We do not suggest that the models are complete and 100% correct. The main goal (at least of the models presented in this thesis) is to help researchers within the criminological area to gain more insight in different phenomena.

More specifically, for this thesis three domains have been chosen as case studies, namely 1) biologically determined violent behaviour, 2) social learning of delinquent behaviour during adolescence, and 3) spatio-temporal dynamics of crime. For these three case studies (which are addressed, respectively, in Part II, III, and IV), relevant criminological theories have been identified and formalised as computational models. For more information about these theories, see the introductions of the respective parts.

3. Artificial Intelligence

Artificial Intelligence (AI) is a very broad research area, which aims to create intelligence by means of computational methods [26]. Within AI, a large number of different techniques are applied for this purpose. In this thesis the scope is on techniques related to modelling and simulation. The relevant concepts are explained in some more detail below.

Modelling and Simulation

A model could be defined as a representation of an object, system, or idea in some form other than that of the entity itself [27]. Furthermore, a model is a simplified version of reality. A model can be static (e.g. a model of a building) or dynamic (e.g. the model of a process). To make a model of a certain process, one represents the most important elements that occur within that process and their relations. This way, the modeller is not distracted by elements with only a small or even no contribution. One of the things one can do with a model is to study the modelled process by simulation. Simulation of a process is the imitation of that process over time within an artificial environment.

When developing a simulation model of a process, the modeller usually starts with an informal theory. This theory is assumed to describe the process in an informal, but correct manner. The next step in the modelling process is to formalise the theory. This is usually done by identifying relevant concepts in the theory, as well as relationships between them, and formalising these concepts and relationships in some modelling environment. There are multiple modelling environments available (e.g., programming languages like C++ or Java, numerical modelling toolkits like MatLab or Excel, or dedicated simulation environments like LEADSTO) in which one can formalise a theory. When the theory is formalised in enough detail to perform simulation experiments with it, the experimental results of these simulations can offer new insights, that go beyond the insights one had on the basis of the theory only. For example, when a model predicts roughly the behaviour described by the theory, however with some small deviations, then these predictions can be used to create a refined theory.
In addition to the fact that computers can process the consequences of a theory much easier than human beings, there are several other reasons for studying a model instead of the real thing. For instance, sometimes such a reason is that is too dangerous to test something in real life. Within the criminological domain, one can think of a situation with a paedophile. Can you really let him alone in a classroom full of toddlers, to investigate his behaviour? In this case it would be better to investigate the existing literature in order to make a correct model of the paedophile, the toddlers and classroom, and simulate their behaviour to see what happens. Another example is when one wants to investigate which strategy would be best to use for a police officer in order to prevent crime. The researcher can have police officers perform each type of strategy in the real world, and then evaluate these afterwards, but this is both time and money consuming. In this case a model of a city and guardians set with different parameters could do the trick. Note that, when making a model, certain choices have to be made. Since it is not feasible to model all aspects of a certain process in detail, usually only the most relevant aspects are taken.

Social Simulation

Within the general area of social simulation, two perspectives can be distinguished, namely population-based simulation and agent-based simulation.

The classical approaches to simulation of processes in which groups of larger numbers of agents and their interaction are involved are population-based: a number of groups are distinguished (populations) and each of these populations is represented by a numerical variable indicating their number or density (within a given area or location) at a certain time point. Such a simulation model takes the form of a system of difference or differential equations expressing temporal relationships for the dynamics of these variables. An example of population-based modelling is presented in Chapter IV.3, which focuses on the spatio-temporal dynamics of crime in a city. In the model presented in that chapter, three groups are distinguished (guardians, passers by and offenders) that are represented by a number that indicates the amount of agents in the group. When simulating the behaviour of these agents, each time step a percentage of each group moves. In the case of a population-based model the number of agents that move does not have to be discrete, since they are modelled as a density instead of as individuals. The model has the form of differential equations. An example of such an equation for the moving of agents from one location to another is the following:

\[ g(L, t + \Delta t) = g(L, t) + \eta \cdot \left( \left( c(L, t) / c \right) \cdot g \cdot g(L, t) \right) \Delta t \]

This formula expresses that the number of guardians present at a location \( L \) at time point \( t + \Delta t \) is equal to the number of guardians at that location before \( g(L, t) \) plus the number of agents that move \( \eta \cdot \left( \left( g(L, t) / g \right) \cdot c \cdot p(L, t) \right) \). This movement is based on the attractiveness of that location for the type of agents (in this case, guardians). The attractiveness for guardians is dependent (in this simple case) on the offenders present at that location \( c(L, t) \).

