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Understanding crowd behaviour

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Chapter 5

The CROSS Model - A Computational Crowd Model

In this chapter, the computational modelling phase will be described (phase 2). This comprises a step in which theories and ideas will be transformed and translated into variables and formulas, i.e. formalisation. Section 4.2 described the multi-agent design as being the most suitable given the requirements of the CROSS model: 1) multi-levelness; 2) behaviour description at the cognitive level; and 3) interplay between individuals and their physical and social context. While agent-based modelling is a common approach in modelling crowd behaviour (see table 5.1), a rich description of the individual in a crowd at the functional level has been rarely found in crowd behaviour simulations. Such an extended internal description is important, as it allows for answering and exploring the *why* and *how* questions. The computational model is the result of a process of formalisation. Formalisation is an important phase, as computational models forces one to be concrete and specific where most theories and ideas are not. The computational model is realised as crowd simulation by implementation in Java and by use of the MAS toolkit Repast.

The multi-disciplinary approach that was taken in developing the theoretical model will also be adopted in the computational model. Before commencing the translation of the theoretical model, existing simulation models were studied to see whether they were wholly or partly suitable for use in the computational model.

5.1 Existing crowd models

Crowd behaviour simulations exist since the late seventies. The recent overview of current crowd research, provided by Challenger et al. (2009c) explicitly includes several learning points on the current state of crowd simulation (Challenger, Clegg, & Robinson, 2009a), the following in particular:

1. Real-time systematic observations and expert knowledge are vital to the development of a realistic simulation model. They form the foundation of the assumptions (e.g. typical crowd behaviour, direction of movement) and also provide data for validation.

2. The most realistic simulation tools are populated by intelligent, autonomous agents, capable of making independent decisions and reacting to environmental conditions.
3. Most simulation tools are not based sufficiently on research literature.
4. Future simulation tools should aim to include:
 - (a) Groups of people within a crowd.
 - (b) Emotions of individuals.
 - (c) Interface between people and traffic.

These learning points fit the approach taken for the CROSS model. The CROSS model is based on current knowledge gained from recent literature and observations in crowd research. Consequently, crowd behaviour is modelled by describing behaviour at the individual level using agents. A CROSS agent is sensitive to its physical and social environment, whereas its internal state gives rise to the behaviour it shows. As the focus is on behavioural patterns, this thesis also includes groups within a crowd. Although emotions are not modelled as such, certain cognitive states could be linked to emotions, e.g. an agent that walks away from a crowded area because the safety goal is dominant could be considered being afraid. The last point, i.e. interaction between people and traffic, can be interpreted in a broader sense as the need to include the interaction between people and the environment, which is achieved in this thesis.

Challenger et al. (2009c) tend to focus on the practical performance of the tools of crowd simulation, e.g. computational power, believable agents and practical training needs. In this thesis, the focus is on the explanatory or descriptive power of crowd simulation. The crowd behaviour simulations that are used most frequently in practice usually involve movement of pedestrians. They are used to gain an understanding of not only the way people walk in designed spaces (Therakomen, 2001), but also the way people move during an evacuation (Still, 2000; Helbing, Farkas, & Vicsek, 2000). In addition to pedestrian movement a strong focus lies on riot situations (Granovetter, 1978; Feinberg & Johnson, 1988; Jager, Popping, & van de Sande, 2001; Epstein, 2002; Patten & Arboleda-Flórez, 2004; Mosler & Schwarz, 2005). Other simulations concentrate on specific patterns of crowd behaviour, such as consensus (Johnson & Feinberg, 1977), conformity (Tarnow, 1996) or crowd tipping (Silverman, Johns, Weaver, O'Brien, & Silverman, 2002). Table 5.1 provides an overview of several crowd simulation models. This overview does not aim to be complete, but highlights the main representatives of computational crowd behaviour models. The major differences between these models concern the purpose and the use of their simulations, i.e. to display a methodology, to reproduce a specific type of crowd behaviour or to gain a better understanding of crowd behaviour, as is the case in this thesis.

Table 5.1: A comparison between several simulations of crowd behaviour. They can be distinguished from each other by the following elements: level of description (individual level or not); the incorporation of context (physical and/or social); the inclusion of the description the internal world of an individual (physical, intentional and/or functional level); the focus of the simulation (understanding, reproducing or as a methodological study); and the behaviour described in the simulation.


Crowd behaviour simulation	Agent = Individual		Context		Cognition			Focus		Behaviour
	Physical	Social	Physical	Social	Physical	Intentional	Functional	Physical	Functional	
Johnsson (1977)	+	+	-	+	-	-	-	Understanding	-	Consensus
Granovetter (1978)	+	-	-	-	-	+	-	Methodology	-	Collective behaviour riot
Threshold model										
Feinberg (1988)	+	+	-	+	-	-	-	Understanding	-	Role agitators on consensus
Tarnow (1996)	+	+	+	+	-	-	-	Understanding	-	Group conformity & violence
Phase model										
Tucker (1999)	+	+	+	-	-	-	-	Reproduce	-	Arc & ring patterns
Still (2000)	+	+	+	+	+	-	-	Reproduce	-	Emergent behaviour
Legion										
Therakomen (2001)	+	+	+	+	+	+	-	Understanding	-	Movement in urban space
Mouse.class										
Jager (2001)	+	+	+	+	+	+	-	Understanding	-	Cluster, fight, approach-avoidance
Musse (1997)	+	+	+	+	-	+	-	Reproduce	-	Group inter-relation, collision avoidance
Epstein (2002)	+	+	+	+	+	-	-	Methodology	-	Civil violence
Silverman (2002)	+	+	+	+	+	+	-	Methodology	-	Crowd tipping
Game theoretic agents										
Patten (2004)	-	-	-	+	-	-	-	Reproduce	-	Group violence
Epidemic theory										
Helbing (2005)	+	+	+	+	-	-	-	Reproduce	-	Pedestrian movement, Evacuation
Social forces model										
Mosler (2005)	+	+	-	+	+	+	-	Understanding	-	Escalation processes
PAX model										
Nguyen (2005)	-	+	+	+	-	+	-	Reproduce	-	Interaction civilians-military
Cognitive crowd model										
Fridman (2009)	+	+	+	+	+	-	+	Reproduce	+	Pedestrian movement, social comparison
Wijermans (2011)	+	+	+	+	+	-	+	Understanding	+	Behaviour dynamics
CROSS model										



