Towards Integration of Biological, Psychological, and Social Aspects in Agent-Based Simulation of Violent Offenders

Tibor Bosse, Charlotte Gerritsen, and Jan Treur

Description Page

Abstract

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Most closely related work:

- Baal, P.H.M. van (2004). *Computer Simulations of Criminal Deterrence: from Public Policy to Local Interaction to Individual Behaviour*. Ph.D. Thesis, Erasmus University Rotterdam. Boom Juridische Uitgevers.
- Brantingham, P. L., & Brantingham, P. J. (2004). Computer Simulation as a Tool for Environmental Criminologists. *Security Journal*, 17(1), 21-30.
- Liu, L., Wang, X., Eck, J., & Liang, J. (2005). Simulating Crime Events and Crime Patterns in RA/CA Model. In F. Wang (ed.), *Geographic Information Systems and Crime Analysis*. Singapore: Idea Group, pp. 197-213
- Cohen, L.E. and Felson, M. (1979). Social change and crime rate trends: a routine activity approach. *American Sociological Review*, vol. 44, pp. 588-608.
- Delfos, M.F. (2004). *Children and Behavioural Problems: Anxiety, Aggression, Depression and ADHD; A Biopsychological Model with Guidelines for Diagnostics and Treatment.* Harcourt book publishers, Amsterdam.
- Moir, A., and Jessel, D. (1995). *A Mind to Crime*: *the controversial link between the mind and criminal behaviour.* London: Michael Joseph Ltd; Penguin.
- Raine, A. (1993). *The Psychopathology of Crime: Criminal Behaviors as a Clinical Disorder*. New York, NY: Guilford Publications.

The first three references are related to this paper because they describe simulations of criminal behaviour. However, they focus only on social/environmental aspects, and not on the integration of biological, psychological, and social aspects. The fourth reference is related to this paper because it provided the criminological background that we used for our simulation model. The last three references are related to this paper because they provided the biological and psychological background that we used for our simulation model.

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Abstract

In the analysis of criminal behaviour, a combination of biological, psychological and social aspects may be taken into account. Dynamical modelling methods developed in recent years often address biological, psychological, or social dynamical systems separately. This paper 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. It is shown how within a certain (multi-agent) social context, biological factors such as certain brain deviations, testosterone levels and serotonin levels, affect cognitive and emotional functioning in such a way that a crime is committed when the perceived opportunity is there. The paper presents 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.

1. Introduction

Within Criminology, the analysis of criminal behaviour is a central issue. Such an analysis involves different types of aspects, such as biological, psychological, and social aspects and their mutual interactions; e.g., (Towl and Crighton, 1996; Turvey, 1999; Bartol, 2002; Moir and Jessel, 1995; Raine, 1993; Cohen and Felson, 1979). Usually such analyses are made by criminologist researchers or practitioners in a nonexact manner, without using any formalisation or computer support. The interplay between the various aspects involved may be complex and dynamic. Therefore such a task requires a rare combination of expertise in different knowledge domains. But even if such a combination of expertise is available, often it is not straightforward and in certain cases may be quite difficult indeed. Therefore computer support is more than welcome, both concerning the expertise in the different knowledge domains and the complexity of the dynamical aspects of the integrated process. Due to the difficulty to address this area within Criminology, the few contributions made to the literature often address only one or some of these types of aspects, for example, social and environmental aspects, as in (Baal, 2004).

In recent years much progress has been made in biological, cognitive, and social complex dynamical systems modelling within areas such as Artificial Intelligence, Computational Biology/Artificial Life, Cognitive Science, and Computational Social Science/Organisation Theory. The methods developed in these areas usually address one of the disciplines separately. For example, in social simulation the agents usually are assumed to show simple behaviours, and their internal cognitive systems are not taken into account. Similarly, in cognitive modelling often biological factors are not addressed (Gray, 2007).

However, when an integrated modelling approach is applied, this opens the perspective to address the analysis of criminal behaviour in more exact, formalised and computer supported manners. Thus, the way is paved to a more solid basis and computer support for simulation and analysis in the area of Criminology. The research discussed here explores this potential. It identifies on the one hand useful knowledge from the literature in Criminology and the different disciplines underlying it (e.g., Delfos, 2004; Moir and Jessel, 1995;

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Raine, 1993; Towl and Crighton, 1996), and on the other hand it exploits dedicated agent-based modelling techniques (Bosse, Jonker, Meij, and Treur, 2007). The aim is, by combining these, to develop an integrated computer-supported method to criminal behaviour analysis and management. The work reported here has been performed in close collaboration with a team of scientists from different disciplines, among whom outstanding criminologists and psychologists. They consider the approach explored here as having a high potential to develop support for both policy makers and practitioners in management of crime in society.

As part of this enterprise, agent-based dynamical models for different types of criminal behaviour are being developed. These models may incorporate behavioural agent models from an external perspective, as well as models for internal dynamics. Behaviour models from an external perspective may involve rather complex temporal relationships between (1) external factors in the criminal's social context that occur as stimuli and (2) his or her actions, mediated by his or her characteristics. Models of internal dynamics usually can be expressed by direct temporal/causal relationships between stimuli and internal states, between different internal states, and between internal states and actions. The internal states may involve, for example, cognitive, decision, reasoning, normative/ethical, attentional, emotional, and personality aspects. In addition, they may involve underlying biological aspects such as specific types of brain deviations, levels of hormones or neurotransmitters. Example of aspects related to the wider social context are the observed level of social or organised security control, expectations about acceptance of certain actions within society or within a peer group, and social dynamics within groups. Such dynamical models are being collected in a model library. Moreover, relationships between such models are to be established, for example the fact that one model M_2 refines another model M_1, or that a model M_1 from an internal perspective generates the behaviour of a model M_2 from an external perspective.

As a first step in that direction, this paper presents one generic simulation model for the behaviour of violent criminals. As input, certain parameters can be set with respect to biological and cognitive characteristics of a type of criminal, and social and environmental aspects of its environment. As output, simulation traces are generated that show the behaviour over time of such a type of criminal under these circumstances.

In comparison to existing work in the analysis of criminal behaviour, an important distinction is that the agent-based modelling approach presented here focuses on the dynamical aspect of criminal behaviour. Most approaches to the analysis of criminal behaviour that have been proposed are basically static and usually based on profiling, i.e., they assume a number of fixed criminal profiles, whose behaviour depends in a deterministic way of certain personality characteristics, thereby ignoring the fact that these characteristics often are quite context-sensitive and may change over time; e.g., (Alison, Bennell, Mokros, and Ormerod, 2002). In contrast, the proposed approach (1) takes the dynamical systems perspective on behaviour as a point of departure, which considers behaviour as emerging from a dynamic interplay of various components and aspects, and (2) provides an integrated approach to model such complex dynamical systems incorporating biological, psychological and social aspects.

In this paper, Section 2 discusses three specific types of criminals used as a case study: the violent psychopath, someone with an antisocial personality disorder and someone diagnosed with an intermittent explosive disorder. In Section 3 the proposed methodology is discussed. In Section 4 the simulation model is presented and in Section 5 the settings for the model are discussed. Section 6 discusses some of the simulation results. Section 7 presents the validation of the simulation model. Finally, Section 8 is a discussion about the approach and its possible applications.

2. Three Types of Violent Criminals

Criminals are found in a large variety of types. One classification is to divide criminals into violent offenders and non-violent offenders. The case study made in this paper is taken from the group of violent offenders.

When considering violent offenders different aspects need to be addressed that play an important role in their violent behaviour namely *cognitive and behavioral* aspects (such as low arousal, impulsiveness), *socially related* aspects (such as feeling guilt, remorse, having a theory of mind, empathy), and *biological* aspects (such as brain deviations, hormone levels, neurotransmitter levels).

When a closer look at the group of violent offenders is taken, a wide variety of types can be distinguished e.g. schizophrenics, serial killers, violent rapists, psychopaths. This paper focuses on three types of violent offenders for which these biological, cognitive and social aspects have extensively been studied in the literature: the violent psychopath, the offender with an antisocial personality disorder (APD), and the offender who suffers from an intermittent explosive disorder (IED); e.g., (Cleckley, 1976; Hare, 1970, 1993; Quay, 1965, Raine, 1993; Moir and Jessel, 1995, pp. 123-183; Bartol, 2002, pp. 87-120; Turvey, 1999, pp. 193-207). In this section, these types of criminals are briefly introduced. Section 2.1 discusses the violent psychopath. In Section 2.2 the person with APD is described, and the person with IED is discussed in Section 2.3. Finally, in Section 2.4, these aspects are summarised and compared from a modelling perspective, i.e., some characteristics are introduced that are useful to consider when modelling criminal behaviour, and it is explained to what extent these characteristics hold for the three types of violent criminals.

2.1 The Violent Psychopath

Cognitive and Behavioural Aspects

Psychopaths do not show feelings like the rest of us. They lack the normal mechanisms of anxiety arousal, which ring alarm bells of fear in most people. Confronted with trial and danger, even their skin does not sweat and becomes clammy like the skin of normal people (Moir and Jessel, 1995, p.157; Raine, 1993, pp. 159-165). Violent psychopaths, who are almost always males, can be described as predators and are usually proud of it. They lack the usual type of more impulsive aggressive behaviour, i.e., violence accompanied by an emotional discharge (usually anger of fear) and an excitement arousal (in the sympathetic nervous system). Instead, their kind of violence is similar to predatory aggression, that is accompanied by minimal or no sympathetic arousal and is planned, purposeful, and without emotion. This is correlated with a sense of superiority; they like to exert power and have unrestricted dominance over others, ignoring their needs and justifying the use of whatever they feel compelling to achieve their goals and avoid adverse consequences for their acts. As it happens with predators, psychopaths are capable of having extremely heightened attention in certain situations. An important trigger for psychopathic violent behaviour is the use of drugs and/or alcohol. They are more likely to turn to alcohol and drugs and their brain reacts in a different way to the effects of drugs and alcohol. For a psychopath, using drugs or alcohol can become a compulsion and, through a genetic and neurological mechanism, result in violent behaviour (Moir and Jessel, 1995, p.201; Raine, 1993, p.98).

Social Aspects

Psychopaths are characterised by a disregard for social obligation and a lack of concern for the feelings of others. They display pathological egocentricity, shallow emotions, lack of insight, poor control of beings and remorse, anxiety or guilt in relation to their antisocial behaviour. They are usually callous, manipulative individuals, incapable of lasting friendship and of love. They use charm, manipulation, intimidation and violence to control others and to satisfy their own selfish needs. Lacking in conscience and in feelings for others, they violate social norms and expectations without the slightest sense of guilt or regret (Moir and Jessel, 1995, p.150; Raine, 1993, p.8).

Biological Aspects

Psychopaths have a specific deviation in the brain: the frontal lobes are disconnected from the limbic area. The frontal lobes are the area of the brain that is concerned with conscience, guilt and remorse and is the residence of our morality (Raine, 1993, pp. 109-113). The limbic area generates feelings (Moir and Jessel, 1995, p.157; Raine, 1993, p.115). Because of the disconnection, psychopaths cannot express their emotions in terms of feeling. They know the difference between right and wrong, but the difference does not matter to them. It is hard for a psychopath to understand or imagine the pain of other people (Moir and Jessel, 1995, p.158; Raine, 1993, pp. 7-8). Furthermore, violent psychopaths have a high level of testosteron, which makes them more aggressive in their behaviour, and low levels of serotonin, which makes them easily bored, and stimulates them to seek sensation. Once they reach adulthood, their condition is incurable. However, only a fraction of psychopaths develops into violent criminals (Moir and Jessel, 1995, p. 267).

2.2 Antisocial Personality Disorder

Cognitive and Behavioural Aspects

Persons with an Antisocial Personality Disorder seem to have a cluster of traits that make them prone to show violent behaviour. They have a low emotional boiling point, which can lead to inappropriate and aggressive reactions to minor provocations. They are sparked into a violent act, losing control of themselves (Moir and Jessel, 1995, p.163). In contrast to the emptiness of feeling of the psychopath, someone with APD shows emotion in the form of an outburst or anger, but hardly emotions other than these.
APD types usually have abnormally low levels of arousal and they soon become habituated to stimuli and are often bored (Moir and Jessel, 1995, pp. 74-80, 173-174; Delfos, 2004, p.100; Raine. 1993, pp. 222-224; Sperry, 2003, p.38). This explains how some of them can initiate violent acts: they are only stimulated when engaged in actions providing strong stimuli. Therefore, they often seek risk and use drugs in the search for stronger stimuli. Risk-seeking behaviour and substance abuse can be seen as attempts to escape feeling empty or emotionally void.

Social Aspects

Central to understanding individuals diagnosed with APD is that, in social context, they cannot experience emotions associated with either empathy or suffering of others. They tend to be more hostile, less affiliative, and have problems with moral understanding (Moir and Jessel, 1995, p.178; Raine, 1993, p.7; Sperry, 2003, p.40; DSM-IV, p.706). The APD usually comes to attention because of a gross disparity between behaviour and the prevailing norms, and is characterised by at least: callous unconcern for the feelings of others; gross and persistent attitude of irresponsibility and disregard for social norms, rules and obligations; incapacity to maintain enduring relationships; very low tolerance to frustration in social contacts; a low threshold for discharge of aggression, including violence towards others; incapacity to experience guilt and to profit from experience, particularly punishment.
APD offenders have a serious lack of feelings of guilt and remorse in comparison to the non-violent population, but most of them are still capable of having feelings of guilt and remorse (Moir and Jessel, 1995, p.164; Sperry, 2003, p.40; DSM-IV, p.706). In line with what is stated above, this disorder is characterised by a long standing pattern of a disregard for other people’s rights, often even violating these rights. This pattern of behaviour usually has occurred since the age of 15, and consists of failure to conform to social norms, deceitfulness, impulsivity, irritability and aggressiveness, a reckless disregard, a consistent irresponsibility and often lack of remorse.

Biological Aspects

The aggressive behaviour of the violent APD offender is likely to be related to low serotonin levels and an inadequate control mechanism due to brain damage (Moir and Jessel, 1995, p.177; Raine, 1993, p.85). Brain damage in the frontal lobes, the limbic system or both results in a brain deficient in the normal control systems – the brakes on behaviour are faulty. The violent APD offender has been shown to have this sort of abnormality. Although all criminals discussed in this paper have damage in the frontal or temporal lobes or in the limbic system in some combination (Moir and Jessel, 1995, p.180; Raine, 1993, pp.109-115), within the person with APD in particular, the brain mechanism that generates feelings is connected to the frontal cortex (the area which is involved in learning from the consequences of our behaviour). This explains why the APD type is capable of remorse sometimes (Moir and Jessel, 1995, p.180; Raine, 1993, pp.109-115).
The anxiety associated with certain types of Antisocial Personality Disorder may represent the limit of emotions experienced, or there may be physiological responses without analogy to emotions experienced by others.
Low levels of serotonin in the violent offender with APD do not produce aggression per se, but it increases the tendency to respond aggressively to provocation (Moir and Jessel, 1995, p.177; Raine, 1993, p.85; Sperry, 2003, p.40; DSM-IV, p.706). Also the hormone of aggression is involved in the person with APD: (s)he has a high rate of testosterone, which is associated with a lack of inhibition, and more aggressiveness.

