Investigating Crowd Behaviour during Emergency Evacuations Using Agent-Based Modelling

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Abstract

In the present paper we argue that the effectiveness of interventions/design solutions supporting emergency evacuation of crowds in socio-technical systems, depends on the appropriateness of the models used for the crowd behaviour. After reviewing basic approaches already used to model escaping crowds, the knowledge about crowd behaviour provided by modern social psychology is briefly presented. Agent-based modelling is proposed as an adequate bottom-up approach to model a number of psychological crowd effects on individual psychomotor behaviour, which in turn influence crowd behaviour. The basic features of the agent-based model developed for the passengers of a metro on fire are presented as an example of an escaping crowd, to show the merits of the proposed modelling approach.

Keywords: Crowd Model, Agent-Based Modelling, Co-evolution, Emergency Evacuation

1 Introduction

Interventions aiming to support the evacuation of a crowd embedded in a socio-technical system under safety critical conditions, fall in two categories: (i) at the level of the infrastructure (e.g. design appropriate barriers and escape routes), and (ii) at the organisational level (e.g. design plans for emergency rescue). To design any type of intervention, a model of the *behaviour of the crowd* is required.

In general, a crowd is defined as a set of individuals in the same physical environment, who share a common goal (Musse & Thalmann, 1997). The fans of a football game, the spectators in a theatre, the passengers at the metro, are all typical examples of crowds. The term *crowd behaviour* designates the dynamics of the whole group of people forming the crowd, which, as will be shown later in this paper, has some particular characteristics.

The effectiveness of the interventions/design solutions for emergency evacuation depends on the appropriateness of the models used for the crowd behaviour. However, the development of such models is not an easy task, and is far form being a solved problem.

Existing models of crowd behaviour during evacuations can be classified in two broad categories: *top-down* and *bottom-up* formed models. Top-down models examine crowd behaviour at a macro-level, ignoring variations on the individual behaviour of people participating in the crowd, and consequently its particular dynamics. Crowd behaviour is described in the form of overall statistical data (e.g. 5% of the population remains trapped in a specific enclosure). In engineering systems research, these models are usually incorporated in discrete event simulations whose goal is primarily the alleviation of duplicate or conflicting procedures, or the design of issues related to infrastructure, providing the means to assess mathematically expressed variables (e.g. egress time), for alternative implementations.

However, the primal jeopardy in the evolution of an evacuation has its source on the dynamics emerged ad hoc, as the incident evolves. Knowledge on the particularities of the evacuation process is necessary, in order to come about with efficient interventions that would assist the evacuees during the escape. This is the scope of the bottom-up approaches to crowd modelling. By modelling the local interactions between the evacuees and their environment, the behaviour of the group emerges through the co-evolution of the crowd and its environment. In this way, the designer may form an accurate image about the crowd evacuation process, and both generate and assess efficient alternative design solutions.

So far, two different types of bottom-up crowd models have been used: *queuing* and *network* models (Santos and Aguirre, 2004; Watts, 1987). *Queuing* models, as their name implies, are based on *queuing theory*. They were originally introduced to model congestion phenomena, often encountered when crowds are physically constrained to use spatially limited resources (e.g. trying to exit a building through a door), aiming at the elimination of physical bottlenecks (e.g. testing the width of some exit). *Network* models address the same issues, but through a different approach. Although the behaviour of the crowd is modelled in a bottom-up fashion, space is represented by a set of nodes and arcs connecting them, building thus a network of possible routes. In this way, the agents who colonise a specific node can travel on interconnected neighbouring nodes, based on the weights of the relation modelled within each arc (e.g. Galea et al., 1996). The environmental parameters affect the individuals through the alterations on the weighting factors characterising a connection between nodes, while each node has the capacity of hosting several passengers (ibid.).

In the present paper, the *agent-based modelling* is proposed in order to model the collective behaviour of escape crowds. As it will be shown, this approach is more appropriate, from the previous ones, to model a number of psychological crowd effects on individual psychomotor behaviour, which in turn influence crowd behaviour.