The models that focus on methodology either demonstrate show the explanatory power of simulation or explain what level of detail is required to develop realistic simulations. The work of Granovetter (1978) is an excellent example of the explanatory power of simulation. In his study, Granovetter makes sociological/psychological theory explicit (e.g. norms) and he illustrates the causal influence of individual variation within an interacting group. In addition, Granovetter is setting an example in terms of being transparent about what the model does and does not do. Epstein (2002) uses a similar approach and demonstrates how simulation can be used to understand the complex dynamics of civil violence. The work of Silverman (2002) supports the development of a tool to reproduce realistic crowd behaviour. In this study, Silverman interestingly integrates theories on human behaviour into a cognitive framework to produce human-like behaviour in a simulation.

Models that focus on reproducing outcomes of crowd behaviour do not necessarily require a realistic description. Nevertheless, including relevant factors based on current knowledge/literature on crowd behaviour can be considered a way to add realism to the simulation outcome. In the models of Musse and Thalmann (2001), Helbing et al.(2005), and Still (2000) this is clearly shown by addressing the role of the social context in models of crowd behaviour. Tucker et al. (1999), on the other hand, provide an empirical validation for the simulation of the basic movement patterns in crowds. Nguyen et al. (2005) takes an innovative approach by incorporating groups within a crowd. However, to reduce computation time, Nguyen eliminates the individual level at which behaviour is generated. The way in which Fridman and Kaminka (2009) model crowd behaviour stands out, as they translate social theory into a cognitive architecture (SOAR). Most models use simple rules and then add the relevant elements. Fridman and Kaminka, however, start from a highly detailed model of cognition by adding social elements. In this thesis, merging social and cognitive theories is considered crucial. Unfortunately, Fridman and Kaminka's model is not grounded very well in the field of crowd research. It gives the impression of formalising the myth of uniformity by relating similarity in behaviour in crowds to the formation of homogeneous groups.

The models that aim for an understanding of crowd behaviour differ from each other. For instance, Johnson(1977) and Feinberg (1988) model consensus from a viewpoint that relates to the myth of suggestibility. Although current insights imply that their assumptions are outdated, their work should be placed in its own time, as they incorporated the knowledge that was available back then. Furthermore, they used the simulation tool adequately by testing as well as reporting about these tests. Tarnow (1996), on the other hand, seems to ignore the body of knowledge available at the time and describes crowd behaviour (i.e. conformity and violence) in terms of fluid dynamics (i.e. fluid phases). The analogy with fluids comes across as an arbitrary link between the physical and the social world. However, the main objection lies in the fact that the assumptions and relationships of his model are based on Le Bon's group mind myths. The other modern models that are developed with the aim of understanding are theoretically and empirically based. They distinguish themselves by providing a description of the internal world of an individual. For instance, Jager (2001) provides a simple description of clustering and approach-avoidance, yet specifically focuses on providing an explanation that involves the interplay between the external and internal world of an individual. Therakomen (2001) also shows this



broadness in integrating elements from both the external and the internal world, in this case, to understand the role of urban space in crowd movement. Mosler (2005) describes escalation processes between civilians and the military, providing a more refined description of internal processes. These last three models are in line with the view taken in this thesis. To understand crowd behaviour, a richer description at the intra-individual level is required.

The models that replicate behaviour are capable of generating realistic and valid movement patterns. These reactive models are based on boid/flocking-like rules (Reynolds, 1987), building on the knowledge available at the time in order to develop behaviour rules. Their design is, however, not suitable for answering the 'why' and 'how' questions.

The overview of a selection of existing models positions the approach chosen in this thesis, plus it provides a further rationale for the choices made. An agent-based approach is adopted by most models. In addition, it has also become clear that the aim is understanding which justifies the inclusion of the intra-individual level. Nonetheless, the overview of models shows the difficulty of formalising theory and limiting oneself to a minimal set of theories. In crowd behaviour, a wide diversity of behaviour and influences play a role. Therefore, a framework that allows for multiple behaviours and influences is needed to gain a general understanding of crowd behaviour. Based on these criteria, the existing models are either too simplistic to represent general crowd behaviour, they focus too specifically on a certain type of behaviour, or they do not incorporate the modern foundation of crowd research. It was therefore not possible to use any of the existing models for this study. The criteria justify the choices that were made, i.e. to stress the incorporation of both the physical and social context as well as the rich description of the internal world (i.e. cognition) of an individual. In this respect, the interplay between these factors is considered more important than including all potentially relevant factors.

5.2 Computational crowd model

The formalisation of the theoretical model described in chapter 3 allows for the exploration of crowd dynamics by running simulation experiments with the CROSS model. Multi-agent systems allow for the formalisation of the theoretical CROSS model, as all requirements can be incorporated, namely the multiple levels, a cognitive level of description and the dynamics of crowd behaviour (see chapter 4). A new computational model was developed, as existing simulation models did not reflect the CROSS model (see previous section).

The CROSS model represents a situated crowd (see figure 5.1). In computation terms a world is built that contains both the physical environment in which the agents 'live' as well as the agents themselves. In the remainder of this chapter, the formalisation of the environment and the agents will be described by specifying the concepts and relationships of the theoretical CROSS model.