In contrast, in the last decades there has been a growing interest in the area of Agent Based Social Simulation (ABSS). In ABSS, which integrates approaches from agent-based computing, computer simulation, and the social sciences, researchers try to exploit agent-based simulation to gain a deeper understanding of social phenomena [1, 12]. ABSS makes use of the agent-based modelling paradigm [29]. According to this
paradigm, a number of intelligent entities (or agents) are identified in the process under investigation, which have several characteristics like autonomy, pro-activeness, reactivity, and social behaviour [31]. ABSS combines the advantages of the agent paradigm (e.g., autonomy of the individual agents) with those of social simulation (e.g., the possibility to perform (possibly large-scale) social “experiments” without much effort), and turns out to be particularly appropriate to analyse phenomena within the criminological domain. Indeed, in recent years, a number of papers have successfully tackled criminological questions using ABSS, (e.g., [3, 6, 7, 17, 19, 20, 21]).

In the area of agent-based modelling it is often taken as a presupposition that simulations based on individual agents are a more natural or faithful way of modelling, and thus will provide better results (e.g., [2, 13, 28]). Here, the behaviour of the agents is specified in detail. Currently, there are a number of approaches to do this, including the Belief-Desire-Intention (BDI) approach, distributed constraint optimisation (DCOP), distributed partially observable Markov decision problems (POMDP), and auctions and game theoretic approaches [10]. In this thesis the main focus is on the BDI approach. The BDI-model bases performance of actions on beliefs, desires and intentions, (e.g. [8, 25]): an action is performed when the agent has the intention to do this action and it has the belief that the opportunity to do the action is there. Beliefs are created on the basis of stimuli that are observed. The intention to do a specific type of action is created if there is a certain desire, and there is the belief that in the given world state, performing this action will fulfil this desire.

4. Methodology

Theories used in Criminology are often informal and multi-interpretable. There are usually many relevant contributors to behaviour which makes it difficult to use a theory for anything else than as a guideline. Investigating dynamics or making predictions is not possible solely based on an informal theory. Our contribution to the solution of this problem is the formalisation of these theories. We have combined and formalised different theories from all sides of the criminological spectrum. The main AI goals we had in mind while doing this are to analyse and combine existing theories, to predict future behaviour and to perform a meta-analysis of the theory.

The methodologies used in the different parts of this thesis differ. In part II we analysed criminal behaviour on both a biological and a cognitive level. First we formalised existing informal domain knowledge, then we combined this into a simulation model and analysed the behaviour of this model. Based on this model we were able to obtain a more clear insight in the different aspects of the behaviour of certain types of violent offenders.

In part III we use a different methodology. In this part we first explored existing theories, in order to develop a model of learning of criminal behaviour during adolescence. After our model was able to simulate behaviour according to the theory we started collaboration with Dr. Frank Weerman, an empirical researcher from the NSCR (Netherlands Institute for the Study of Crime and Law Enforcement), who could provide us with real world data. He and his colleagues had performed a large longitudinal study on juvenile delinquency, and had gathered a lot of empirical data, which we were allowed to use. We used part of the data as a training set, to fine-tune the formulae in our model. After we distinguished a number of interesting variants of the model, we tested (by simulation) these models on the remaining data. Based on these simulations we could evaluate the models.
Part IV again started with an exploration of existing work and theories. In this research we started working from the beginning with Prof. dr. Henk Elffers (from both the department of Criminology of the VU University Amsterdam and from the NSCR), who is an expert in (Environmental) Criminology. In this part, we focused on the development of a model that could function as an analysis tool for researchers. We developed a model that simulates behaviour according to the relevant theory. Based on that model, we adjusted certain parameters to see what would happen if one changed a policy. The main reason for abstracting from real world details in this part is that we do not look at the entire picture. It is almost impossible to simulate the dynamics of crime movement according to reality because the numbers of relevant contributors are endless. Thus, we can not predict the exact outcome of a changed policy. However, we can show the influence of a certain alteration in policy on an abstract level. Therefore, part III explores the effects of such alterations.