2.3 Intermittent Explosive Disorder

Cognitive and Behavioural Aspects

There is a class of violent offenders who are capable of acts just as savage as the psychopath's but who nevertheless retain full ability to show remorse and regret. This type of disorder is called Intermittent Explosive Disorder (IED) (Moir and Jessel, 1995, p.184; DSM-IV, pp. 663-667). An Intermittent Explosive Disorder is a disorder of impulse control characterised by severel episodes in which aggressive impulses are released and expressed in serious assault or destruction of property although no such impulsiveness or aggressiveness is shown between episodes.

Social Aspects

Offences by persons with IED are almost always associated with an unpremeditated outburst, a disproportionate reaction and consequent injury, usually to an acquaintance or family member. After the episode the offender has no recollection of his actions and has feelings of remorse.

Biological Aspects

What seems to be happening is that the brain itself generates a form of miniature epileptic fit. An electrical storm in the rage areas spreads to the rest of the brain. A defect in various areas of the limbic system can have a similar outcome; the affected patient has the sensation of feelings that occur in a vacuum – there is no reason or cause for them, but they have been generated internally by this glitch in the system. The mechanism for processing emotions has produced a rogue emotion of its own and it cannot control its own creation. This causes a sudden and inexplicable alteration in mood. It only takes a mild trigger to produce this abnormal electrical discharge, e.g. the meeting of someone with negative, provoking behaviour (Moir and Jessel, 1995, p.187; DSM-IV, pp. 663-667).

2.4 Comparison

When comparing the three types of violent offenders described above, it turns out that they can be distinguished by taking a number of basic characteristics into account (see Table 1 for an overview):

Anxiety Threshold: this is the threshold that needs to be passed by certain stimuli, in order to make a person anxious. Thus, when a person's anxiety threshold is high, it is very difficult for this person to become anxious (and as a result, (s)he hardly knows any fear). This seems to be the case for the violent psychopath: in these persons, a notion of fear is almost completely not showing. In contrast, persons with APD and IED have a medium anxiety threshold. Nevertheless, in some special circumstances (i.e., during the short episodes of aggressiveness described above) the anxiety threshold of a person with IED suddenly becomes much higher.

Excitement Threshold: this is the threshold that needs to be passed by certain stimuli, in order to make a person excited. Thus, when a person's excitement threshold is high, it is very difficult for this person to become excited (and as a result, (s)he is often bored). This is the case for the violent psychopath and for persons with APD. These persons are very hard to excite and are very often bored. This can be related to their low serotonin level (e.g., Quay, 1965, Raine, 1993). Persons with IED have a medium excitement threshold. But under certain circumstances (during aggressive rage) their excitement threshold is low, and they get excited very easily.

Theory of mind: The notion of theory of mind (e.g., Humphrey, 1984; Dennett, 1987; Baron-Cohen, 1995) covers two concepts: 1) having the understanding that others (also) have minds, which can be described by different and separate mental concepts, such as the person's own beliefs, desires, and intentions, and 2) being able to form theories as to how those mental concepts such as the person's own beliefs, desires, and intentions play a role in his or her behaviour. The violent psychopath has a limited theory of mind, which is however highly developed in a very specific sense. He or she can make the distinction between himself and another person, and is able to form theories about another person's beliefs, desires and intentions, in particular, as far as this is of use to achieve his or her own goals, for example, by manipulating the other person, in case of self interest. A person with APD has a less developed theory of mind and is not able to make the distinction between him and someone else. Persons who are diagnosed with IED normally have a medium theory of mind and can make the distinction between themselves and others, but when they have an aggressive episode, their theory of mind decreases and they are not able to distinguish between themselves and others anymore.

Positive and negative emotional attitude towards others: these concepts express the extent to which a person may have positive or negative feelings with respect to other persons. For the violent psychopath, both attitudes are low: these persons hardly show any emotion concerning other persons, so for them, both the positive and the negative emotional attitude towards others is low. For the offender with APD, the situation is slightly different. Like the violent psychopaths, these persons do not have much positive feelings towards others, but they may have some negative feelings towards others. Finally, offenders with IED usually have a normal (medium) positive and negative emotional attitude towards others, but during the episodes of discontrol, all their positive feelings disappear, and quite substantial additional negative feelings arise.

Aggressiveness*:* since the case study focuses on violent offenders, by definition this considered type of criminal is aggressive, which can be related to a high level of testosterone; e.g., (Delfos, 2004, p.65, p.68, pp.83-85, p.112). However, the criminals with IED only become highly aggressive during a short period, whereas the other two types are always aggressive.

Impulsiveness: when someone acts impulsive, this means that the action was not planned. Many types of violent criminals are impulsive, but they differ in the type of impulsive action they perform. While the APD offender may lash out in disproportionate overreaction, the psychopath, with his emotional detachment, will impulsively take whatever course of action will supply him with the necessary gratification. (Moir and Jessel, 1995, p. 176; Webster and Jackson, 1997; Hart and Dempster, 1997). Persons with IED normally have a medium impulsiveness but when they have a seizure they become highly impulsive.

Sensitivity to alcohol: Persons with brain deviations are more likely to turn to drinking and taking drugs. Moreover, their brains react in a different way to the effects of drugs and alcohol. For psychopaths and persons with APD, only a small amount of alcohol or drugs can become a compulsion and, through a genetic and neurological mechanism, result in violent behaviour. Persons with IED can have seizures triggered by the smallest amount of alcohol; a tiny stimulus may be all that is necessary to unleash the electrical storm in the emotional centre of the limbic system; e.g., (Moir and Jessel, 1995, p.201, p.258).

	Anxiety threshold	**Excitement threshold**	**Theory of mind (Care)**	**Theory of mind (Self Interest)**	**Positive emotional attitude to others**	**Negative emotional attitude to others**	**Aggressive-ness**	**Impulsive-ness**	**Sensitive to alcohol**
Violent Psychopath	high	high	low	high	low	low	high	high	yes
Antisocial Personality Disorder (APD)	medium	high	low	low	low	medium	high	high	yes
Intermittent Explosive Disorder (IED)	normally: medium in episode: high	normally: medium in episode: low	normally: medium in episode: low	normally: medium in episode: low	normally: medium in episode: low	normally: medium in episode: high	normally: medium in episode: high	normally: medium in episode: high	yes

Table 1 Overview of commonalities and differences in characteristics for the three types of violent criminals

3. Modelling Approach

The challenge is to model the biological, psychological and social aspects in an integrated manner. On the one hand, qualitative aspects have to be addressed, such as beliefs, desires, and intentions, certain brain deviations, and some aspects of the environment such as the presence of certain agents. On the other hand, quantitative aspects have to be addressed, such as testosterone and serotonin levels, and in the environment distances and time durations. Furthermore, it should be possible to model on a higher level of aggregation or abstraction, as it would not be feasible, for example, to model the brain anatomy at the level of neurons.

The modelling approach based on the modelling language LEADSTO (Bosse, Jonker, Meij, and Treur, 2007) fulfils these desiderata. It is possible to use it to model at higher levels of aggregation, and it integrates qualitative, logical aspects and quantitative, numerical aspects; cf. (Bosse, Jonker and Treur, 2007). This integration allows the modeller to exploit techniques from both areas. As the latter type of aspects are fully integrated in the former, methods for logical analysis can be exploited. Conversely, as the former type of aspects are fully integrated in the latter, a simulation environment is offered that extends the usual possibilities to simulate dynamical systems by numerical methods by incorporating qualitative elements.

The language LEADSTO enables to model direct temporal dependencies between two state properties in successive states by means of so-called *dynamic properties*, which are comparable to rules as occurring in specifications of a simulation model; for example:

If in the current state, state property p holds,
then in the next state, state property q holds

Here basic (atomic) state properties can have a qualitative, logical format, such as an expression desire(d1), expressing that desire d1 occurs, or a quantitative, numerical format such as an expression has_value(x, v) which expresses that variable x has value v. Such atomic state properties can be combined to more complex state properties by taking conjunctions by means of the logical operator 'and'.

To be more precise, the LEADSTO format is defined as follows. Let α and β be state properties of the form 'conjunction of ground atoms or negations of ground atoms'. In the leads to language the notation $\alpha \twoheadrightarrow_{e, f, g, h} \beta$, means:

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

For more details of the language LEADSTO, see (Bosse, Jonker, Meij, and Treur, 2007).

4. The Integrated Simulation Model

In this section the simulation model that has been developed is described in more detail. In Appendix A a complete overview of the model is given.

4.1 Global Structure of the Simulation Model

The integrated simulation model has been built by composing a number of submodels for different aspects, including (but not limited to) a model based on beliefs, desires and intentions (BDI) and a model for the environment. The BDI-model bases the preparation and performing of actions on cognitive state properties of type belief, desire and intention, and is described in Section 4.2. The BDI-model describes how desires can lead to intentions and how intentions can lead to actions, when the appropriate opportunities are there. It needs as input desires and beliefs in opportunities. For these elements additional models have been developed. More specifically, the integrated simulation model is composed of submodels for the biological, psychological and social/environmental aspects in the following manner:

1. a submodel for reasoning about *beliefs, desires and intentions*, based on the BDI-model (Section 4.2)

2. a submodel to *determine desires* needed as input for the BDI-model; this model incorporates various biological and psychological aspects and their interactions (Section 4.3)
3. a submodel to determine how observations lead to *beliefs in an opportunity* as needed as input for the BDI-model; this model is based on the Routine Activity Theory (Section 4.4)
4. a *geographical model* of the world; this is represented by a labeled graph of locations and connections (Section 4.5)
5. a submodel for the *multi-agent society*; this concerns generation of the actions for the different types of agents to let them move in the world and to determine the effects of all actions performed (Section 4.6).

Note that the biological and psychological aspects of the criminal are addressed in the submodels 1. and 2., the social and environmental aspects are addressed in submodels 4. and 5., and submodel 3. relates society aspects to psychological aspects.

4.2 Reasoning about Beliefs, Desires and Intention

Part of the model for criminal behaviour presented in Section 4 is inspired by the socalled BDI-model, a model that bases the preparation and performing of actions on beliefs, desires and intentions (e.g., Georgeff and Lansky, 1987; Bratman, Israel and Pollack, 1988; Rao and Georgeff, 1991; Jonker, Treur, and Wijngaards, 2003). The BDI-model incorporates a pattern of reasoning to explain behaviour in a refined form. Instead of a process from desire to action in one step, as an intermediate stage first an intention is generated, and from the intention the action is generated. Thus the process is refined into a two-step process. See Figure 1 for the generic structure of the BDI-model. In this figure, the box indicates the borders of the agent, the circles denote state properties, and the arrows indicate dynamic relationships. Note that the picture does not show issues like recovery from failure (re-planning), or multiple possible actions to fulfil a given desire, which are taken into account in the standard BDI-model.

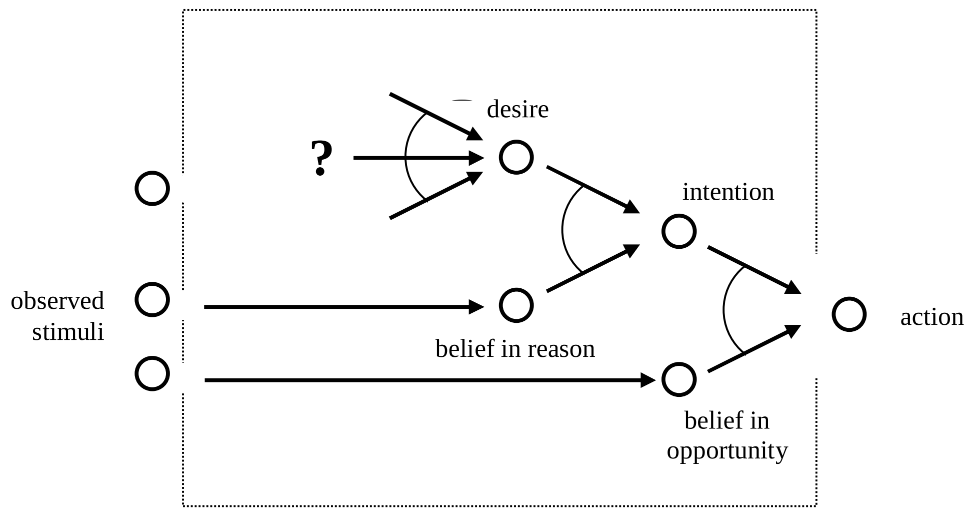

Figure 1 Structure of the Generic BDI-model

In the BDI-model an action is performed when the subject 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 sensed or 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 (this is the kind of rationality criterion discussed above; e.g., what is called means-end analysis is covered by this). As whether or not a given action is adequate to fulfill a given desire depends on the current world state, this belief may depend on other beliefs about the world state.

For the submodel to reason about beliefs, desires, and intentions presented in this paper, parts of the generic BDI-model have been reused. In particular, the following dependencies are used (shown in *formal* LEADSTO format), which correspond to some of the arrows in Figure 1:

desire(d1) $\wedge$ belief(satisfies(a1, d1)) $\twoheadrightarrow_{0.2,\, 0.2,\, 1,\, 1}$ intention(a1)
intention(a1) $\wedge$ belief(opportunity_exists_for(a1)) $\twoheadrightarrow_{0.2,\, 0.2,\, 1,\, 1}$ to_be_performed(a1)

Note that the beliefs used here both depend on observed stimuli, as shown in Figure 1. Furthermore, $\wedge$ stands for the conjunction operator (and) between the atomic state properties (in the graphical format denoted by an arc connecting two (or more) arrows). Often dynamic properties in LEADSTO are presented in *semi-formal* format, as follows:

At any point in time
if desire d1 is present
and the belief that action a1 satisfies d1 is present
then the intention for action a1 will occur

At any point in time
if the intention for action a1 is present
and the belief that there is an opportunity to perform a1 is present
then the action a1 will be performed

Within this BDI-based submodel, for reasons of simplicity, per desire only one action that can satisfy the desire is included (and one intention for that action). When a number of intentions are possible for one desire, then the model can be extended by a more specific decision making approach, such as utility-based multi-objective decision making, to rank the possible actions with respect to the degree in which they can fulfil the desire.