5.2.1 Environment formalisation

The environment describes all objects that are not agents. It represents the physical space, such as the terrain an agent is able to stand on and move on. But it also

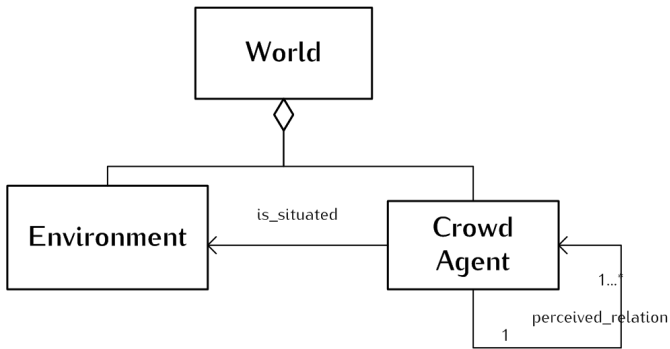


Figure 5.1: Conceptual overview of the CROSS model.

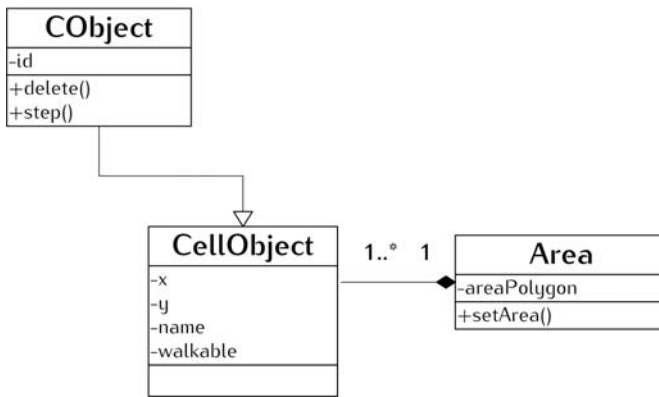


Figure 5.2: Class diagram of the environment, that is represented by cells that are walkable or non-walkable. An area indicates a set of cells that share properties (walkable (bar, toilet or stage)).

represents the objects that are relevant for a festival context, such as a bar, toilets, and a stage. In this way, the agents can distinguish between walkable and non-walkable areas on the festival terrain, or between specific objects that may fulfil the agents' goals, e.g. listening to music near the stage, having something to eat or drink at the bar, or going to the toilet (see the following section on agent formalisation).

In the CROSS model, a terrain of $256m^2$ is represented by a grid layer representing the relevant areas (i.e. collections of cells), such as the bar, stage, toilets, or terrain that is walkable ($210m^2$ walkable terrain) or non-walkable¹. Figure 5.2 shows the class diagram of the environment.

¹Movement of agents is not represented on a grid space, but on a continuous layer that allows for movement within a cell or for a cell to be partly occupied. It is computationally cheaper to represent the physical areas on a grid layer and to have Repast provide the relationship between the 'movement' layer and the grid layer.

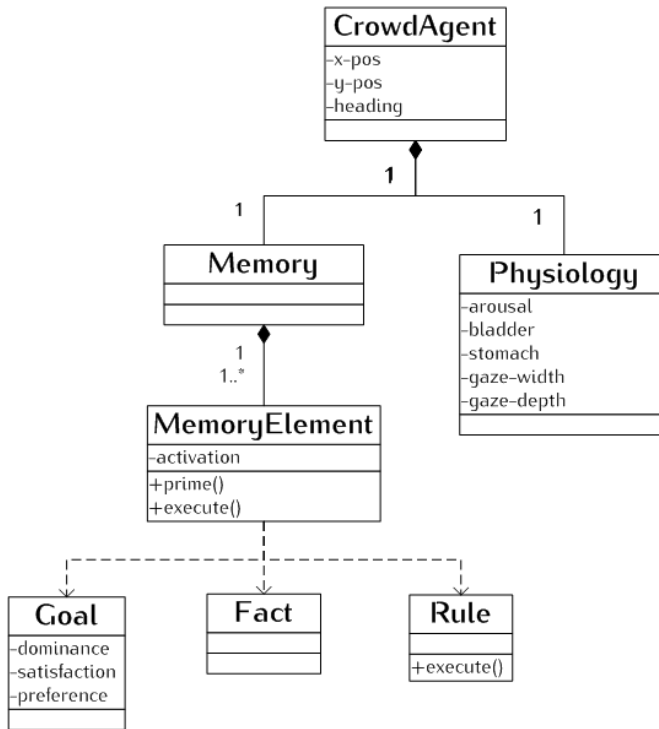


Figure 5.3: Class diagram of a crowd agent. The structure comprises physiology and a memory. The latter consists of three memory elements, i.e. goals, facts and rules.

5.2.2 Agent formalisation

The largest part of the CROSS model concerns agents. An agent represents a computational individual in a crowd that has some properties and sensitivities towards itself and its environment that give rise to the behaviour it will display. As described in chapter 3 an agent is situated (embodied and embedded). The structure of a cognitive architecture is adopted involving physiology (architecture) and memory (internal representation) to represent the internal state of an agent. The content of physiology and memory is based on the context of a crowd. Embodiment shapes the description of physiology by the incorporation of limited perception, arousal, bladder and a stomach. Embeddedness allows an agent to recognise, to interpret and to be affected by the environment which is represented as knowledge in memory, for instance recognising a friend or a social setting. Figure 5.3 shows the class diagram of the general structure of an agent.

Architecture | physiology

Architecture represents the structure of cognition, i.e. the physical properties of the human body (embodiment) and also the notions that represent the physiological state

Table 5.2: An overview of the architecture variables.

Architecture variables			
Variable	description	range	type
Gaze width	width of sight	180 deg	CONST
Gaze depth	Depth of sight	0.8	CONST
Body size	Area an agent occupies	40x40cm	CONST
Arousal	Level of attention	[0,1]	DOUBLE
Bladder	Level of fullness	[0,1]	DOUBLE
Stomach	Level of fullness	[0,1]	DOUBLE

of the agent (arousal, stomach and a bladder). Each notion is translated into a variable concerning the physiology of the agent.