In principle, the research presented in all parts has the same goal, namely to develop an analytical tool to gain better insight in the processes described in these parts. However in Part II and IV a different methodology has been used than in Part III. In Part II and IV a theory was taken and formalised, and the process was simulated according to the theory. The methodology used in Part III is different. Here, the formal model is not only based on a theory but also on empirical data. Future behaviour was then simulated based on the model. The results of these simulations were artificially generated data. We then compared the artificially generated data with another set of empirical data that was available, in order to validate the model. Note that the data we used to develop the model was a different subset of the empirical data than the data we used to compare the results.

5. Modelling Approach

In the different research projects we performed throughout the thesis we used a couple of existing modelling languages and environments. These modelling languages and environments will be explained in this section.

TTL

To model different aspects of crime, an expressive modelling language is needed. There are qualitative aspects that need to be addressed, such as physical aspects (e.g. brain deviations), observations, beliefs, decisions to perform a certain action and some aspects of the environment such as the presence of certain agents. But there are also quantitative aspects that need to be modelled, e.g. the reputation of locations or, when taking a physiological perspective, the level of hormones and neurotransmitters. These quantitative aspects can best be represented by real numbers and mathematical formulae.

Another requirement of the modelling language to be chosen is its suitability to express the basic mechanisms of crime-related processes on the one hand (for the purpose of simulation), and on the other hand more global properties (for the purpose of logical analysis and verification). For example, basic mechanisms of movement of crime involve decision functions for individual agents, whereas global properties are the types of statements like “the location of hot spots changes over time”.

The predicate-logical Temporal Trace Language (TTL) fulfils all of these requirements [4]. It integrates qualitative, logical aspects and quantitative, numerical aspects. This integration allows the modeller to exploit both logical and numerical
methods for analysis and simulation. Moreover it can be used to express dynamic properties at different levels of aggregation, which makes it well suited both for simulation and logical analysis.

The TTL language is based on the assumption that dynamics can be described as an evolution of states over time. The notion of state as used here is characterised on the basis of an ontology defining a set of physical and/or mental (state) properties that do or do not hold at a certain point in time. These properties are often called state properties to distinguish them from dynamic properties that relate different states over time. A specific state is characterised by dividing the set of state properties into those that hold, and those that do not hold in the state. Examples of state properties are ‘agent 1 has a high level of testosterone’, ‘agent 1 is risk seeking’, ‘agent 1 performs an assault on agent 2’, or ‘there are 5 guardian agents at location A’. Real value assignments to variables are also considered as possible state property descriptions.

To formalise state properties, ontologies are specified in a (many-sorted) first order logical format: an ontology is specified as a finite set of sorts, constants within these sorts, and relations and functions over these sorts (sometimes also called signatures). The examples mentioned above then can be formalised by n-ary predicates (or proposition symbols), such as, for example, performed or number_of-guardians, which can be used to define more complex atoms like performed(assault_at(a1,a2)) or number_of_guardians(locA, 5). Such atoms are called state ground atoms (or atomic state properties). For a given ontology Ont, the propositional language signature consisting of all ground atoms based on Ont is denoted by APROP(Ont). One step further, the state properties based on a certain ontology Ont are formalised by the propositions that can be made (using conjunction, negation, disjunction, implication) from the ground atoms. Thus, an example of a formalised state property is number_of_guardians(locA, 5) & number_of_guardians(locB, 3). Moreover, a state S is an indication of which atomic state properties are true and which are false, i.e., a mapping S: APROP(Ont) → {true, false}. The set of all possible states for ontology Ont is denoted by STATES(Ont).

To describe dynamic properties of crime-related processes (such as the biological and psychological processes inside a person, or the learning of (criminal) behaviour), explicit reference is made to time and to traces. A fixed time frame T is assumed which is linearly ordered. Depending on the application, it may be dense (e.g., the real numbers) or discrete (e.g., the set of integers or natural numbers or a finite initial segment of the natural numbers). Dynamic properties can be formulated that relate a state at one point in time to a state at another point in time. A simple example is the following (informally stated) dynamic property about the number of guardians at a certain location:

For all traces γ,
there is a time point t such that
at location A, there are at least x guardian agents.