Assuming that beliefs in reason for intentions are internally available, what remains to be generated in this model are the desires and the beliefs in opportunities. For desires, there is no generic way (known) in which they are to be generated in the standard model. Actually, in many applications of the model it is assumed that certain desires are just there. In other cases, generation of desires depends on domain-specific knowledge, which also seems to be the case for criminal behaviour. In particular a number of biological aspects play a role here as well, such as certain brain deviations and levels of serotonin. This will be discussed in some further detail in Section 4.3. For beliefs in opportunities, they are strongly dependent on the (social) environment, which is the next theme discussed. The general pattern used is that an observation of a suitable target and the observation that no social control is present lead to the belief in an opportunity; in other words, the notion of opportunity is based on two of the three criteria as indicated in the Routine Activity Theory by (Cohen and Felson, 1979) which is one of the most influential theories within Criminology to explain the occurrence of crime. The third criterion of the Routine Activity Theory, the presence of a motivated offender, is indicated by the intention in the BDI-model. This way, the presence of the three criteria together leads to the action to perform a criminal act, as indicated by (Cohen and Felson, 1979).

4.3 The Submodel to Determine Desires

To determine desires a rather complex submodel is used incorporating, for example, biological dynamical system models for testosteron, serotonin, adrenalin, insulin and blood sugar levels over time. Also brain configuration aspects are incorporated in this submodel. These biological aspects are related to a number of psychological elements that are relevant for the generation of desires, such as levels of arousal, agressiveness, impulsiveness, risk-taking, thrill-seeking, understanding others, and feeling for others. The biological and psychological aspects involved are of different types. On the one hand there are qualitative aspects, such as anatomical aspects concerning brain deviations (e.g., the absence of certain connections). On the other hand there are quantitative aspects, such as biochemical aspects concerning testosterone levels and serotonin levels.

To model these, both causal and logical relations (as in qualitative modelling) and numerical relations (as in differential equations) have to be integrated in one modelling framework. This integration was accomplished, using the LEADSTO language as a modelling language.

The variety of biological and psychological aspects that were found relevant in the literature (such as Moir and Jessel, 1995; Raine, 1993; Bartol, 2002; Delfos, 2004) and are taken into account in this model, covers:

(a) the extent to which a theory of mind was developed (to understand others)
(b) dynamics of testosterone levels and aggressiveness
(c) dynamics of dealing with anxiety
(d) social-emotional attitudes with respect to others (e.g., feel pity for someone)
(e) stimuli assessment; excitement arousal and thrill seeking
(f) dynamics related to serotonin levels
(g) interactions of blood sugar, insulin and impulsiveness

For more details of how the model incorporates these aspects, see Figure 2 and Appendix A[†]. Different combinations of such elements lead to different types of (composed) desires, for example:

- the desire to perform an exciting planned nonaggressive nonrisky action that harms somebody else (e.g., a pick pocket action in a large crowd),
- the desire to perform a exciting impulsive aggressive risky action that harms somebody else (e.g., killing somebody in a violent manner in front of the police department)

The following LEADSTO rule generates a composed desire out of the different ingredients covered by (a) to (g) above:

LP31
A combination of values for theory of mind, aggressiveness, the desire to cope with anxiety, the desire to ignore anxiety, the desire for actions with strong stimuli, impulsiveness, emotional attitude towards others(pos) and emotional attitude towards others(neg) will lead to a specific composed desire, represented as “d(x1, x2, x3, x4, x5, x6, x7, x8)”.
∀x1,x2,x3,x4,x5,x6,x7,x8:SCALE
theory_of_mind(x1) ∧ aggressiveness(x2) ∧ desire_to_cope_with_anxiety(x3) ∧ desire_to_ignore_anxiety (x4) ∧
desire_for_actions_with_strong_stimuli(x5) ∧ impulsiveness(x6) ∧ emotional_attitude_towards_others(pos,x7) ∧
emotional_attitude_towards_others(neg,x8) →→ desire(d(x1, x2, x3, x4, x5, x6, x7, x8))

Note that, in the above and the following LEADSTO rules, the values for the timing parameters e, f, g, h (see Section 3) have been left out. In the presented simulations, for each of these rules the default parameter combination (0, 0, 1, 1) has been chosen. For future work, it is planned to investigate whether it is beneficial to use more realistic temporal parameter settings that correspond to the literature.

4.4 The Submodel to Determine Opportunities

In the use of the BDI-model to model criminal behaviour, the notion of opportunity is based on two of the three criteria as indicated in the Routine Activity Theory by (Cohen and Felson, 1979):

- a suitable target
- absence of a guardian

This was specified by the following local property in LEADSTO format:

[†] The relationship between psychological and biological states can be modelled more precisely, for example taking feedback loops into account. For a further elaboration of this, see (Bosse, Gerritsen and Treur, 2007b).

LP41

When agent a1, who is a criminal, is at location l and he observes a passer by at location l and he does not observe a guardian at location l, then agent a1 believes that there is an opportunity to assault someone.

∀a1,a2:AGENT ∀l:LOCATION

observes(a1,agent_of_type_at_location(a1,criminal,l)) ∧ observes(a1,agent_of_type_at_location(a2,passer_by,l)) ∧

[∀a3:AGENT not observes(a1,agent_of_type_at_location(a3,guardian,l))] ↠ belief(opportunity(assault))

The third criterion of the Routine Activity Theory is the presence of a motivated offender. This part is covered in the model by the submodel to determine desires (see Section 4.3).

The generic rule to generate the action performance from the intention and the belief in the opportunity is specified within the BDI-submodel as:

LP33

The belief that there is an opportunity to perform a certain action combined with the intention to perform that action will lead to the performance of that action.

∀a:ACTION

belief(opportunity(a)) ∧ intention(a) ↠ to_be_performed(a)

In this dynamic property, the third criterion of the Routine Activity Theory, the motivated offender, is represented by the intention to perform some action. One step earlier, within the BDI-submodel, this intention is generated by a desire and a belief in a reason to go for the action to fulfill the desire, according to the following rule:

LP32

Desire d(x1, x2, x3, x4, x5, x6, x7, x8) combined with the belief that a certain action will lead to the fulfillment of that desire will lead to the intention to perform that action.

∀x1,x2,x3,x4,x5,x6,x7,x8:SCALE ∀a:ACTION

desire(d(x1, x2, x3, x4, x5, x6, x7, x8)) ∧ belief(satisfies(a, d(x1, x2, x3, x4, x5, x6, x7, x8))) ↠ intention(a)

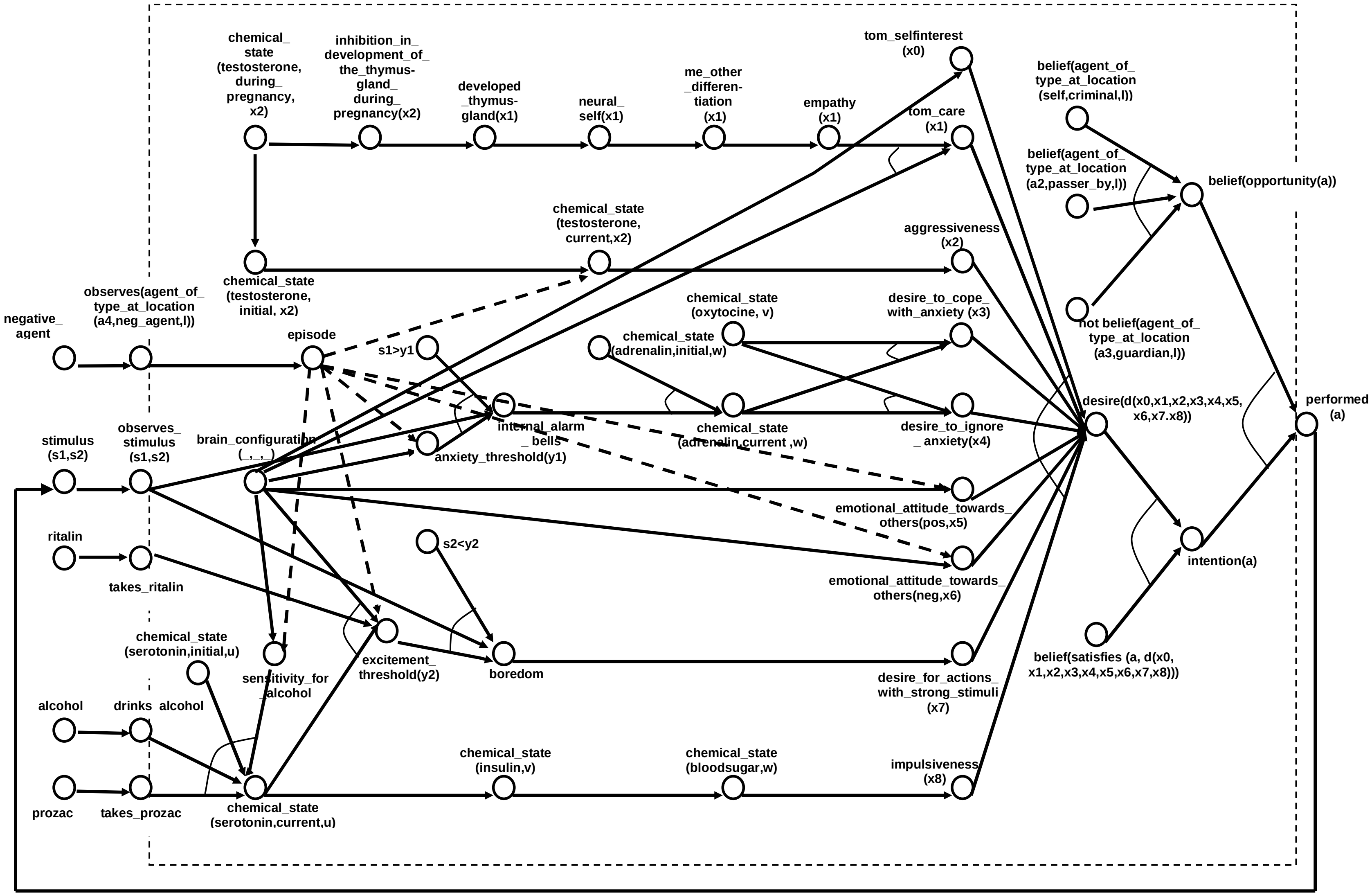

Figure 2 Graphical Overview of the Simulation Model

4.5 The Geographical Environment Model

For the simulation presented in this paper, the social, multi-agent aspect is modelled by an environment, in which a number of agents move around and sometimes meet at the same location. Four types of agents are considered. One of the agents is the *criminal* agent that is analysed, the others are potential victims (*passers-by*) and *guardian* agents. The passers-by are assumed to be suitable targets, for example, because they look rich and/or weak. However, as also the guardians are moving around, such targets may be protected, whenever at the same location a guardian is observed by the criminal. This models the aspect of social control. Finally, in some simulations also agents with provoking behaviour are present. This was done in order to ensure that they could trigger an aggressive episode in a criminal with Intermittent Explosive Disorder when (s)he encounters them. From now these types of agents are referred to as *negative agents*. In case a criminal agent with IED encounters such a negative agent, then part of the biological model is activated in order to ensure that the criminal enters an episode (see the left hand side of the model in Figure 2).

The interaction between a specific agent and the environment is modelled by (1) observation, which takes information about the environment as input for the agent (e.g., about at which location it is, where suitable targets are, and whether social control is present), and (2) initiating actions, which is an output of the agent affecting the state of the world (e.g., going to a different location).

The geographical information of the world in which the criminal and the guardians are active is described by a labeled graph as depicted in Figure 3. Here relevant locations are indicated by nodes A, B,…, and routes connecting locations by edges E1, E2,… Each time step, the agents move from location to location via these edges, by randomly selecting one of the edges that is connected to the current location. Edges have lengths related to them, so that travelling over them takes time, depending on these lengths. However, during travelling, agents cannot meet each other; encounters between agents only take place at the locations.

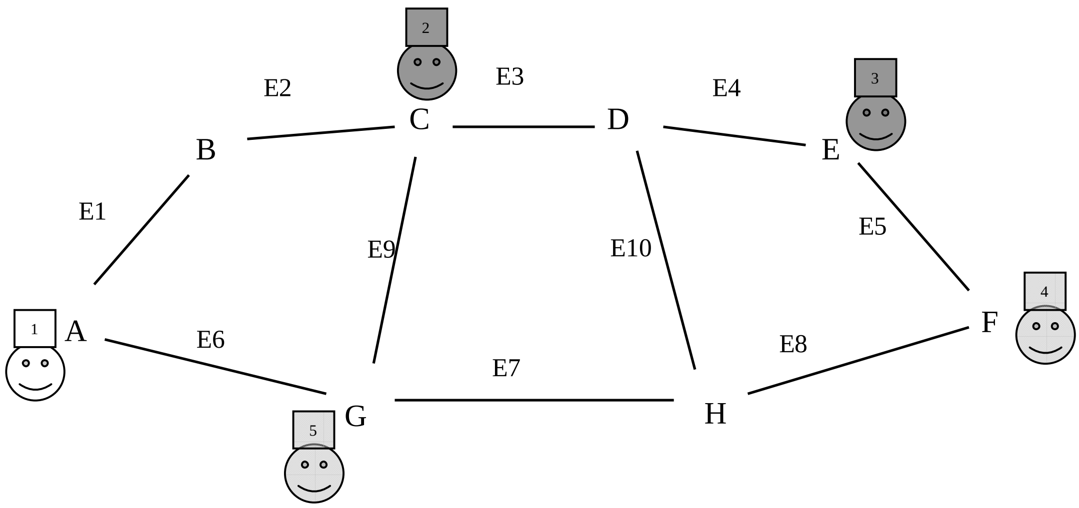

Figure 3 Example World Geography with an initial distribution of agents over locations. The light agents are criminals, the dark agents are guardians, and the transparent agents are passers-by. Note that this situation does not show any “negative agents”.

4.6 The Submodel for the Dynamics of the Society

To model the dynamics of the agents moving around in the environment, a number of dynamic properties are used that relate successive states to each other. Roughly spoken the following cycle is used for each of the agents: observe, determine next action, determine effects of this action. In some more detail, the model is based on the following LEADSTO properties:

1. Properties expressing what is *observed*; for example, observing stimuli or other agents:

At any point in time
if another agent is present at the agent's location,
then the agent will observe this

2. Properties expressing which *next action* is to be undertaken; for example,

   At any point in time
   if the agent currently is at location l
   and it has stayed at this location for duration s,
   and location l is connected to edge e1, e2, and e3
   then it will move (randomly) to e1, e2, or e3

   Within the model, probabilities are used to make random choices between different options.