Having a body is reflected in the constraints in perception, movement and information processing that are relevant in a crowd context. This incorporates notions of limited perception (*gaze-width* and *gaze-depth*) and area occupation (*body area*). Perception is restricted by defining a *gaze-width* and *gaze-depth*. The default *gaze-width* of sight is set to 180 degrees, as an individual can see what is in front of him. The *gaze-depth* is set to 0.8 meter, which restricts the perception of the local surroundings an agent can be affected by to two people standing behind each other. The global perception of elements in the physical environment, for instance, the stage, bar and toilets is hard coded, which means that the agent knows where these places are. It is recognised that, in reality, individuals can perceive more than just their local surroundings, but for the purpose of this study the focus is restricted to the local surroundings. The following implementation involves an agent occupying space. This is important, not only to be able to incorporate the role of density, but also to add a crucial element of realism, as a person simply cannot walk right through another person. The dimensions of an individual are based on the average proportions of a person, i.e. 30x50 cm, which is implemented as 40x40 cm as squares are computationally cheaper to work with (Still, 2000; Haak & van der Burgh, 1994).

The physiological state, i.e. the variables *arousal*, *bladder*, and *stomach* are represented as a range varying between 0 and 1. For arousal, the range varies from a low to a high state of attention. Stomach and bladder are represented in terms of how full they are. Table 5.2 shows an overview of these architecture variables.

Representations | memory

Representations enable an individual to live in a complex and dynamic world. The knowledge that is required to understand and act in the world an agent lives in is stored in one of the memory elements: *goals*, *facts*, and *rules*. A memory element always has an activation value. The meaning and effect of this activation value depends on the type of memory element (goal, fact or rule). In the theoretical CROSS model, this abstract structure is described. It must be refined for an individual in a crowd at a festival by specifying goal, fact and rule content. An overview of this structure is provided in the class diagram of a crowd agent in figure 5.4.

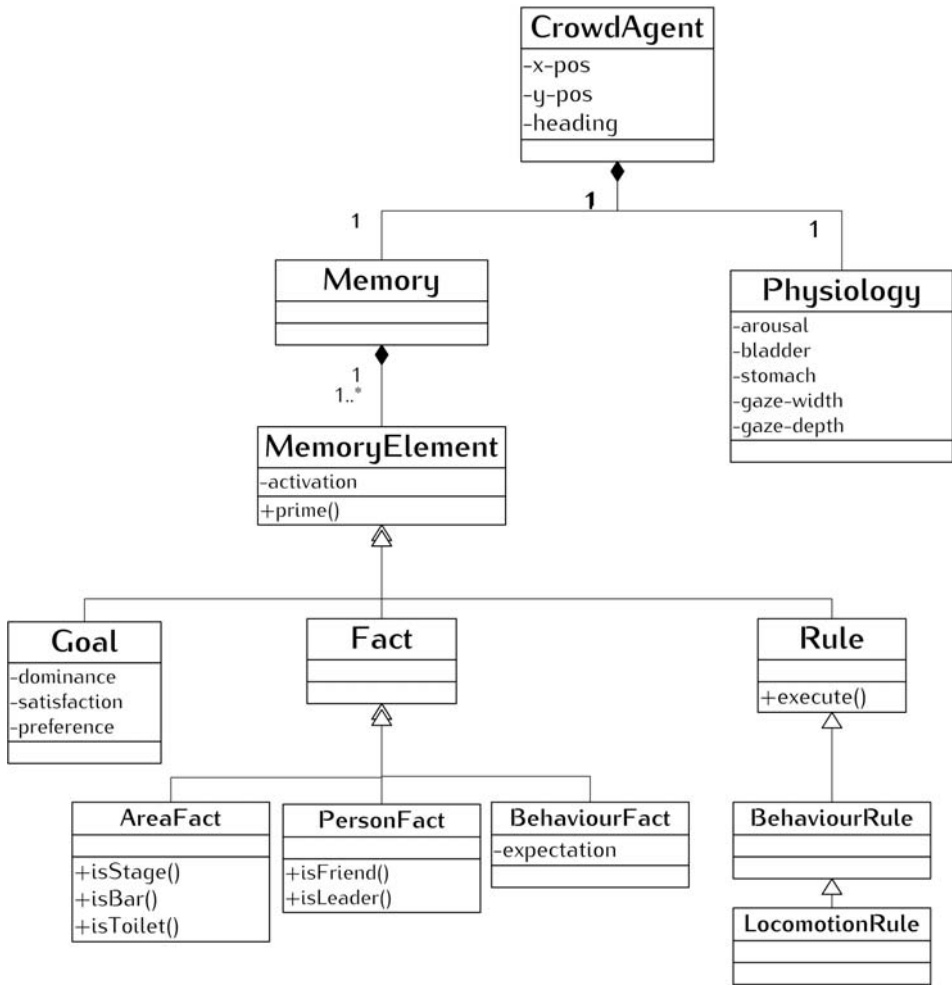


Figure 5.4: Class diagram of a crowd agent with the full memory structure.

Goals The first type of memory element is goal. A goal represents an agent’s desired state. Four goals can be distinguished: *subsistence*, *safety*, *social* and *identity*. Respectively, they represent the desire a) to preserve energy, b) to remain safe, c) to belong to a group, and lastly, d) to enjoy the festival individually. As mentioned earlier, each memory element has an activation value. For goals, the activation value represents the dominance ($goalDom$) of that goal (g), as shown in equation 5.1. Dominance is the discrepancy between the desired ($PREF_g$) and the current ($Satis_g$) level of satisfaction.

$$goalDom_g = PREF_g - Satis_g \quad (5.1)$$

The level of satisfaction ($Satis_g$) will change over time, on the basis of what is perceived. The preferred level of satisfaction ($PREF_g$) is fixed, and represents an attribute of an agent. For example, an agent with a high preference level for the safety goal

Table 5.3: The goal instantiations in the CROSS model.