A trace γ over an ontology Ont and time frame T is a mapping γ : T → STATES(Ont), i.e., a sequence of states γ (t ∈ T) in STATES(Ont). The temporal trace language TTL is built on atoms referring to, e.g., traces, time and state properties. For example, ‘in trace γ at time t property p holds’ is formalised by state(γ, t) |= p. Here |= is a predicate symbol in the language, usually used in infix notation, which is comparable to the Holds-predicate in situation calculus. Dynamic properties are expressed by temporal
statements built using the usual first-order logical connectives (such as \(\neg, \land, \lor, \implies\)) and quantification (\(\forall\) and \(\exists\); for example, over traces, time and state properties). For example, the informally stated dynamic property introduced above is formally expressed as follows:

\[
\forall \gamma: \text{TRACES} \exists t: \text{TIME} \exists i: \text{INTEGER} \\text{state}(\gamma, t) \models \text{number _ of _ guardian(loca, i)} \land i \geq x
\]

In addition, language abstractions by introducing new predicates as abbreviations for complex expressions are supported. For more details of TTL, see [4].

**LEADSTO**

To be able to perform (pseudo-)experiments, only part of the expressivity of TTL is needed. To this end, the executable LEADSTO language [5] has been defined as a sublanguage of TTL, with the specific purpose to develop simulation models in a declarative manner. In LEADSTO, direct temporal dependencies between two state properties in successive states are modelled by executable dynamic properties. The LEADSTO format is defined as follows. Let \(\alpha\) and \(\beta\) be state properties as defined above. Then, the notation \(\alpha \rightarrow\rightarrow_{e,f,g,h} \beta\) means:

*If state property \(\alpha\) holds for a certain time interval with duration \(g\), then after some delay between \(e\) and \(f\) state property \(\beta\) will hold for a certain time interval with duration \(h\).*

As an example, the following executable dynamic property states that “if an agent \(a\) goes to a location \(l\) during 1 time unit, then (after a delay between 0 and 0.5 time units) this agent will be at that location for 5 time units”:

\[
\forall a: \text{AGENT} \forall l: \text{LOCATION} \\text{performed}(a, \text{go_to_location}(l)) \rightarrow\rightarrow_{0, 0.5, 1, 5} \text{is_at_location}(a, l)
\]

Based on TTL and LEADSTO, two dedicated pieces of software have been developed [4, 5]. First, the LEADSTO Simulation Environment takes a specification of executable dynamic properties as input, and uses this to generate simulation traces. Second, to automatically analyse the resulting simulation traces, the TTL Checker tool has been developed. This tool takes as input a formula expressed in TTL and a set of traces, and verifies automatically whether the formula holds for the traces. In case the formula does not hold, the checker provides a counter example, i.e., a combination of variable instances for which the check fails.

**Matlab**

Matlab is a numerical computing environment maintained by The MathWorks [32]. This environment allows easy matrix manipulation, plotting of functions and data, implementation of algorithms, creation of user interfaces and interfacing with programs in other languages. In the current thesis, Matlab has mainly been used for simulation purposes. Matlab has as advantage over the earlier mentioned TTL and LEADSTO environments that it has a higher computational efficiency, which allows the modeller to run very large simulations in a short amount of time. For example, in the research project concerning the spatio-temporal dynamics of crime (see Part IV) we performed
simulations with a large number of locations and over a long period. Matlab was the appropriate environment for these simulations. Further, we wanted to visualise the results of the simulations in terms of animations in a two-dimensional space. Matlab also provides good facilities for this.

**Microsoft Office Excel**

In the research project concerning social learning (Part III in the thesis) we performed simulations in the Microsoft Office Excel environment. This environment features calculation, graphing tools, pivot tables and a macro programming language. Although this software originally was not designed for simulation experiments, it fitted our requirements very well. First, it can easily import and handle the large set of numbers that resulted from the empirical study used in Part III. As explained in that part, we were working with empirical data from a large network of students, which were all (possibly) connected to each other, and were already available in terms of comma Separated Values (CSV) files. A second motivation to use Excel for this project was the fact that it could adequately perform the mathematical operations that were required by the model, including operations such as searches and lookups in different data sheets.

### 6. Overview

To illustrate the contribution of the interdisciplinary research between AI and Criminology in three different domains, this thesis consists of three parts. These parts are dedicated to different domains within criminology and for each of these domains it is illustrated how AI techniques can be beneficial in understanding, analysing or predicting criminal behaviour. Each of the parts starts with an elaborate introduction. Below you will find a short description of the contents of each of the parts.