3. Properties expressing the *effects of actions* undertaken; for example,

   At any point in time
   if the agent starts to move to a next location over edge e
   and edge e has length d,
   then it will arrive at the next location after duration d

Also to model such properties the LEADSTO modelling language introduced in Section 3 was used.

A visualisation of the part of the model (in particular, the part dealing with biological/psychological aspects of the criminal) is provided in Figure 2. The circles denote state properties, and the arrows indicate local dynamic (LEADSTO) properties. Note that the characteristics to be set at forehand and the inputs for the model over time together constitute all the circles in Figure 2 that have no incoming arrow (except the beliefs that lead to the belief that there is an opportunity; these are created on the basis of the social/environmental model, which is not shown in Figure 2). These inputs for the model are to be included in scenarios for simulation.

5. Settings for the Model

The model can be set with initial characteristics to tune it to a specific type of violent criminal: the violent psychopath, the person with APD or the person with IED. The idea is that, if the characteristics of a specific type of violent criminal are set as input, the model has to show the behaviour as known for this specific type of criminal as output. More specifically, the characteristics to be set at forehand are as follows: testosterone level during pregnancy, basic adrenalin level, basic serotonin level, basic oxytocine level, brain configuration (for sensitivity to alcohol, anxiety threshold, excitement threshold and emotional attitude toward others) and beliefs about which action satisfies which desire. Inputs for the model over time are: stimuli (i.e., external events that have a certain impact on arousal, anxiety, ...), taking alcohol, taking Prozac, and taking Ritalin.

Finally, some characteristics of the environment have to be set at forehand: presence of certain types of agents (criminals, guardians, passers-by) at certain locations.

<u>Violent psychopath</u>

For the trace discussed in the next section, the following initial state properties have been chosen for the violent psychopath: the testosterone level during pregnancy is high, the basic adrenalin level is medium (value 5), the basic level of serotonin is low (value 3) and the basic level of oxytocine is low. The brain is configured for the following characteristics: high theory of mind with respect to self interest, low theory of mind with respect to care, sensitivity for alcohol, a high anxiety threshold (value 8), a high excitement threshold (value 8), a low positive emotional attitude towards others and a low negative emotional attitude towards others. The psychopath has a belief that assaulting someone can be done in such a manner that this will lead to the fulfillment of a desire that is characterised by the following elements: high theory of mind with respect to self interest, low theory of mind with respect to care, high aggressiveness, a low desire to cope with anxiety, a low desire to ignore anxiety, a high desire for actions with strong stimuli, high impulsiveness, a low positive emotional attitude towards others and a low negative emotional attitude towards others.

In addition, some inputs for the model over time are provided. These inputs are as follows: initially there is a rather neutral stimulus present, which is not very dangerous nor exciting (both aspects have value 2), alcohol is used during the whole scenario, no Prozac is taken and no Ritalin is taken.

Finally, the initial characteristics of the environment are set as shown in Figure 3: the violent psychopath is at location A, there are guardians at location C and E, and there are passers-by at location F and G. There are no "negative agents" in this scenario.

Antisocial Personality Disorder

The following initial settings have been chosen for the person with an Antisocial Personality Disorder: the testosterone level during pregnancy is high, the basic adrenalin level is medium (value 5), the basic level of serotonin is low (value 3) and the basic level of oxytocine is low. The brain is configured for the following characteristics: low theory of mind with respect to self interest, low theory of mind with respect to care, sensitivity for alcohol, a medium anxiety threshold (value 5), a high excitement threshold (value 8), a low positive and a medium negative attitude towards others. The person with APD has a belief that assaulting someone will lead to the fulfillment of a desire that is characterised by the following elements: a low theory of mind (both for self interest as for care), high aggressiveness, a high desire to cope with anxiety, a low desire to ignore anxiety, a high desire for actions with strong stimuli, high impulsiveness, a low positive emotional attitude towards others and a medium negative emotional attitude towards others. The initial settings of the environment are identical to the environment used for the violent psychopath.

Intermittent Explosive Disorder

For the trace of the person diagnosed with IED, as discussed in the next section, the following initial state properties have been chosen: the level of testosterone during pregnancy was high, the basic adrenalin level is medium (value 5), the basic level of serotonin is low (value 3) and the basic level of oxytocine is low. The brain is configured for the following characteristics: medium theory of mind for self interest, medium theory of mind for care, sensitivity for alcohol, a medium anxiety threshold (value 5), a medium excitement threshold (value 5), both a medium positive and negative emotional attitude towards others and this person is extra sensitive to negative events. The person with IED has a belief that assaulting someone can be done in such a manner that this will lead to the fulfillment of a desire that is characterised by the following elements: a low theory of mind (both for self interest as for care), high aggressiveness, a high desire to cope with anxiety, a low desire to ignore anxiety, a high desire for actions with strong stimuli, high impulsiveness, a low positive emotional attitude towards others and a high negative emotional attitude towards others.

The initial characteristics of the environment are identical to the characteristics used in the previous 2 scenarios (i.e., criminal at location A, guardians at location C and E, and passers-by at location F and G), with one difference: now, there are "negative agents" at location B and H.

6. Example Simulation Traces

A number of simulation traces have been generated for the behaviour of the three types of violent offenders under different circumstances. In this section, per offender one specific simulation trace is described in detail. In Section 6.1, the trace of the behaviour of the violent psychopath is described. Next, Section 6.2 addresses the simulation of the behaviour of someone with APD, and Section 6.3 discusses the simulation trace of someone diagnosed as having IED. In Section 6.4 the issue of validation of such simulation traces is addressed.

6.1 The Violent Psychopath

Figure 4 depicts the biological/psychological aspects of the behaviour of the violent psychopath agent within the example simulation trace, such as change of serotonin levels and the generation of beliefs, desires and intentions. In such pictures, time is on the horizontal axis, and the different state properties are on the vertical axis. A dark box on top of a line indicates that a state property is true at that time point. In Figure 4, the upper five lines contain the state properties that are relevant for the BDI-based model, i.e., beliefs, desires, intentions, and actions. The rest of the lines contain the state properties that address the biological and psychological aspects (in alphabetical order). The graph at the bottom of the picture displays the amount of environmental stimuli the violent psychopath experiences. Finally, the environmental aspects (such as the locations of the different agents in the world) are shown in Figure 5.

As can be seen in Figure 4, the initial settings mentioned earlier lead to the following characteristics in the psychopath criminal type agent: the insulin level is high, the anxiety threshold is high (value 10), the person is sensitive for alcohol, and his emotional attitude towards others, both positive and negative, is low. In addition, he has a low neural self. This leads to a low me-other differentiation, low empathy, and eventually, to a low theory of mind with respect to care. His high level of initial testosterone leads to a high current level of testosterone, which in turn leads to high aggressiveness. Moreover, the medium level of initial adrenalin leads to a medium current level of adrenalin (value 5). This current level of adrenalin, combined with a low level of oxytocine, leads to a low desire to cope with anxiety and a low desire to ignore anxiety. Furthermore, the low initial serotonin level (value 3) leads to a low current level of serotonin (also value 3). This current level of serotonin combined with sensitivity for alcohol and taking alcohol leads (at time point 2) to a decreased level of serotonin (value 0). The current serotonin level also leads to an increased excitement threshold (from value 10 to value 13). The high insulin level leads to a low blood sugar level and a high impulsiveness.

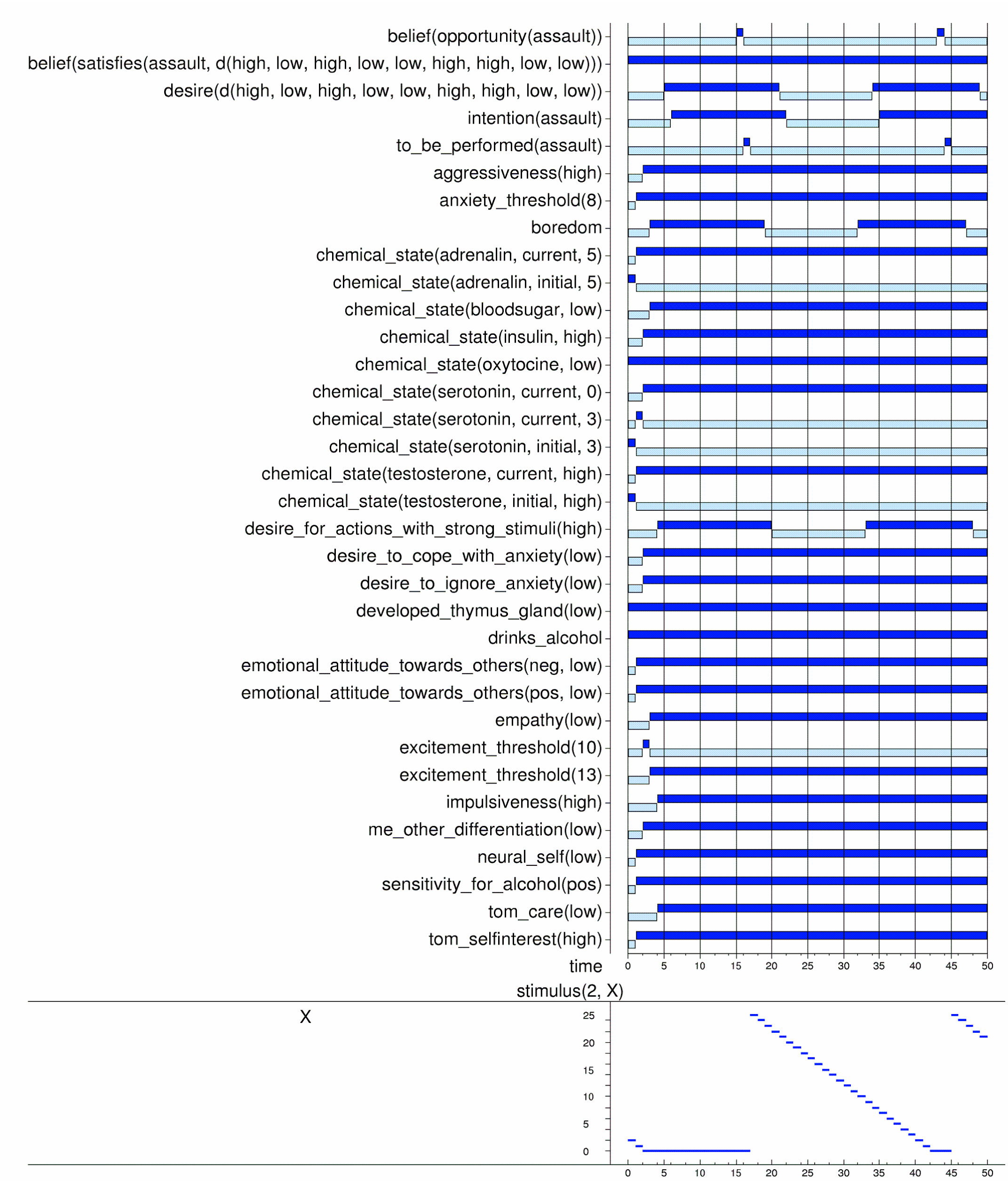

Figure 4 Example simulation trace: the biological/psychological aspects of the violent psychopath's behaviour

When the excitement threshold is higher than the strength of the observed stimuli, then the violent psychopath will become bored. This leads to the desire for actions with strong stimuli at time point 4. As a result of this desire and several other characteristics mentioned above, the violent psychopath eventually (time point 5) develops a desire for an action that is characterised by the following aspects: a low theory of mind, high aggressiveness, a low desire to cope with anxiety, a low desire to ignore anxiety, a high desire for actions with strong stimuli, high impulsiveness, a low positive attitude towards others and a low negative attitude towards others. This desire, combined with the belief that assaulting someone will lead to the satisfaction of such a desire, leads to the intention to assault someone at time point 6.

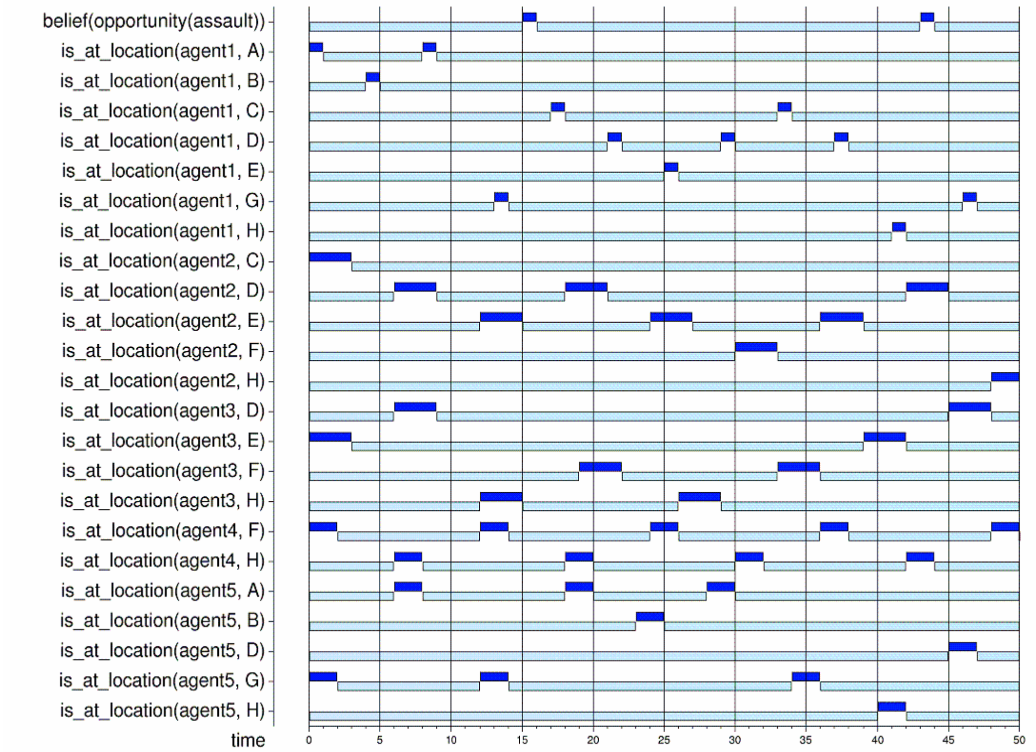

Figure 5 Example simulation trace: the social/environmental aspects of the violent psychopath's behaviour

In the meantime, the agent has started to move around in the world (see Figure 5). In total, in this example trace, which was kept simple for reasons of presentation, there are 5 agents in the world: agent 1 is a criminal (i.e., the violent psychopath described in Figure 4), agents 2 and 3 are guardians, and agents 4 and 5 are passers-by (i.e., potential victims). These agents are moving through the world. For example, agent 1 starts at location A (time point 0), then moves to location B (time point 4), and so on. Note that the time that an agent takes to travel to a location depends on the length of the edge to that location, and the duration that an agent stays at a location depends on the agent's personal preference (see local property LP41 in Appendix A). When a criminal meets a passer-by without a guardian present then the criminal will believe that there is an opportunity to assault the passer-by. As can been seen in Figure 5, there is an opportunity to assault a passer-by at time point 15. This opportunity has arisen because agent 1 is at location G and agent 5 is also at this location, and there are no guardians present (agents 2 and 3 are respectively at location E and H). At time point 43 there is another opportunity for agent 1 to assault someone. This is because agent 1 is at location H together with agent 5, and agents 2 and 3 are not present.