Goals	description
Identity	Need to be an unique individual
Social	Need to belong to group
Safety	Need to remain safe
Subsistence	Need to preserve energy
General properties	value: satisfaction - dominance range: [0,1] type:DOUBLE

can be seen as someone who is more easily scared. An overview of the goals in the CROSS model is given in table 5.3.

Facts A fact is defined as a unit of declarative or factual knowledge (a so-called chunk). Memory stores the knowledge that an agent needs to interpret perception, or to compare various kinds of behaviour. Three types of facts can be distinguished: area facts, person facts, and behaviour facts. All facts allow a person to recognise points of interests (stage, bar, toilet), other people (friend, leader), or the behaviour someone exhibits. In addition to allowing recognition of behaviour, behaviour facts convey expectations of the extent to which a particular behaviour satisfies an agent's goals. An overview of the facts in the CROSS model is provided in table 5.4.

Table 5.4: The facts defined in the CROSS model.

Facts	description	
AreaFact	recognise a stage, bar, toilet (x,y)	CONST
PersonFact	identify friend, leader {true,false}	CONST
BehaviourFact	expectation to walk, run, dance {explD,expSoc,expSaf,expSub}	CONST
General properties	activation: range: type:	retrieve time [-inf,inf] DOUBLE

The activation for this type of chunk is related to the time it takes to retrieve a fact from memory. This implies that facts with a high activation level are easily retrievable, i.e. they appear rapidly. In this way, one could also include forgetting, by disabling facts below a certain threshold from being retrieved. The activation (A_i) of a behaviour rule (i) is represented by equation 5.2. This equation is a neuron activation equation that increases the activation of the memory elements that are primed and thus become more probable or relevant for the agent at that moment (Anderson,



2007). It fits the view that what is active or dominant in the cognitive system will affect behaviour, think of the concept of saliency. The activation equation consists of two parts, the base-level activation (B_i) and the associative activation (the $W_j S_{ji}$ values). To represent the activation (A_i), only the base-level activation B_i is specified. Activation represents a measure for the relevance in a given situation, i.e. the history of element usage. Anderson (Anderson, 2007, p110.) puts it as follows: "The base-level learning activation equation specifies how the pattern of past occurrences of an item predicts the need to retrieve it." In this equation, t_k is the time since the k th practice of an item. To implement this activation function, a computational efficient approximation function for B_i is used, see then equation 5.3 (Petrov, 2006). This function generates the typical base-level activation dynamics: a sharp peak directly after usage, decay in absence of use, and gradual accretion with regular use (Petrov, 2006). It is more efficient than the original activation function, as it does not need to register every usage of the memory element. Only the last k -times when the memory element was used is stored. Index i allows for finding the stored time step (t_i) of history element usage. Time step t_n corresponds with the time a memory element started to exist, whereas n represents the total number of uses.

$$A_i = B_i + \sum_{j \in C} W_j S_{ji} \quad (5.2)$$

$$B \approx \ln \left[\sum_{i=1}^k \frac{1}{\sqrt{t_i}} + \frac{2(n-k)}{\sqrt{t_n} + \sqrt{t_k}} \right] \quad (5.3)$$

Rules | behaviour The last type of memory element are rules. Rules refer to the internal representations of an action, which is called procedural knowledge. In the CROSS model, behaviour rules concern motor action. A *behaviour rule* allows an agent to exhibit specific behaviour in as far as this behaviour is known. For the sake of simplicity, relevant behaviour of an agent in a crowd has been restricted to **walking**, **running**, and **dancing**. All three types of behaviour concern *locomotion rules*, as they describe the spatial movement of the agent. The activation value of a behaviour rule differs from the dominance connotation of goals and from the retrieval time of facts. For behaviour rules, the activation value gives rise to a hierarchy in the behaviour an agent knows and is thus able to exhibit. The higher the activation, the more likely the behaviour will be chosen. The changes in activation over time result in a dynamic ordering of behaviour. The activation value of a rule is similar to the facts described in activation equation 5.2. However, the way activation is used is different. For a fact, usage concerns the retrieval time, but for a rule, it concerns the order in which behaviour will be selected for execution. An overview of the behaviour rules in the CROSS model is given in table 5.5².

Processes | perception and behaviour selection

The dynamic element of the CROSS model is the continuous interaction of an agent with its environment via two processes: *perception* and *behaviour selection*. Figure

²There is only a minor difference between walking and running, as it can be deemed to reflect speeding up in optically reasonable terms.

Table 5.5: The rules in the CROSS model.

Behaviour Rules	description
Walk	movement in space - $v = 0.4$ m/tick
Run	movement in space - $v = 0.48$ m/tick
Dance	movement on the spot - occupation shift
General properties	activation: dynamical ordering range: $[-inf,inf]$ type: DOUBLE

5.5 shows this continuous loop of perception that changes the internal state of an individual (`perceive()`) as well as the behaviour selection that uses the internal state to choose a behaviour (`behaviourSel()`).

Perception Perception describes the changes in the agent’s internal state as a result of the external and internal setting at a particular moment. In the CROSS model, perception is ‘hard-coded’, which means that there is no intelligent algorithm behind perception. Instead, the lines of influence described in section 3.3.3, *priming*, *physiology update* and *memory update*, are formalised. Perception starts with retrieving information from the world that is visible to an agent (`getInfo()`). Depending on what is perceived, the corresponding internal representation is made more active (`prime()`). This is followed by the specific update of physiology (`updatePhysiology()`), and of memory elements, i.e. goals (`updateGoals()`) and facts (`updateFacts()`). This sequence of functions involving perception is visualised in figure 5.6.

The `getInfo()`-function retrieves the environment information for each particular agent, while taking the constraints on perception into account. This environment information includes both other agents that are visible to the agent and their behaviour, and the local density. Next the corresponding internal representations of the visible persons and behaviour are primed. Priming implies an increase in the activation of a memory element in accordance with the activation function described in equation 5.2. Algorithm 5.1 illustrates, in pseudo code, the use of the activation function. The function calculates the approximation of the base-level activation of a memory element, as in equation 5.3.