2 Properties of Escaping Crowds

People constituting a crowd are, by nature, different. Indeed, demographics (i.e. age, gender, etc.), anthropometrics (i.e. height, weight, etc.), ethnographics (i.e. race, nationality, social class, etc.) are some of the properties that render a crowd a greatly heterogeneous entity. Under a bottom-up approach, the behaviour of a crowd is defined as a collection of consecutive states, for each individual in it, and collectively for the whole. If we define as S_t the state of an individual in a crowd at time t (i.e. the position in space and her/his psychomotor state at time t), the question to be answered by a model of crowd behaviour is which will be her/his state S_{t+1} at *t+1* and how this new state of the particular individual will affect the collective?

According to crowd and social psychology, collective performance is dependent on both the physical and the psychological interactions of a wide set of individuals, in time and space (e.g. Le Bon, 1971). Physically, individuals within a crowd are constrained by each other and by their environment. These interactions are shaped by the geometry of the enclosures, delimited by walls, rails, barriers, debris etc., as well as by external perturbations (e.g. a propagating fire). At a psychological level, individuals in escape crowds go through sentiments such as panic, fear and impatience. Such issues are traditionally dealt by the crowd and social psychology literature (e.g. ibid; Moscovici, 1981; Brown, 1985), in order to describe how these emotional states influence the individual behaviour in the crowd, and vice versa.

2.1 The Influence of the Crowd on the Individual

An individual in a crowd is subject to a form of self-reference, where s/he simultaneously acts on it, as one of its constituents, and gets influenced by it, as the crowd possesses some properties that have an influence on all of its members, individually. However, the submission under a common goal (i.e. the escape to a safe place in the case of escape crowds), gives rise to mental unity among the individuals, which Le Bon (1971) characterises as the *crowd mind*. Once the crowd mind is established, several properties that the individuals possess outside the crowd are vanished, while others appear, due to the membership in it.

This process of unification in the crowd propagates among its members, and is driven through three principal mechanisms, namely anonymity, contagion and suggestibility. As a result, homogenisation is established in the behaviour of the individuals, as the intentionality of the individual vanishes in favour of the intention of the collective. In Le Bon's words (op.cit.) "the individual becomes an automaton whose will is difficult to be controlled". Furthermore, under the mechanisms of suggestibility and contagion, norms and social properties have no influence on the individual. Each person acts as a stimulus to the other (Mann, 1981) and this process is independent of the individual merits that a person might have (e.g. education). Under this effect, known as de-individualisation**,** "the savant is equalised with the imbecile" (Le Bon, op.cit.) and this process proceeds downwards (Moscovici, 1981). As a result, the individual in a crowd is often unable to carry out simple tasks that demand a certain degree of intelligence for their performance (e.g. using a fire extinguisher in a fire) while the judgement abilities are degraded.

Alongside with the strict temporal constraints, individuals show preference in short-term goals, than long-term goals (Helbing et al., 2000), which could assure better performance during the escape process (e.g. unwillingness to pass through a small fire). Finally, as a product of anonymity, the individuals are apt to actions that outside the escape crowd would be subjected to ethical restrictions (e.g. stepping over others).

2.2 Modelling Implications on Crowd Behaviour

From the above, it can be concluded that the behaviour of the individual in a crowd can be considered as reflexive, event-driven and thus context-dependent, resembling to Hollnagel's (2002) scrambled mode of control. Forward-thinking can be considered as having no significance in the formation of hers/his activity, while the behaviour of each individual can be considered as if it lacks meta-cognition. Therefore, the interactions between the individuals and with their environment can be approximated by simple rules. The collective performance of the whole can be considered as emergent, unfolding in a bottom-up fashion, through the interactions of multiple agents, as if they form a homogeneous group. Overall, rephrasing Daniellou (1996), we can argue that crowd behaviour is an original creation, under a unique set of environmental conditions. It is thus unpredictable, yet not random.

To provide an example of an agent-based model of an escaping crowd and show its merits, in the following paragraphs we describe the basic features of the model developed for the passengers of a metro on fire.

3 An Agent-Based Model of an Escaping Crowd during a Metro Fire

Due to the limited space of the paper, the model of the crowd that is formed by the passengers in a metro train on fire will be presented here, at a descriptive level. Such a descriptive modelling can lead to the formulation of the rules that drive the passengers' behaviour. Agent-based simulations can therefore be developed, using an object-oriented language (e.g. C++, C#, Java etc.) and a relative toolkit, such as RePast (cf. http://repast.sourceforge.net), SWARM (http://www.swarm.org) etc.