When going back to Figure 4, one can see that the psychopath's beliefs about opportunities are also depicted there. When such a belief is present, together with the intention to assault someone, the actual action to assault the passer-by is performed. This happens twice in the trace: at time point 16 and 44.

Finally, note that, when a violent psychopath assaults someone, this significantly raises the amount of stimuli he experiences. The values of these stimuli are shown in the bottom part of Figure 4. When this value passes his excitement threshold, he will stop being bored. As a consequence, also his desire for actions with strong stimuli will be fulfilled, and his desire and intention for an action that is characterised by this desire (among others) will disappear. However, after a while, the increased value of the experienced stimuli will gradually decrease and the psychopath will be bored again. This will lead to new desires, new intentions, and eventually (at time point 44), to a new assault.

6.2 Antisocial Personality Disorder

The simulation trace of a person with APD is quite similar to the simulation trace of the violent psychopath. The reason for this is that the characteristics of both types of agents are very similar. The only differences are that the violent psychopath has a high theory of mind with respect to self interest while the person with APD has a low theory of mind for self interest; furthermore the psychopath has a low negative emotional attitude towards others while the person with APD has a medium negative emotional attitude towards others. Because the differences in the simulation traces are so small, the trace of the person with APD is not shown.

6.3 Intermittent Explosive Disorder

Figure 6 depicts the biological/psychological aspects of the behaviour of the IED agent within the example simulation trace. As shown by Figure 6, the IED criminal initially has a desire (represented as desire(medium, medium, high, low, low, high, high, medium, medium)) for actions that are characterised by the following elements: a medium theory of mind (for self interest as well as for care), high aggressiveness, a low desire to cope with anxiety, a low desire to ignore anxiety, a high desire for actions with strong stimuli, high impulsiveness and both a medium positive and negative emotional attitude towards others. However, at time point 10 the criminal is at location G, where he meets a negative agent (called agent 8, not shown in Figure 6). This causes an episode of aggressiveness, which leads to an increased anxiety and excitement threshold, a highly negative emotional attitude towards others, a decreased theory of mind, and a new composed desire (low theory of mind for self interest and care, high aggressiveness, low desire to cope with anxiety, low desire to ignore anxiety, high desire for actions with strong stimuli, high impulsiveness, low positive emotional attitude towards others and a high negative emotional attitude towards others). Notice that aggressiveness and impulsiveness already occurred in the previous desire, but now the brakes are no longer there: no concern for other persons or anxiety plays a role anymore. This desire, combined with the belief that performing an assault leads to the satisfaction of this desire, leads to the intention to assault someone. At time point 15, the IED criminal is again at location G, but now together with a passer by (agent 5) without a guardian present (agents 2 and 3 are respectively on location H and E). This leads to the belief that there is an opportunity to assault someone. This belief combined with the intention leads to the performance of the assault. Because of the assault, the stimuli of the world increase, which satisfies the desires of the criminal.

Although the simulation examples as presented here involve only 8 agents, it has been found that they easily scale to a society of several hundreds of agents (processing time staying within one hour). However, the overall pattern for such larger numbers is not essentially different from the traces shown here.

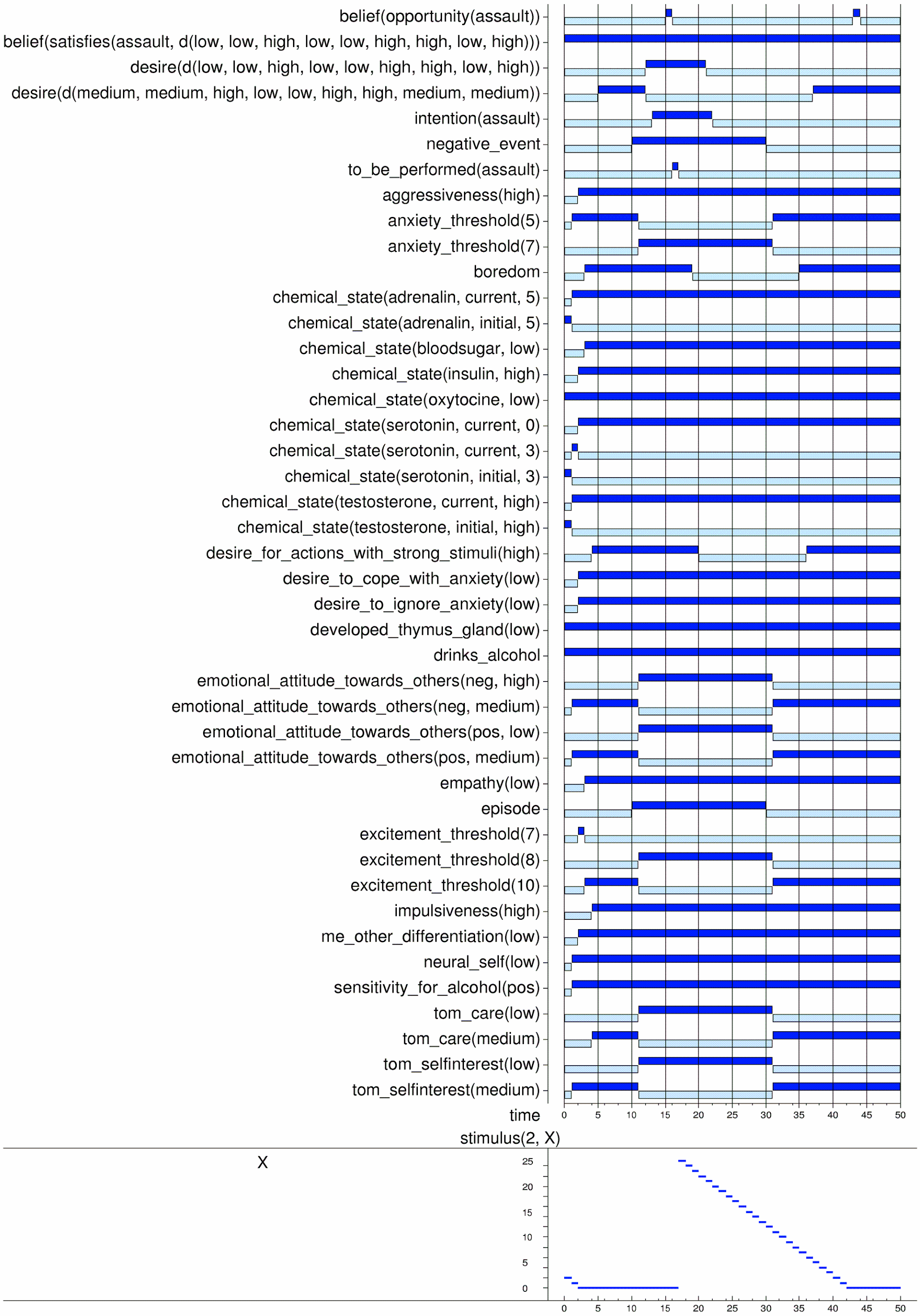

Figure 6 Example simulation trace: the biological/psychological aspects of the behaviour of someone with IED

7 Validation of the Simulation Model

The simulation model has been made with the aim to formalise, in a computationally useful manner, the analysis of the criminal behaviour of the type as described based on the literature in Section 2. A main criterion for validation is whether the behaviour shown by the model indeed corresponds to behaviour of the types of offenders as described in Section 2. Here some aspects may need some more discussion. Two views on such behaviour are possible: an external view or an internal view. The external view abstracts from the internal functioning of the underlying biological and psychological systems, and describes how the circumstances an agent meets in the environment relate to certain actions of the agent. In contrast, the internal view addresses all details of the dynamics of the underlying biological and psychological systems. Validation can be done according to these two views.

Validation for the internal view needs empirical data for the different types of violent offenders in the process of committing a crime on all of the biological and psychological states as described: levels of adrenaline, blood sugar, arousal, et cetera. To obtain such empirical data in the process of committing a crime will be extremely difficult, if not impossible. On the other hand, in the literature as discussed in Section 2, a number of dynamical patterns for the internal view are described, based on research under different circumstances. If these descriptions are taken as a basis, then validation from the internal view is possible. The simulation results indeed show the dynamic patterns in the underlying mechanisms as described in Section 2. Concerning validation from the external view, the simulation results indeed show the behaviour as described in Section 2. In this sense the model has been validated positively.

However, notice that the validation as discussed is a relative validation, only with respect to the literature that forms the basis of Section 2, such as (Moir and Jessel, 1995; Raine, 1993; Delfos, 2004). In cases that the available knowledge about the behaviour and biological, cognitive and social functioning of such a criminal type is improving, the validation of the model from the internal view and the model itself can be improved accordingly. The modelling approach as put forward supports such an incremental development and improvement. The simulation model has been specified in a conceptual, not implementation-dependent manner, and is easy to maintain. In this sense the approach anticipates further development of the research area of criminal behaviour.

8. Discussion

In this article, a method to analyse criminal behaviour based on integrated dynamic modelling is proposed. A generic model has been presented for the behaviour of violent criminals. As input certain parameters with respect to biological, cognitive and social aspects can be set. As output simulation traces are generated that show the behaviour of a violent offender over time under certain circumstances. As a case study, this method has been applied to analyse the behaviour of three types of violent criminals. It has been found that the model indeed shows the behaviour as known for these criminals. The model takes into account a cognitive modelling approach to the preparation of actions based on beliefs, desires and intentions (BDI) in a more or less standard manner (e.g., Jonker, Treur, and Wijngaards, 2003). However, for this standard BDI-model, desires and beliefs about opportunities are required as input. Concerning the former, additional biological, cognitive, and emotional aspects have been used as a basis to generate desires. For the latter, additional social aspects have been used to generate beliefs on opportunities based on two specific criteria (suitable target, presence of guardian) as indicated by the Routine Activity Theory in (Cohen and Felson, 1979). For the generation of desires various other aspects as found in the literature are taken into account, varying from specific types of brain deviations, and serotonin and testosterone levels, to the extent to which me-other differentiation and a theory of mind were developed.

Thus the model integrates biological, cognitive and socially related aspects in the process of desire generation, as extracted from literature, in particular (Raine, 1993; Moir and Jessel, 1995; Delfos, 2004). These involve both qualitative aspects (such as the anatomy of brain deviations, and presence or absence of agents at a specific location in the world), and quantitative aspects (such as distances and time durations in the world and hormone ands neurotransmitter levels).

To achieve the integration of different aspects, the proposed modelling approach (based on the LEADSTO language) integrates qualitative, logical aspects and quantitative, numerical aspects. This integration allows to exploit techniques from both areas. As the latter type of aspects are fully integrated in the former, this results in a declarative specification for which automated methods for logical analysis can be exploited. Conversely, as the former type of aspects is fully integrated in the latter, a simulation environment is offered that extends the usual possibilities to simulate dynamical systems using numerical methods, by incorporating qualitative elements.

Only few papers on simulation of criminal behaviour can be found in the literature, and they usually address a more limited number of aspects than the modelling approach presented in this paper. For example, Brantingham and Brantingham, (2004) discuss the possible use of agent modelling approaches to criminal behaviour in general, but do not report a specific model or case study. Moreover, in (Baal, 2004) a model is presented with emphasis on the social network and the perceived sanctions. However, this model leaves the psychological and biological aspects largely unaddressed. The same applies to the work reported in (Melo, Belchior, and Furtado, 2005), where an emphasis is on the environment, and police organisation.

Within the literature of Agent-Based and Cognitive Modelling, a number of approaches have similarities with the approach presented in this paper. To start, the presented approach, and in particular the BDI-submodel, obviously has some similarities with the literature on which it was based, such as (Georgeff and Lansky, 1987; Bratman, Israel, and Pollack, 1988; Rao and Georgeff, 1991). However, traditionally, within BDI-models no general model for generation of desires (or goals) is included. In many cases desires are just assumed to be there, or even communicated to the agent as goals it should adopt. This holds for the traditional BDI-based approaches mentioned above as well as for application-oriented frameworks based on BDI concepts, such as PRS (Georgeff and Ingrand, 1989). Nevertheless, in recent years, extensions of BDI models are being developed in which this is the case, e.g., in Jadex (Pokahr, Braubach, and Lamersdorf, 2005). One aspect that is addressed particularly there is the revision of desires as a result of undertaken actions that fulfill them. Another aspect relevant for desire generation is the biological substrate of the agent. Sometimes desires are just inherent to a certain biological makeup or state. The current paper takes a similar approach, namely to incorporate both biological and psychological factors into a submodel for generation of desires. Within the paper, a number of biological aspects as found in the literature have been taken into account in the dynamic generation of desires, varying from specific types of brain deviations, and serotonin and testosterone levels, to the extent to which a substrate for theory of mind was developed. Moreover, the generation of beliefs in opportunities has been based on environmental and social aspects involving two specific criteria (suitable target, presence of guardian) as indicated by the Routine Activity Theory in (Cohen and Felson, 1979).

Another novel approach in the literature that is worth comparing with our approach is the cognitive architecture CoJACK (Evertsz, Ritter, Busetta, Pedrotti, and Bittner, 2008). It is based on JACK, a Java-based Intelligent Agent Modelling Framework, and, like the approach presented in this paper, makes use of the BDI paradigm. Similar to our approach, CoJACK extends this paradigm with biological and psychological factors underlying behaviour. However, the intended applications of CoJACK are different: its main aim is the development of virtual agents within (military) simulation environments, whereas the current paper focuses on modelling the behaviour of violent criminals. As a result, the biological and psychological factors considered are different. For example, CoJACK addresses concepts such as fatigue and fear, whereas the current approach addresses concepts that are specific for criminal behaviour, such as aggressiveness and impulsiveness.