Every time a memory element is used, the time is stored in `primeTimes`. In accordance with approximation function 5.3, this only requires storing the last k -times of usage instead of all the times an element was used³. The base-level activation is calculated based on the number of times the element is used (`timesUsed`), on the duration of existence of the element (`lifeSpan`), and on the time of usage since the k th use (`useSpan`).

The *physiology update* is conducted by setting the arousal, stomach and bladder levels. *Arousal* is represented by a threshold function that relates density to a state of alertness. Algorithm 5.2 specifies the threshold function that describes an increase in arousal when density increases. The choice for these numbers is related to the fact

³ $K = 1$, Petrov (2006) indicates that this already works quite well.

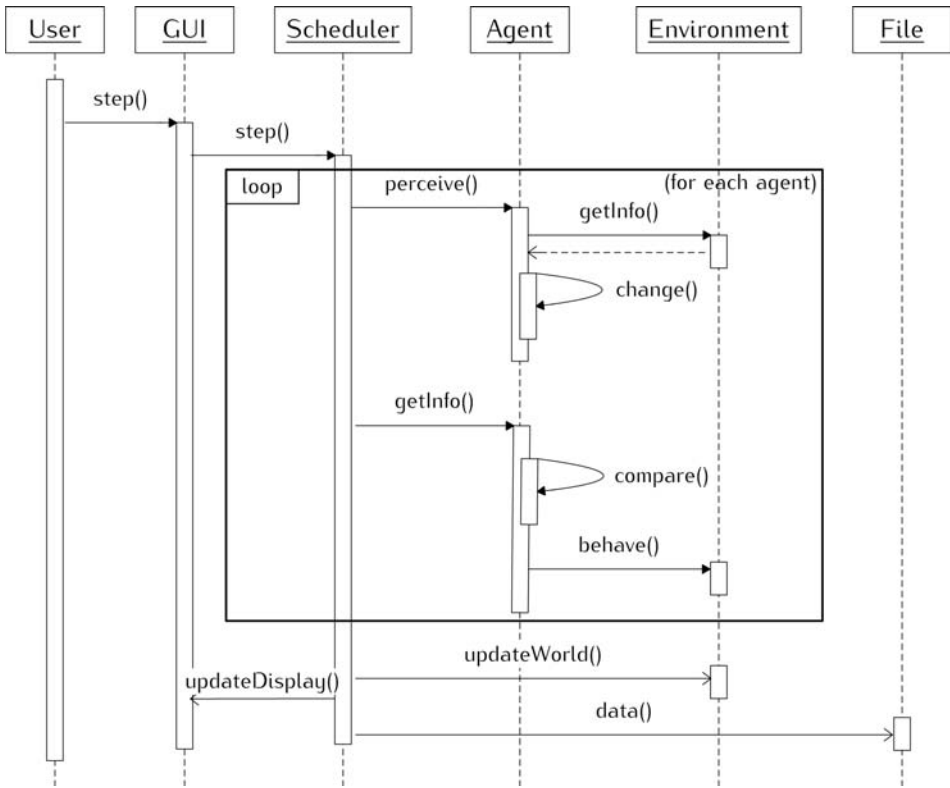


Figure 5.5: Time sequence diagram of processes in the CROSS model.

that as soon as density imposes restrictions on the freedom of movement, an increasing effect on arousal occurs. The relationship between locally perceived density and arousal is represented in a simplistic way, using a relative scale between zero and one. The lower boundary (zero) will never be reached in this scenario, as every agent is assumed to be awake. The upper boundary (1) is related to the point where density is at such a high level that 1) it is not relevant for the scope of this thesis and 2) differentiation in arousal is not needed, as the arousal level, due to the extreme pressure, would be so high that it is reasonable to assume a maximum state of awareness.

The bladder and stomach represents ‘fullness’ following a linear function. A bladder will increase in fullness unless emptied via a toilet visit, whereas the stomach functions in the opposite way, becoming increasingly empty unless filled by having a drink or something to eat. Regarding the pseudo-code for bladder (algorithm 5.3) and stomach (algorithm 5.4), one can see they concern a very simplistic function that causes an agent go to the bar or toilet motivated by an internal drive. This choice was made purely on the basis of context, because at a festival people drink and go to the toilet. This is driven by physiological goals. However, also social goals are involved in exhibiting this behaviour.

Memory update represents the change in the content of memory elements caused by external and internal perception. It concerns an update of the goals (i.e. satisfying

Algorithm 5.1: Pseudo-code for priming. The activation level is based on the times of usage, and an approximation function for the baselevel activation see equation 5.3.

```

currentTime = getTick();
primeTimes.addFirst(currentTime); //FIFO (first in - first out principle)
++timesUsed;
lifeSpan = currentTime - tFirstUse;
forall primeTimes do
  useSpan = currentTime - primeTimes.last(); bsum
  +=  $\ln \left( \frac{1}{\sqrt{\text{primeTimes}[i]}} + \frac{2(\text{timesUsed}-1)}{\sqrt{\text{lifeSpan} + \sqrt{\text{useSpan}}}} \right)$ ;
end

```

Algorithm 5.2: Formalisation of arousal. A threshold function related to the density level observed by an agent.

```

if density < 3 then
  | arousal = 0.3;
end
else if density > 10 then
  | arousal = 1;
end
else
  | arousal = density / 10;
end

```

Algorithm 5.3: Formalisation of the bladder - a linear function related to time - in the course of 1000 ticks an agent will probably need to go to the toilet based on the physiological urge

```

if toiletVisit == true then
  | bladder = 0;
end
else
  | bladder += 0.0010; // after 1000 ticks the bladder is full
end

```

Algorithm 5.4: Formalisation of the stomach - a linear function related to time - during 1000 ticks an agent will need to go to the bar based on the physiological urge

```

if barVisit == true then
  | stomach = 1;
end
else
  | stomach -= 0.0010; // after 1000 ticks the stomach is empty
end