Part II focuses on the biological and cognitive aspects of criminal behaviour. Certain types of violent criminal behaviour can best be explained by taking a combination of biological, psychological and social aspects into account [23, 24]. Dynamical modelling methods developed in recent years often address biological, psychological, or social dynamical systems separately. This research makes the first step in the development of an agent-based modelling approach for criminal behaviour in which these aspects are integrated in one dynamical system. Based on existing literature on violent offenders, the approach provides the analyst more insight in how certain types of violent behaviour may result from an interaction between biological factors (e.g., certain brain deviations, testosterone levels and serotonin levels), cognitive and emotional factors (e.g., aggressiveness and impulsiveness) and social factors (e.g., the presence or absence of certain other agents). The approach consists of one generic model for the behaviour of violent offenders with parameters that can be set to obtain simulation traces for three known types of offenders. This enables the analyst to find out whether an offender of a certain type may show certain behaviour under given circumstances, but also (in the opposite direction) to determine what kind of scenario or circumstances could lead to certain given behaviour.

Part III addresses development and validation of a dynamic agent-based approach to simulate the dynamics of delinquent behaviour among adolescents [9, 22]. More specifically, a model has been developed that can simulate the development of youth delinquency in a classroom. The approach has been used to perform simulation experiments in which the delinquency of 250 pupils was dynamically calculated over a couple of years. This expected delinquency is based on personal characteristics on the
one hand and the delinquency of peers on the other hand. A second dataset has been used to validate the model, using a specifically developed accuracy measure. The validation shows that the model predicts delinquency substantially better than a baseline model that only uses the delinquency of the previous year. Next the same model is used to perform so-called “what-if simulations”, or computer-supported thought experiments. An interesting question is, for example, “what would happen if we placed one bad child in a classroom full of teacher’s pets”? The answers to these questions may be very useful for policy making. Since these what-if simulations make use of the (validated) model developed earlier, which was tested against several datasets, the outcomes also are expected to have some validity. However it is not guaranteed that they have the same level of validity as the outcomes from the original simulations, because each new scenario in principle may introduce new factors that can influence the results.

Part IV focuses on the spatio-temporal dynamics of crime. Within the routine activity paradigm, it is argued that crime takes place when a motivated offender finds an insufficiently guarded attractive target [11, 15]. Although this theory has as advantage that it is very clear and understandable at an abstract level [14], this simplicity seems to vanish as soon as one zooms into concrete questions on underlying processes. For example, what governs whether a motivated offender will find an attractive target? This research proposes to use social simulation techniques to answer these types of questions. As such, simulation should be seen 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 analytical methods. Simulation is -in such an application- not an empirical, but a theoretical method, which uses computer generated instances of realisations of processes. In the current research, this approach is used to investigate various aspects of spatio-temporal dynamics of crime, including situations in which the targets are static as well as dynamic, and where different strategies for guardianship are used.

This thesis ends with a concluding chapter in which will be explained what has been done. We will discuss the research presented in the different parts in relation to the research goal mentioned in this introduction to draw conclusions about the usefulness of research between AI and Criminology for both research areas. Further we will discuss possible future directions for this research area.

Some discussion may exist about the terminology used and the assumptions made throughout the chapters of this thesis. Obviously, informal theories are often multi-interpretable. While formalising such theories certain choices need to be made, as was also the case in this thesis. For example, we used the word ‘displacement’ to indicate the spatio-temporal dynamics of crime throughout this thesis. In addition, while we used the word ‘criminal’ to indicate a person who commits a certain delinquent act, in the field of criminology the more correct word ‘offender’ is used. The latter term emphasises the fact that every person could in principle be someone who breaks the rules, without stigmatising people for life. We agree with this view; however we sometimes used the word ‘criminal’ to make a strict distinction between the three types of agents used in our computational models, namely criminals, passers by and guardians. We also acknowledge that passers by may well become criminals if the opportunity arises and the same can be said about guardians; they also can break the rules if the opportunity outweighs the consequences. Similarly, passers by can count as guardians when they prevent a crime from happening, and insufficient guardians can be seen as passers by. Thus, to conclude, in practice the distinction between these three
types of agents is not so clear at all, but for the sake of simplicity we made the distinction when building our simulation models.

References
16. Genesis 2:16-17