The current model forms a good basis for further development. It will not be difficult to take into account other or new useful literature on relevant (biological, cognitive, social) factors and their relationships as soon as it is made available. The model was kept simple in the generation of intentions for a given integrated desire: only one intention is possible per desire. When a number of intentions are possible for a given desire, then more specific decision making aspects come in the play, for example, involving utility-based (multi-objective) decision making; e.g., as described in (Cornish and Clarke, 1986), or sophisticated planning mechanisms as described in (Georgeff and Ingrand, 1989). Also such approaches can easily be added to the model. In the current model, only few quantitative aspects have been incorporated, but this can be extended easily, as is shown, for example, in (Bosse, Delfos, Jonker, and Treur, 2005), where numerical adaptation techniques are part of the model. Also approaches as proposed in (Gottfredson and Hirschi, 1990) can be incorporated.

In addition, the model may be extended with probabilistic notions. Although the presented version of the model incorporates only deterministic relationships, the latest version of LEADSTO (see Bosse, Jonker, Meij, and Treur, 2007) enables the modeller to specify non-deterministic dependencies of the format $\alpha \twoheadrightarrow \beta 1 \vee \beta 2$, where different probabilities can be attached to the consequents $\beta 1$ and $\beta 2$. This may be a promising direction, for example, to model biological processes for which only knowledge exists about rough correlations, instead of well-established causal relations. A drawback is however that this approach forces the analyst to perform large numbers of simulations (as in Monte Carlo simulation) instead of just one. This direction will be further explored in future research.

The team of outstanding domain experts from psychology and criminology who have evaluated the work reported here, consider it as quite valuable and promising. In their view this work is a substantial step to obtain a solid basis to develop future applications to support policy makers and practitioners who have to handle the problem of crime in society. However, still there is quite some way to go. The problem of crime in society has substantial complexity and is a major challenge to be addressed. Therefore steps in this direction are to be considered with an appropriate extent of modesty. At this point in time ready-to-use applications are asked far too much, as much more work on research and development has to be invested, both in modelling and in the empirical area. For the empirical area systematic validation experiments to be set up are a challenge by themselves. For the modelling area, given the modest perspective as sketched, dynamical models for criminal behaviour of the types as discussed above can be useful in a number of ways. In the first place, as shown in the current paper, they can be used to simulate behaviour for given scenarios of circumstances occurring over time. This can be used to find out for such a given scenario of circumstances, whether a criminal of a certain type may show certain behaviour under these given circumstances. Moreover, as to be explored further in future work, such a model can be used in the opposite direction, i.e., given a certain behaviour, to determine what kind of scenario of circumstances could lead to this behaviour. Some initial steps in this direction have been made in (Bosse, Gerritsen, and Treur, 2007a). More generally, the model can be used in the situation that the circumstances and/or the behaviour are only partially given. In that case, the model can be used to complete this partial information, i.e., to find out which (completed) behaviour could be consistent (or inconsistent) with which (completed) circumstances, and to find out which additional information should be investigated to determine one or more completions of the partial information that are realistic (Both, Gerritsen, Hoogendoorn, and Treur, 2007). Finally, such a model can be used for therapeutical reasoning. For example, it may be used to predict which behaviour a certain type of criminal will show if circumstances are avoided or slightly changed (what-if reasoning). Using this approach, the behaviour of the subject can be modified by selecting or avoiding the appropriate circumstances. Another possible use of such a model in therapeutical reasoning is to determine a (cognitive) training program for the criminal to adapt the relationship between circumstances and behaviour.

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References

1. Alison, L.J., Bennell, C., Mokros, A. and Ormerod, D. (2002). The personality paradox in offender profiling: A theoretical review of the processes involved in deriving background characterstics from crime scen actions. Psychology, *Public Policy, and Law*, vol. 8, pp. 115-135
2. American Psychiatric Association (1994). *Diagnostic and Statistical Manual of Mental Disorders, 4th ed (DSM-IV)*. Washington (DC), American Psychiatric Association.
3. Ashby, R. (1960). *Design for a Brain*. Second Edition. Chapman & Hall, London.
4. Baal, P.H.M. van (2004). *Computer Simulations of Criminal Deterence: from Public Policy to Local Interaction to Individual Behaviour*. Ph.D. Thesis, Erasmus University Rotterdam. Boom Juridische Uitgevers.
5. Baron-Cohen, S. (1995). *Mindblindness*. MIT Press.
6. Bartol, C.R. (2002). *Criminal Behavior: a Psychosocial Approach*. Sixth edition. Prentice Hall, New Jersey.

7. Bosse, T., Delfos, M.F., Jonker, C.M., and Treur, J., Analysis of Adaptive Dynamical Systems for Eating Regulation Disorders. *Simulation Journal (Transactions of the Society for Modelling and Simulation)*, vol. 82, 2006, pp. 159-171.
8. Bosse, T., Gerritsen, C., and Treur, J. (2007a). *Case Analysis of Criminal Behaviour*. In: Proceedings of the 20th International Conference on Industrial, Engineering & Other Applications of Applied Intelligent Systems, IEA/AIE'07. Lecture Notes in Artificial Intelligence. Springer Verlag, 2007, pp. 621-632.
9. Bosse, T., Gerritsen, C., and Treur, J. (2007b). *Grounding a Cognitive Modelling Approach for Criminal Behaviour*. In: Vosniadou, S., Kayser, D., and Protopapas, A. (eds.), Proceeding of the Second European Cognitive Science Conference, EuroCogSci'07. Lawrence Erlbaum Associates, 2007, pp. 776-781.
10. Bosse, T., Jonker, C.M., Meij, L. van der, and Treur, J. (2007). A Language and Environment for Analysis of Dynamics by Simulation. *International Journal of Artificial Intelligence Tools*, vol. 16, 2007, pp. 435-464.
11. Bosse, T., Jonker, C.M., and Treur, J., (2007). Simulation and Analysis of Adaptive Agents: an Integrative Modelling Approach. *Advances in Complex Systems Journal*, vol. 10, 2007, pp. 335-357.
12. Both, F., Gerritsen, C., Hoogendoorn, M., and Treur, J. (2007). *Model-Based Default Refinement of Partial Information within an Ambient Agent*. In: Proceedings of the First International Workshop on Artificial Intelligence Methods for Ambient Intelligence. Published in M. Mühlhaüser, A. Ferscha and E. Aitenbichler (eds.), Constructing Ambient Intelligence: AmI-07 Workshops Proceedings. Communications in Computer and Information Science (CCIS), vol. 11, Springer Verlag, 2008, pp. 34-43 .
13. Brantingham, P. L., & Brantingham, P. J. (2004). Computer Simulation as a Tool for Environmental Criminologists. *Security Journal*, 17(1), 21-30.
14. Bratman, M.E., Israel, D.J., and Pollack, M.E. (1988). Plans and resource-bounded practical reasoning. *Computational Intelligence*, vol. 4 issue 3, 2008, pp. 349-355.
15. Cleckley, H. (1976). *The Mask of Sanity*. Fifth edition, MO: Mosby, St Louis.
16. Cohen, L.E. and Felson, M. (1979). Social change and crime rate trends: a routine activity approach. *American Sociological Review*, vol. 44, pp. 588-608.
17. Cornish, D.B., and Clarke, R.V. (1986). *The Reasoning Criminal: Rational Choice Perspectives on Offending*. Springer Verlag.
18. Delfos, M.F. (2004). *Children and Behavioural Problems: Anxiety, Aggression, Depression and ADHD; A Biopsychological Model with Guidelines for Diagnostics and Treatment*. Harcourt book publishers, Amsterdam.
19. Dennett, D.C. (1987). *The Intentional Stance*. MIT Press. Cambridge Massachusetts
20. Evertsz, R., Ritter, F. E., Busetta, P., Pedrotti, M., and Bittner, J. L., (2008). CoJACK - Achieving Principled Behaviour Variation in a Moderated Cognitive Architecture. In: *Proceedings of the 17th Conference on Behavior Representation in Modeling and Simulation*, Orlando, FL, U. of Central Florida.
21. Georgeff, M.P., and Ingrand, F.F. (1989). Decision-making in an embedded reasoning system. In: *Proceedings of the 11th International Joint Conference on Artificial Intelligence, IJCAI'89*, Detroit, Michigan, 1989.
22. Georgeff, M. P., and Lansky, A. L. (1987). Reactive Reasoning and Planning. In: *Proceedings of the Sixth National Conference on Artificial Intelligence*, AAAI'87. Menlo Park, California. American Association for Artificial Intelligence, 1987, pp. 677-682.
23. Gottfredson, M., and Hirschi, T. (1990). *A General Theory of Crime*. Stanford University Press.
24. Gray, W.D., (Ed.)(2007). Integrated Models of Cognitive Systems. New York: Oxford University Press.
25. Hare, R.D. (1970). *Psychopathy: Theory and Research*. Wiley, New York.
26. Hare, R.D. (1993). *Without Conscience: the Disturbing World of the Psychopaths Among Us*. Pocket books, NY.
27. Hart, S.D., and Dempster, R.J. (1997). Impulsivity and Psychopathey. In: C.D. Webster and M.A. Jackson (eds.), *Impulsivity: Theory, Assessment and Treatment*. Guilford, New York.
28. Humphrey, N. (1984). *Consciousness Regained*. Oxford University Press.
29. Jonker, C.M., Treur, J., and Wijngaards, W.C.A., (2003). A Temporal Modelling Environment for Internally Grounded Beliefs, Desires and Intentions. *Cognitive Systems Research Journal*, vol. 4(3), 2003, pp. 191-210.
30. Liu, L., Wang, X., Eck, J., & Liang, J. (2005). Simulating Crime Events and Crime Patterns in RA/CA Model. In F. Wang (ed.), *Geographic Information Systems and Crime Analysis*. Singapore: Idea Group, pp. 197-213
31. Melo, A., Belchior, M., and Furtado, V. (2005). Analyzing Police Patrol Routes by Simulating the Physical Reorganisation of Agents. In: Sichman, J.S., and Antunes, L. (eds.), *Multi-Agent-Based Simulation VI, Proceedings of the Sixth International Workshop on Multi-Agent-Based Simulation, MABS'05*. Lecture Notes in Artificial Intelligence, vol. 3891, Springer Verlag, 2006, pp 99-114.
32. Moir, A., and Jessel, D. (1995). *A Mind to Crime*: *the controversial link between the mind and criminal behaviour.* London: Michael Joseph Ltd; Penguin.
33. Pokahr, A., Braubach, L., and Lamersdorf, W. (2005). Jadex: A BDI reasoning engine. In: Bordini, R.H., Dastani, M., Dix, J., and El Fallah Seghrouchni, A. (eds). *Multi-Agent Programming: Languages, Platforms and Applications*. Springer Verlag, 2005, pp. 149–174.

34. Port, R.F., and Gelder, T. van (eds.). (1995). *Mind as Motion: Explorations in the Dynamics of Cognition*. MIT Press, Cambridge, Mass.
35. Quay, H.C. (1965). Psychopathic Personality: Pathological Stimulation-Seeking. *American Journal of Psychiatry*, vol. 122, pp. 180-183.
36. Raine, A. (1993). *The Psychopathology of Crime: Criminal Behaviors as a Clinical Disorder*. New York, NY: Guilford Publications.
37. Rao, A.S. & Georgeff, M.P. (1991). Modelling Rational Agents within a BDI-architecture. In: Allen, J., Fikes, R. and Sandewall, E. (eds.), *Proceedings of the Second International Conference on Principles of Knowledge Representation and Reasoning, (KR'91).* Morgan Kaufmann, pp. 473-484.
38. Sperry, L. (2003). *Handbook of Diagnosis and Treatment of DSM-IV-TR Personality Disorders.* Brunner-Routledge, New York.
39. Towl, G.J., and Crighton, D.A. (1996). *The Handbook of Psychology for Forensic Practitioners*. Routledge, London, New York.
40. Turvey, B. (1999). *Criminal Profiling: an Introduction to Behavioral Evidence Analysis*. Academic Press.
41. Webster, C.D., and Jackson, M.A. (eds.) (1997). *Impulsivity: Theory, Assessment and Treatment*. Guilford, NY.

Appendix A - Overview of the Simulation Model

All local properties (LP's) that have been used for the simulation model are provided below in textual form, both in an informal notation and in a formal (LEADSTO) notation. Many of these properties are based on theories and experiments presented in the literature on criminal behaviour. References are given to be able to trace back this source material. Note that some of the formulae and their specific values (e.g., the value of 10 in LP15) have been estimated in order to get an effect as qualitatively described in the literature, rather than that they are known from this literature. However, if more biological knowledge becomes available, such values can be validated and, if needed, easily be incorporated in an improved form in the approach. In a similar manner, the model may be extended with probabilistic aspects, and more realistic timing parameters may be chosen.

The model is composed of the following submodels (see also Section 4.1):

1. a submodel to *determine desires* needed as input for the BDI-model; this model incorporates various physical and mental aspects and their interactions
2. a submodel for reasoning about *beliefs, desires and intentions*, based on the BDI-model
3. a submodel for the *multi-agent society*; this lets agents move in the world and determines the effects of actions performed.
4. a submodel to determine how observations lead to *beliefs in an opportunity* as needed as input for the BDI-model; this model is based on the Routine Activity Theory
5. a *geographical model* of the world; this is represented by a labeled graph of locations and connections

Each of these submodels is described by LEADSTO properties.

A.1 The Submodel to Determine Desires

This submodel covers many mental and physical elements, modelled by about 40 LEADSTO properties, which can be grouped according to the following aspects:

- Development of a Theory of Mind
- Interactions for Testosterone and Aggressiveness
- Dealing with Anxiety
- Social-Emotional Attitudes
- Stimuli Assessment
- Interactions involving Serotonin
- Interactions involving Blood Sugar, Insulin and Impulsiveness
- Development of Episodes

Development of a Theory of Mind

LP1

A certain level of testosterone during pregnancy will lead to the same level of inhibition in development of the thymus gland during pregnancy. In this property (and in many others), SCALE indicates the set {low, medium, high}.
(Delfos, 2004, pp. 47)

∀x:SCALE
chemical_state(testosterone,during_pregnancy,x) $\twoheadrightarrow_{0, 0, 1, 1}$
inhibition_in_development_of_thymus_gland_during_pregnancy(x)

LP2a

A high level of inhibition in development of the thymus gland during pregnancy leads to a low developed thymus gland. In this property (and the two properties below), p stands for the duration of the pregnancy, and l stands for the life time of the person.

inhibition_in_development_of_thymus_gland_during_pregnancy(high) $\twoheadrightarrow_{0,0,p,l}$ developed_thymus_gland(low)

LP2b

A medium level of inhibition in development of the thymus gland during pregnancy leads to a medium developed thymus gland.

inhibition_in_development_of_thymus_gland_during_pregnancy(medium) $\twoheadrightarrow_{0,0,p,l}$ developed_thymus_gland(medium)

LP2c

A low level of inhibition in development of the thymus gland during pregnancy leads to a high developed thymus gland.

inhibition_in_development_of_thymus_gland_during_pregnancy(low) $\twoheadrightarrow_{0,0,p,l}$ developed_thymus_gland(high)

LP3

A certain level of development of the thymus gland leads to the same level of development of a neural self. (Delfos, 2004, p. 48, p. 54)

∀x:SCALE

developed_thymusgland(x) $\twoheadrightarrow_{0,0,1,1}$ neural_self(x)

LP4

A certain level of development of the neural self leads to the same level of development of the “me-other differentiation” (i.e., the ability to distinguish between the self and others).