```

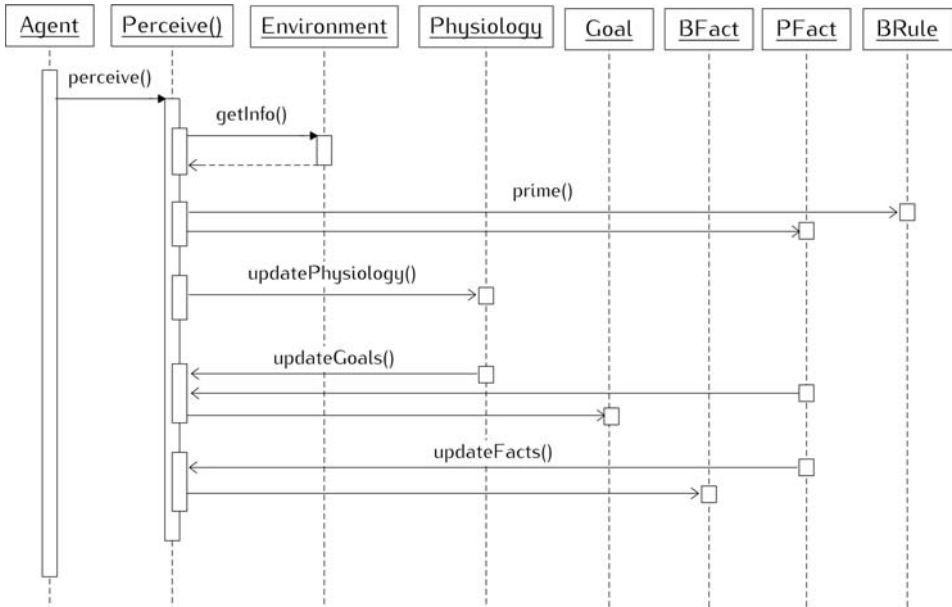


Figure 5.6: Time sequence diagram of an agent's perception.

them more or satisfying them less) and of the expectations in behaviour facts, making a certain type of behaviour more or less suitable in a particular context. Each goal has its own relationships and when satisfaction changes, all these relations will be defined depending on context-related knowledge or assumptions. The subsistence goal is directly related to the physiological state. Therefore, the satisfaction of this goal takes over the most prominent physiological urge, bladder or stomach, (see algorithm 5.5).

The safety goal is related to the subjective perception of density (see section 3.1.1). The formalisation of the safety goal represents the simple assumption of feeling unsafe when standing in crowded areas or areas that are perceived to be crowded⁴. The subjectivity of density perception depends on whether the satisfaction level is considered low or high, based on the preference of the agent. Locally perceived density will affect each agent's safety goal in the same way. However, the preference for safety, which is a heterogeneous attribute, makes the effect subjective and unique for each agent. The effect of local density is described using a sigmoid function, which is a smooth step-function represented by equation 5.4.

$$\text{Safety}(d) = 1 - \frac{1}{1 + \exp^{((-12d/\text{maxD})-6)}} \quad (5.4)$$

The social goal represents the need to belong to a group. In a festival setting, satisfaction is related to staying close to others, preferably friends. The satisfaction of

⁴It is, of course, acknowledged that being in a large group or standing close together can also increase the feeling of safety. This may, for instance, be the case for young males who show 'spontaneous' aggressive behaviour without an external interaction trigger, as was discussed Adang's initiation-escalation model (section 2.2.3). This is, however, not addressed here.

the social goal is formalised as a threshold function related to the number of agents or friends nearby. This is shown in algorithm 5.6.

The identity goal is related to the distance to the stage, i.e. being closer to the stage increases satisfaction. It concerns listening to music, the visibility of the artist, i.e. the individual enjoyment of the festival⁵. The function to describe this distance-related satisfaction is a threshold function, which is represented in algorithm 5.7

Setting the right increases and decreases of variables (or values) amounts mainly to parameter twisting, meaning that both the fluctuation of behaviour as well as the setting within the vicinity of the stage need to be optically reasonable. Therefore, the simulation was run in several different settings to see whether or not the agents would behave in the desired fashion. For instance, the arc pattern around the stage should be around the stage and should not be occupying the whole festival terrain. This implies that someone near the toilets should not be satisfied about the distance from the stage, unless the preference for this goal is really low of course.

In addition to the goals, the memory update also involves the update of behaviour facts. A behaviour fact is updated as a consequence of perceiving a leader exhibit a behaviour. The perception of a leader increases the expectation of this behaviour satisfying the social goal. The formalisation involves a rise in this specific expectation, but a decay to the default value when no leader is perceived showing this behaviour. This makes socially more desired behaviour merely a temporary effect (see the algorithm 5.8).

Perception is thus achieved via a sequence of methods that retrieves information, primes memory elements and updates physiology, goals and facts. The process is visualised in the time sequence diagram in figure 5.6.

Behaviour selection Behaviour selection is the other main process in the CROSS model. As described in chapter 3, behaviour selection involves a process of selecting ‘optimal’ behaviour within a certain amount of time. The most optimal behaviour is the behaviour that best satisfies the goal that is most dominant at a particular moment. This is the result of comparing behaviour from the agent’s repertoire for as long as it has time to do so. Then a behaviour is chosen and executed. This sequence of behaviour selection is visualised in the time sequence diagram in figure 5.7.

Behaviour selection depends on time. The time an agent has to choose behaviour is implemented as a direct link between the arousal level and the internal time to compare the different behaviours with each other and to choose.

$$time = arousal * 10; \tag{5.5}$$

In line with the amount of time an agent has available, the selection process starts by retrieving the behaviour with the highest activation level. For as long as there is time left, this behaviour is compared to the behaviour that is next in line⁶. The best behaviour option is chosen and used for further comparison. Every retrieval of memory elements takes time, which is based on its activation value. Therefore, it is easier to remember something that is salient, as it has a higher level of activation and thus faster in retrieval time.