(Delfos, 2004, p. 56)

∀x:SCALE

neural_self(x) $\twoheadrightarrow_{0,0,1,1}$ me_other_differentiation(x)

LP5

A certain level of me-other differentiation leads to the same level of empathy.

(Delfos, 2004, p. 57)

∀x:SCALE

me_other_differentiation(x) $\twoheadrightarrow_{0,0,1,1}$ empathy(x)

LP6

A certain level of empathy combined with a brain that is configured for a theory of mind with regard to care of lead to the same level of theory of mind concerning other persons.

(Delfos, 2004, p. 59)

∀x0,x1,x7,x8,z:SCALE ∀x,y:INTEGER ∀s1:SIGN

empathy(z) ∧ brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x7), emotional_attitudes_towards_others(neg,x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) $\twoheadrightarrow_{0,0,1,1}$ tom_care(x1)

LP7

When the brain is configured for a theory of mind with regard to self interest of x, then the theory of mind with regard to self interest is x.

∀x0,x1,x7,x8,z:SCALE ∀x,y:INTEGER ∀s1:SIGN

brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x7), emotional_attitudes_towards_others(neg,x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) $\twoheadrightarrow_{0,0,1,1}$ tom_selfinterest(x0)

Interactions for Testosterone and Aggressiveness

LP8

A certain testosterone level during pregnancy will lead to the same level of initial testosterone.
∀x:SCALE
chemical_state(testosterone,during_pregnancy,x) $\twoheadrightarrow_{0,\,0,\,1,\,1}$ chemical_state(testosterone,initial,x)

LP9a
A certain initial testosterone level will lead to the same level of current testosterone. In this property, p stands for the duration of the initialisation phase (i.e., the period of pregnancy in this case), and l stands for the life time of the person.
(Delfos, 2004, p. 47)
∀x:SCALE
chemical_state(testosterone,initial,x) $\twoheadrightarrow_{0,\,0,\,p,\,l}$ chemical_state(testosterone,current,x)

LP9b
An episode increases the level of testosterone.
(Moir and Jessel, 1995, p. 184-187)
chemical_state(testosterone,current,low) ∧ episode $\twoheadrightarrow_{0,\,0,\,1,1}$ chemical_state(testosterone,current,medium)
chemical_state(testosterone,current,medium) ∧ episode $\twoheadrightarrow_{0,\,0,\,1,1}$ chemical_state(testosterone,current,high)

LP10
A certain level of current testosterone will lead to the same level of aggressiveness.
((Delfos, 2004, p. 65, p. 68, pp. 83-85, p. 112)
∀x:SCALE
chemical_state(testosterone,current,x) $\twoheadrightarrow_{0,\,0,\,1,\,1}$ aggressiveness(x)

Dealing with Anxiety

LP11a
When the brain is configured for an anxiety threshold of x, and the person does not have an episode, then the anxiety threshold is x.
(Moir and Jessel, 1995, pp. 184-187; Raine, 1993, pp. 169-173)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x7), emotional_attitudes_towards_others(neg,x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ not episode $\twoheadrightarrow_{0,\,0,\,1,\,1}$ anxiety_threshold(x)

LP11b
When the brain is configured for an anxiety threshold of x, and the person has an episode, then the anxiety threshold is x-4.
(Moir and Jessel, 1995, pp. 186-188, p. 202)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1,x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x7), emotional_attitudes_towards_others(neg,x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ episode $\twoheadrightarrow_{0,\,0,\,1,\,1}$ anxiety_threshold(x-4)

LP12
When a stimulus with a higher level of danger than the anxiety threshold is observed, internal alarm bells will go off.
(Delfos, 2004, p. 69; Moir and Jessel, 1995, pp. 75-76; Raine, 1993, p. 166, p. 179, p. 222)
∀s1,s2,y:INTEGER
observes_stimulus(s1,s2) ∧ anxiety_threshold(y) ∧ s1>y $\twoheadrightarrow_{0,\,0,\,1,\,1}$ internal_alarm_bells

LP13a

A current adrenalin level lower than 10 combined with internal alarm bells will increase the current adrenalin level by 1.
(Moir and Jessel, 1995, pp. 75-76)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x<10 ∧ internal_alarm_bells $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(adrenalin, current, x+1)

LP13b
A current adrenalin level that is not influenced by internal alarm bells will remain the same.
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ not internal_alarm_bells $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(adrenalin, current, x)

LP14
A certain initial adrenalin level will lead to the same current adrenalin level. In this property, p stands for the duration of the pregnancy.
∀x:INTEGER
chemical_state(adrenalin, initial, x) $\twoheadrightarrow_{0, 0, p, 1}$ chemical_state(adrenalin, current, x)

LP15
When you have an adrenalin level of 10, it will not increase further because 10 is the maximum.
chemical_state(adrenalin,10) $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(adrenalin, 10)

LP16a
A current adrenalin level above 5, combined with a high oxytocine level will lead to the desire to ignore anxiety.
(Delfos, 2004, pp. 67-70, p. 77, pp. 112-118, pp. 214-225, p. 256, pp. 261-264; Moir and Jessel, 1995, pp. 74-82, p. 175, pp. 131-134)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x>5 ∧ chemical_state(oxytocine,high) $\twoheadrightarrow_{0, 0, 1, 1}$ desire_to_ignore_anxiety(high)

LP16b
A current adrenalin level above 5, combined with a high oxytocine level will not lead to the desire to cope with anxiety.
(Delfos, 2004, pp. 67-74, p. 77, pp. 214-225, p. 256, pp. 261-264; Moir and Jessel, 1995, pp. 74-82, pp. 107-110, pp. 131-134, p. 175; Raine, 1993, pp. 169-173)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x>5 ∧ chemical_state(oxytocine,high) $\twoheadrightarrow_{0, 0, 1, 1}$ desire_to_cope_with_anxiety(low)

LP16c
A current adrenalin level higher than 5 combined with a low oxytocine level will lead to the desire to cope with anxiety.
(Delfos, 2004, pp. 67-74, p. 77, pp. 214-225, p. 256, pp. 261-264; Moir and Jessel, 1995, pp. 74-82, pp. 107-110, pp. 131-134, p. 175; Raine, 1993, pp. 169-173)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x>5 ∧ chemical_state(oxytocine,low) $\twoheadrightarrow_{0, 0, 1, 1}$ desire_to_cope_with_anxiety(high)

LP16d
A current adrenalin level higher than 5 combined with a low oxytocine level will not lead to the desire to ignore anxiety.
(Delfos, 2004, pp. 67-74, p. 77, pp. 214-225, p. 256, pp. 261-264; Moir and Jessel, 1995, pp. 74-82, pp. 107-110, pp. 131-134, p. 175; Raine, 1993, pp. 169-173)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x>5 ∧ chemical_state(oxytocine,low) $\twoheadrightarrow_{0, 0, 1, 1}$ desire_to_ignore_anxiety(low)

LP16e

A current adrenalin level of 5 or lower will not lead to the desire to ignore anxiety.
(Delfos, 2004, pp. 67-74, p. 77, pp. 214-225, p. 256, pp. 261-264; Moir and Jessel, 1995, pp. 74-82, pp. 107-110, pp. 131-134, p. 175; Raine, 1993, pp. 169-173)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x<=5 $\twoheadrightarrow_{0, 0, 1, 1}$ desire_to_ignore_anxiety(low)

LP16f
A current adrenalin level of 5 or lower will not lead to the desire to cope with anxiety.
(Delfos, 2004, pp. 67-74, p. 77, pp. 214-225, p. 256, pp. 261-264; Moir and Jessel, 1995, pp. 74-82, pp. 107-110, pp. 131-134, p. 175; Raine, 1993, pp. 169-173)
∀x:INTEGER
chemical_state(adrenalin, current, x) ∧ x<=5 $\twoheadrightarrow_{0, 0, 1, 1}$ desire_to_cope_with_anxiety(low)

Social-Emotional Attitudes

LP17a
When the brain is configured for a positive emotional attitude towards others of x7, and the person does not have an episode, then the positive emotional attitude towards others is x7.
(Delfos, 2004, p. 58, pp. 112-116, p. 118; Moir and Jessel, 1995, pp. 148-149)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos, x7), emotional_attitude_towards_others(neg, x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ not episode $\twoheadrightarrow_{0, 0, 1, 1}$ emotional_attitude_towards_others(pos, x7)

LP17b
An episode decreases the positive emotional attitude towards others.
(Delfos, 2004, pp .112-116; Moir and Jessel, 1995, pp. 187-201, p. 298)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos, x7), emotional_attitude_towards_others(neg, x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ episode $\twoheadrightarrow_{0, 0, 1, 1}$ emotional_attitude_towards_others(pos, low)

LP18a
When the brain is configured for a negative emotional attitude towards others of x8, and the person does not have an episode, then the negative emotional attitude towards others is x8.
(Delfos, 2004, p. 86, p. 89, pp. 112-116; Moir and Jessel, 1995, p. 188, pp. 201-204)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos, x7), emotional_attitude_towards_others(neg, x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ not episode $\twoheadrightarrow_{0, 0, 1, 1}$ emotional_attitude_towards_others(neg, x8)

LP18b
An episode leads to a negative emotional attitude towards others.
(Delfos, 2004, pp. 112-116; Moir and Jessel, 1995, pp. 187-201, p. 298)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos, x7), emotional_attitude_towards_others(neg, x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ episode $\twoheadrightarrow_{0, 0, 1, 1}$ emotional_attitude_towards_others(neg, high)

Stimuli Assessment

LP19a

When the brain is configured for an excitement threshold of y, and there is a serotonin level of z, and the person does not have an episode, then the excitement threshold becomes y+5-z.
(Raine, 1993, pp. 178-180, pp. 222-228; Moir and Jessel, p. 188, pp. 202-204)
∀x,y,z:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x7), emotional_attitudes_towards_others(neg,x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ chemical_state(serotonin, z) ∧ not episode $\twoheadrightarrow_{0,0,1,1}$ excitement_threshold(y+5-z)

LP19b
When the brain is configured for an excitement threshold of y, and there is a serotonin level of z, and the person has an episode, then the excitement threshold becomes y+5-z.
(Delfos, 2004, p. 94, p. 152; Moir and Jessel, 1995, p. 71-82)
∀x,y,z:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x7), emotional_attitudes_towards_others(neg,x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ chemical_state(serotonin, z) ∧ episode $\twoheadrightarrow_{0,0,1,1}$ excitement_threshold(y+3-z)

LP20
Ritalin will decrease the excitement threshold by 1.
(Moir and Jessel, 1995, p. 80)
∀y:INTEGER
takes_ritalin ∧ excitement_threshold(y) $\twoheadrightarrow_{0,0,1,1}$ excitement_threshold(y-1)

LP21
Observation of a stimulus with an excitement level that is lower than the excitement threshold will lead to boredom.
(Delfos, 2004, p. 100; Moir and Jessel, 1995, p. 173; Raine, 1993, pp. 222-224)
∀s1,s2,y:INTEGER
observes_stimulus(s1,s2) ∧ excitement_threshold(y) ∧ s2<y $\twoheadrightarrow_{0,0,1,1}$ boredom

LP22
Boredom leads to a high desire for actions with strong stimuli.
(Delfos, 2004, p. 100; Moir and Jessel, 1995, pp. 74-80, pp. 173-174)
boredom $\twoheadrightarrow_{0,0,1,1}$ desire_for_actions_with_strong_stimuli(high)

Interactions Involving Serotonin

LP23a
When the brain is configured for sensitivity for alcohol s1, and the person does not have an episode, then the sensitivity for alcohol is s1.
(Moir and Jessel, 1995, pp. 201-204, p. 264; Raine, 1993, p. 98, p. 210)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos, x7), emotional_attitude_towards_others(neg, x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ not episode $\twoheadrightarrow_{0,0,1,1}$ sensitivity_for_alcohol(s1)

LP23b
An episode leads to a high sensitivity for alcohol.
(Moir and Jessel, 1995, p. 201, p. 258)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1x7,x8:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos, x7), emotional_attitude_towards_others(neg, x8), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1)) ∧ episode $\twoheadrightarrow_{0,0,1,1}$ sensitivity_for_alcohol(pos)

LP24
An certain initial serotonin level will lead to the same current serotonin level. In this property, p stands for the duration of the pregnancy.
∀x:INTEGER
chemical_state(serotonin, initial, x) $\twoheadrightarrow_{0, 0, p, 2}$ chemical_state(serotonin, current, x)

LP25a
A negative sensitivity for alcohol combined with no alcohol and no prozac will lead to the same serotonin level.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER
sensitivity_for_alcohol(neg) ∧ not drinks_alcohol ∧ chemical_state(serotonin, current, x) ∧ not takes_prozac $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x)

LP25b
A negative sensitivity for alcohol combined with no alcohol and prozac will increase the serotonin level by 1.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER
sensitivity_for_alcohol(neg) ∧ not drinks_alcohol ∧ chemical_state(serotonin, current, x) ∧ takes_prozac ∧ x≤9 $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x+1)

LP25c
A negative sensitivity for alcohol combined with alcohol and no prozac will decrease the serotonin level by 1.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER
sensitivity_for_alcohol(neg) ∧ drinks_alcohol ∧ chemical_state(serotonin, current, x) ∧ not takes_prozac ∧ x≥1 $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x-1)

LP25d
A negative sensitivity for alcohol combined with alcohol and prozac will lead to the same serotonin level.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER
sensitivity_for_alcohol(neg) ∧ drinks_alcohol ∧ chemical_state(serotonin, current, x) ∧ takes_prozac $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x)