⁵Note that the level of satisfaction desired differs from one person to another.

⁶Remember that the behaviours are ordered according to their activation value.

Algorithm 5.5: Formalisation of the subsistence goal satisfaction - a direct link with the physiological state, in which the most prominent physiological urge defines the satisfaction of subsistence.

```
subsSatisfaction = MAX(bladder,stomach);
```

Algorithm 5.6: Formalisation of the social goal satisfaction. A threshold function in which satisfaction is related to the vicinity to friends of others.

```
if nearbyFriends == true then
  | satisfaction = 1;
end
else if nearbyOthers == true then
  | satisfaction += 0.3;
end
else
  | satisfaction -= 0.1;
end
```

Algorithm 5.7: Formalisation of the identity goal satisfaction. A threshold function related to the distance between an agent and the stage.

```
if distance < 3 then
  | satisfaction += 0.05;
end
else if 3 < distance < 7 then
  | satisfaction += 0.01;
end
else if 7 < distance < 20 then
  | satisfaction -= 0.0025;
end
else
  | satisfaction -= 0.01;
end
```

Algorithm 5.8: Formalisation of the behaviour fact update. The perception of a leader's behaviour temporarily increases the expectation to satisfy the social goal of that particular behaviour.

```
forall bFacts do
  | if socExpectation != default then
  | | socExpectation = default;
  | end
end
if leaderPerceived == true then
  | leader.bfact.socialExpectation = 0.4;
end
```

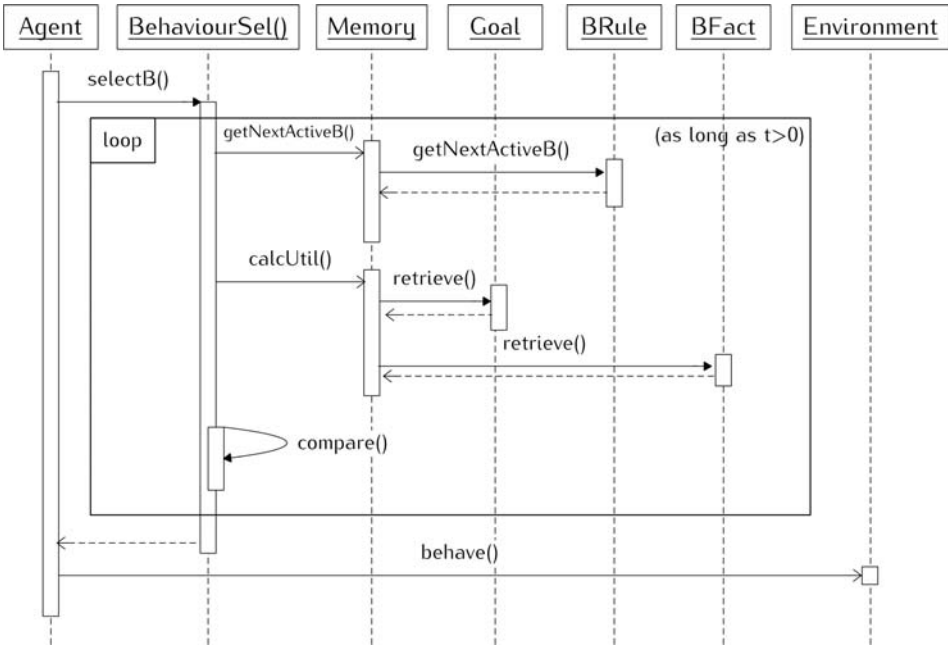


Figure 5.7: Time sequence diagram of the behaviour selection process of an agent.

Comparing behaviour Comparing behaviours to each other is represented in a function that attributes a utility value ($bUtil_b$) to each behaviour under comparison. The utility value represents the relevance of a certain behaviour (b) based on the agent’s internal state, i.e. goal dominance, at that particular time. The comparison function is based on the expectation ($bExpect_g$) of behaviour in combination with goal dominance ($goalDom_g$). The expectation indicates the expected fulfilment of the corresponding goal (g) when exhibiting a certain behaviour. The comparison value incorporates the contribution of all goals in accordance with their dominance.

$$bUtil_b = \sum_{g=1}^4 goalDom_g \cdot bExpect_g \tag{5.6}$$

5.3 Conclusion

In this chapter, the phase of moving from the theoretical model to the computational model was described (phase 2). This formalisation phase distinguishes simulation models from other types of modelling. The formalisation phase is a creative and challenging step to make theories more concrete, precise and explicit. For each relationship and concept in the theoretical CROSS model, a computational equivalent was provided in terms of algorithms and variables. At this point, there is no room for vagueness or ambiguity, as this will not be understood by a computer. This makes the research both vulnerable and powerful. It bridges the gap between theory to a computational version, i.e. a new part is added. This translation is carried out by means



of analogy, assumptions, empirical data or expert opinions. This translation can be vulnerable due to the dangers of using analogy or too many assumptions, or due to a lack of data or knowledge. The strength of simulation research lies in this new part, as the theory or idea is made explicitly. This makes it easier to detect errors, and leads to precise and powerful theories that provide rich explanations.

The current form of the CROSS model is not only a computational representation of a crowd behaviour theory but also a methodology to study crowd behaviour. To be able to answer the research question, both theory and methodology were found to be necessary steps after studying literature (see chapters 1 and 2). In this way, the CROSS model enables to explore and answer the research question. In fact, the design and formalisation of the CROSS model represents the most crucial steps towards answering the research question. With the model in place, it is now possible to apply an empirical methodology and perform experiments on crowd behaviour. As a first step in exploring crowd behaviour, two experiments were performed with the CROSS-model. These experiments will be described in the following two chapters. They do not represent a goal in themselves. The aim of the experiments is to illustrate the explanatory power of the integrative, multi-level and situated approach⁷.

⁷The computational model can be found at [openABM](#) and [SourceForge](#).