LP25e
A positive sensitivity for alcohol combined with no alcohol and no prozac will lead to the same serotonin level.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER
sensitivity_for_alcohol(pos) ∧ not drinks_alcohol ∧ chemical_state(serotonin, current, x) ∧ not takes_prozac $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x)

LP25f
A positive sensitivity for alcohol combined with alcohol and no prozac will decrease the serotonin level by 3.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER
sensitivity_for_alcohol(pos) ∧ drinks_alcohol ∧ chemical_state(serotonin, current, x) ∧ not takes_prozac ∧ x≥3 $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x-3)

LP25g
A positive sensitivity for alcohol combined with no alcohol and prozac will increase the serotonin level by 1.
(Moir and Jessel, 1995, p. 71)
∀x:INTEGER

sensitivity_for_alcohol(pos) $\wedge$ not drinks_alcohol $\wedge$ chemical_state(serotonin, current, x) $\wedge$ takes_prozac $\wedge$ $x \leq 9$ $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x+1)

LP25h
A positive sensitivity for alcohol combined with alcohol and prozac will decrease the serotonin level by 2.
(Moir and Jessel, 1995, p. 71)
$\forall$x:INTEGER
sensitivity_for_alcohol(pos) $\wedge$ drinks_alcohol $\wedge$ chemical_state(serotonin, current, x) $\wedge$ takes_prozac $\wedge$ $x \geq 2$ $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, x-2)

LP26
When you have a current serotonin level of 0, it will not decrease further because 0 is the minimum.
chemical_state(serotonin, current,0) $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, 0)

LP27
When you have a current serotonin level of 10, it will not increase further because 10 is the maximum.
chemical_state(serotonin, current,10) $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(serotonin, current, 10)

LP28
A serotonin level lower than 5 leads to a high insulin level.
(Moir and Jessel, 1995, p. 69)
$\forall$x:INTEGER
chemical_state(serotonin, x) $\wedge$ $x<5$ $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(insulin, high)

Interactions Between Blood Sugar, Insulin and Impulsiveness

LP29a
A high insulin level leads to a decreased blood sugar level.
(Moir and Jessel, 1995, p. 69)
chemical_state(insulin, high) $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(blood_sugar, low)

LP29b
A medium insulin level leads to a medium blood sugar level.
(Moir and Jessel, 1995, p. 69)
chemical_state(insulin, medium) $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(blood_sugar, medium)

LP29c
A low insulin level leads to an increased blood sugar level.
(Moir and Jessel, 1995, p. 69)
chemical_state(insulin, low) $\twoheadrightarrow_{0, 0, 1, 1}$ chemical_state(blood_sugar, high)

LP30a
A low blood sugar level leads to high impulsiveness.
(Moir and Jessel, 1995, p. 69; Raine, 1993, p. 209)
chemical_state(blood_sugar, low) $\twoheadrightarrow_{0, 0, 1, 1}$ impulsiveness(high)

LP30b
A medium blood sugar level leads to medium impulsiveness.
(Moir and Jessel, 1995, p. 69; Raine, 1993, p. 209)
chemical_state(blood_sugar, medium) $\twoheadrightarrow_{0, 0, 1, 1}$ impulsiveness(medium)

LP30c
A high blood sugar level leads to low impulsiveness.

(Moir and Jessel, 1995, p. 69; Raine, 1993, p. 209)
chemical_state(blood_sugar, high) $\twoheadrightarrow_{0, 0, 1, 1}$ impulsiveness(low)

Development of episodes

LP31
When agent a1, who is a criminal, is at location l and observes a 'negative' agent at location l, then agent a1 will have an episode.
(Moir and Jessel, 1995, p. 187)
∀a1,a2:AGENT ∀l:LOCATION
observes(a1,agent_of_type_at_location(a1,criminal,l)) ∧ observes(a1,agent_of_type_at_location(a2, neg_agent,l))
$\twoheadrightarrow_{0, 0, 1, 1}$ has_episode

Consequences of episodes

LP31a
An episode will lead to a decreased anxiety threshold for someone with IED.
(Moir and Jessel, 1995, pp. 184-188)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1,x6,x7:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x6), emotional_attitude_towards_others(neg,x7), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1), ied(pos)) ∧ episode
$\twoheadrightarrow_{0, 0, 1, 1}$ anxiety_threshold(x-4)

LP31b
A certain excitement threshold y combined with a current serotonin level of z and an episode will lead to an excitement threshold of y+3-z for someone diagnosed with IED.
(Moir and Jessel, 1995, pp. 184-188)
∀x,y,z:INTEGER ∀s1:SIGN ∀x0,x1,x6,x7:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x6), emotional_attitude_towards_others(neg,x7), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1), ied(pos)) ∧ chemical_state(serotonin, current, z) ∧ episode
$\twoheadrightarrow_{0, 0, 1, 1}$ excitement_threshold(y+3-z)

LP31c
Someone diagnosed with IED is sensitive for alcohol during an episode.
(Moir and Jessel, 1995, pp. 184-188)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1,x6,x7:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x6), emotional_attitude_towards_others(neg,x7), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1), ied(pos)) ∧ episode
$\twoheadrightarrow_{0, 0, 1, 1}$ sensitivity_for_alcohol(pos)

LP31d
During an episode, someone with IED has a low positive emotional attitude towards others.
(Moir and Jessel, 1995, pp. 184-188)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1,x6,x7:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x6), emotional_attitude_towards_others(neg,x7), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1), ied(pos)) ∧ episode
$\twoheadrightarrow_{0, 0, 1, 1}$ emotional_attitude_towards_others(pos,low)

LP31e

During an episode, someone diagnosed with IED will have a high negative emotional attitude towards others.
(Moir and Jessel, 1995, pp. 184-188)
∀x,y:INTEGER ∀s1:SIGN ∀x0,x1,x6,x7:SCALE
brain_configuration(tom_selfinterest(x0), tom_care(x1), emotional_attitude_towards_others(pos,x6), emotional_attitude_towards_others(neg,x7), anxiety_threshold(x), excitement_threshold(y), sensitivity_for_alcohol(s1), ied(pos)) ∧ episode
$\twoheadrightarrow_{0, 0, 1, 1}$ emotional_attitude_towards_others(neg,high)

A.2 The BDI-Submodel

LP32
A combination of values for theory of mind for care and self interest, aggressiveness, the desire to cope with anxiety, the desire to ignore anxiety, the desire for actions with strong stimuli, impulsiveness, emotional attitude towards others(pos) and emotional attitude towards others(neg) will lead to a specific composed desire, represented as “d(x1, x2, x3, x4, x5, x6, x7, x8)”.
∀x0,x1,x2,x3,x4,x5,x6,x7,x8:SCALE
tom_selfinterest(x0) ∧ tom_care(x1) ∧ aggressiveness(x2) ∧ desire_to_cope_with_anxiety(x3) ∧ desire_to_ignore_anxiety (x4)∧ desire_for_actions_with_strong_stimuli(x5) ∧ impulsiveness(x6) ∧ emotional_attitude_towards_others(pos,x7) ∧ emotional_attitude_towards_others(neg,x8) $\twoheadrightarrow_{0, 0, 1, 1}$ desire(d(x1, x2, x3, x4, x5, x6, x7, x8))

LP33
Desire d(x0, x1, x2, x3, x4, x5, x6, x7, x8) combined with the belief that a certain action will lead to the fulfillment of that desire will lead to the intention to perform that action.
(Rao and Georgeff, 1991)
∀x0,x1,x2,x3,x4,x5,x6,x7,x8:SCALE ∀a:ACTION
desire(d(x0,x1, x2, x3, x4, x5, x6, x7, x8)) ∧ belief(satisfies(a, d(x0,x1, x2, x3, x4, x5, x6, x7, x8))) $\twoheadrightarrow_{0, 0, 1, 1}$ intention(a)

LP34
The belief that there is an opportunity to perform a certain action combined with the intention to perform that action will lead to the performance of that action.
(Cohen, 1979; Rao and Georgeff, 1991)
∀a:ACTION
belief(opportunity(a)) ∧ intention(a) $\twoheadrightarrow_{0, 0, 1, 1}$ performed(a)

A.3 The Submodel for the Society

LP35
When there is a certain stimulus for the excitement threshold and there is an assault, then the stimulus for the excitement threshold will increase by 25.
∀s1,s2:INTEGER
stimulus(s1,s2) ∧ performed(assault) $\twoheadrightarrow_{0, 0, 1, 1}$ stimulus(s1,s2+25)

LP36
When the stimulus for the excitement threshold is 1 or higher and there is no assault, then the stimulus for the excitement threshold will decrease by 1.
∀s1,s2:INTEGER
stimulus(s1,s2) ∧ s2>=1 ∧ not performed(assault) $\twoheadrightarrow_{0, 0, 1, 1}$ stimulus(s1,s2-1)

LP37
When the stimulus for the excitement threshold is 0 and there is no assault, then the stimulus for the excitement threshold stays 0.
∀s1:INTEGER

stimulus(s1,0) ∧ not performed(assault) $\twoheadrightarrow_{0, 0, 1, 1}$ stimulus(s1,0)

LP38
Each stimulus is observed.
∀s1,s2:INTEGER
stimulus(s1,s2) $\twoheadrightarrow_{0, 0, 1, 1}$ observes_stimulus(s1,s2)

LP39
When agent a1 is at location l and agent a2 is also at location l and agent a2 is of type t then agent a1 observes agent a2 (of type t) at location l.
∀a1,a2:AGENT ∀l:LOCATION ∀tTYPE
is_at_location(a1,l) ∧ is_at_location(a2,l) ∧ is_of_type(a2,t) $\twoheadrightarrow_{0, 0, 1, 1}$ observes(a1,agent_of_type_at_location(a2,t,l)

LP40a
If agent a is at a location l, which is connected to two edges, e1 and e2, then agent a goes to one of these edges (with a probability of 50% for each edge).
∀a:AGENT ∀t:TYPE ∀l1,l2,l3:LOCATION ∀e1,e2:INTEGER
observes(a, agent_of_type_at_location(a,t,l1) ∧ neighbours(l1,2) ∧ connected_to_via(l1,l2,edge(e1) ∧
connected_to_via(l1,l3,edge(e2)) ∧ e1>e2 $\twoheadrightarrow_{0, 0, 1, 1}$
performed(a,go_to_location_via_edge(l2,edge(e1))) ∨ performed(a,go_to_location_via_edge(l3,edge(e2)))

LP40b
If agent a is at a location l, which is connected to three edges, e1, e2 and e3, then agent a goes to one of these edges (with a probability of 33% for each edge).
∀a:AGENT ∀t:TYPE ∀l1,l2,l3,l4:LOCATION ∀e1,e2,e3:INTEGER
observes(a,agent_of_type_at_location(a,t,l1) ∧ neighbours(l1,3) ∧ connected_to_via(l1,l2,edge(e1)) ∧
connected_to_via(l1,l3,edge(e2)) ∧ connected_to_via(l1,l4,edge(e3)) ∧ e1>e2 ∧ e2>e3 $\twoheadrightarrow_{0, 0, 1, 1}$
performed(a,go_to_location_via_edge(l2,edge(e1))) ∨ performed(a,go_to_location_via_edge(l3,edge(e2))) ∨
performed(a,go_to_location_via_edge(l4,edge(e3)))

LP41
When agent a goes to location l via edge e, and edge e has length d, and agent a has the tendency to stay at a location for s time units, then after a delay of duration d, agent a is at location l for the next s time units.
∀a:AGENT ∀l:LOCATION ∀e,d,s:INTEGER
performed(a,go_to_location_via_edge(l,edge(e))) ∧ has_length(edge(e),d) ∧ stays(a,s) $\twoheadrightarrow_{d, d, s, s}$ is_at_location(a,l)

A.4 The Submodel to Determine Opportunities

LP42
When agent a1, who is a criminal, is at location l and observes a passer by at location l and does not observe a guardian at location l, then agent a1 believes that there is an opportunity to assault someone.
∀a1,a2:AGENT ∀l:LOCATION
observes(a1,agent_of_type_at_location(a1,criminal,l)) ∧ observes(a1,agent_of_type_at_location(a2,passer_by,l)) ∧
[∀a3:AGENT not observes(a1,agent_of_type_at_location(a3,guardian,l))] $\twoheadrightarrow_{0, 0, 1, 1}$ belief(opportunity(assault))

A.5 The Geographical Environment Model

To model the geographical environment, the following kinds of facts about agent characteristics and the configuration of the world were used:

is_at_location(agent1, 'A')
is_at_location(agent2, 'C')
is_at_location(agent3, 'E')

```
is_at_location(agent4, 'F')
is_at_location(agent5, 'G')
is_at_location(agent6 'B')
is_at_location(agent7, 'H')
is_at_location(agent8, 'D')

is_of_type(agent1, criminal)
is_of_type(agent2, guardian)
is_of_type(agent3, guardian)
is_of_type(agent4, passer_by)
is_of_type(agent5, passer_by)
is_of_type(agent6, passer_by)
is_of_type(agent7, neg_agent)
is_of_type(agent8, neg_agent)

stays(agent1, 1)
stays(agent2, 3)
stays(agent3, 3)
stays(agent4, 2)
stays(agent5, 2)
stays(agent6, 2)
stays(agent7, 2)
stays(agent8, 2)

neighbours('A', 2)
neighbours('B', 2)
neighbours('C', 3)
neighbours('D', 3)
neighbours('E', 2)
neighbours('F', 2)
neighbours('G', 3)
neighbours('H', 3)

connected_to_via('A', 'B', edge(1))
connected_to_via('B', 'A', edge(1))
connected_to_via('B', 'C', edge(2))
connected_to_via('C', 'B', edge(2))
connected_to_via('C', 'D', edge(3))
connected_to_via('D', 'C', edge(3))
connected_to_via('D', 'E', edge(4))
connected_to_via('E', 'D', edge(4))
connected_to_via('E', 'F', edge(5))
connected_to_via('F', 'E', edge(5))
connected_to_via('A', 'G', edge(6))
connected_to_via('G', 'A', edge(6))
connected_to_via('G', 'H', edge(7))
connected_to_via('H', 'G', edge(7))
connected_to_via('H', 'F', edge(8))
connected_to_via('F', 'H', edge(8))
connected_to_via('G', 'C', edge(9))
connected_to_via('C', 'G', edge(9))
connected_to_via('H', 'D', edge(10))
connected_to_via('D', 'H', edge(10))

has_length(edge(1), 1)
has_length(edge(2), 1)
has_length(edge(3), 1)
has_length(edge(4), 1)
has_length(edge(5), 1)
has_length(edge(6), 2)
has_length(edge(7), 2)
has_length(edge(8), 2)
has_length(edge(9), 1)
has_length(edge(10), 1)
```