As already mentioned, an individual in an escape crowd is influenced by the crowd and responds reflexively to environmental stimuli. The collective behaviour therefore cannot be modelled in isolation of the contextual changes that drive individual performance. Such changes are offered for example by an evolving fire, along with the smoke it diffuses. In the following we will describe the way we modelled (i) the space occupied by the metro passengers, (ii) the passengers' motor abilities, (iii) their psychomotor behaviour, and (iv) their interactions with the environmental changes.

3.1 Modelling Space

The Cartesian space of the tunnel was modelled as a Cellular Automaton, divided in a grid of cells. Each one of these cells has the capacity of representing a special piece of infrastructure (e.g. sidewalk, train, power line etc.), having the ability to store variables such as the amount of smoke, whether it is flammable or not, whether it is on fire or not etc. Passengers, moving on this grid, are able to occupy only a specific set of cells (e.g. they can not pass through a cell that represents a piece of the concrete in the tunnel), and receive from it a specific amount of smoke that the cell holds.

3.2 Modelling Physical Abilities

Passengers are given their basic physical skills (i.e. moving speed, vision, resistance to smoke inhalation). Depending on the nature of the cell they are stepping on, their respective capabilities are altered accordingly (e.g. the speed of a passenger is decreased when s/he is stepping on a line compared to the speed when stepping on the sidewalk; the ability to run is reduced when the amount of inhaled smoke is increasing etc.). As the amount of smoke propagates in the tunnel, the amount of inhaled smoke is increasing accordingly for each passenger, as s/he interacts with the particular variable of the cell that holds the amount of smoke at that set of coordinates in the tunnel.

3.3 Modelling Passengers' Psychomotor Behaviour

For our modelling purposes, the passengers' psychomotor behaviour refers to the choice of the direction to follow on the next time step (i.e. which cell to head at, on the grid at *t+1*). Since this choice depends on non-dissociable physical and psychological influences, the notion of the *joint field of influence* was developed, as a product of the synthesis of two interacting, dynamically evolving fields: (i) the *field of comfort*, delimited by the space within which every person can move, without the interference of any obstacle (see Figure 1), and (ii) the *field of influence*, delimited by the space where an individual can receive the influence of some other entity (i.e. another individual or a group of people, united under the *crowd mind*).

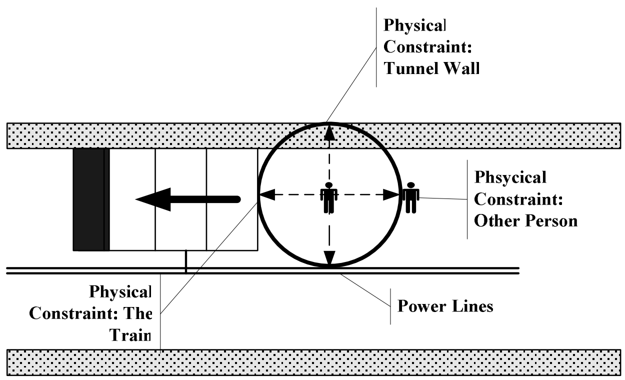

Figure 1: The Field of Comfort for a Passenger Evacuating a Train in a Tunnel

The latter field, models the property of attraction between the individuals (or groups of them) who form a crowd. Literally, each individual exercise a certain influence to the others; however only the passive part of it is of practical use for us. In space, this field is represented by a set of cells, where each of them holds a variable -measure of the intensity of the influence- which is immediately perceived by the individual that steps on it. The range of influence is calculated for each passenger separately, depending on hers/his physical properties (e.g. vision, which is constrained by the presence of smoke, etc.).

Consequently, the passengers' psychomotor behaviour was considered as driven by the joint field of influence, which like a magnetic field attracts positively or negatively the individuals, forcing them into different directions, at each point in space and time. As the individuals move, the values of the joint field of influence, at every point in time and space, co-evolve along with the environment (i.e. smoke and fire).

As it can be seen in Figure 2, if a passenger's field of comfort is independent of the field of influence of some other, then no interaction will take place, physical or psychological. If they are overlapped however, like in the case of A and B, then these two persons will move towards each other. Whether A will move towards B or vice versa, depends to the intensity of the fields of influence (i.e. the more the passengers, the more the intense the influence that the group they form exports), or whether A or B possesses the *charisma* of a leading personality, often encountered in crowds.

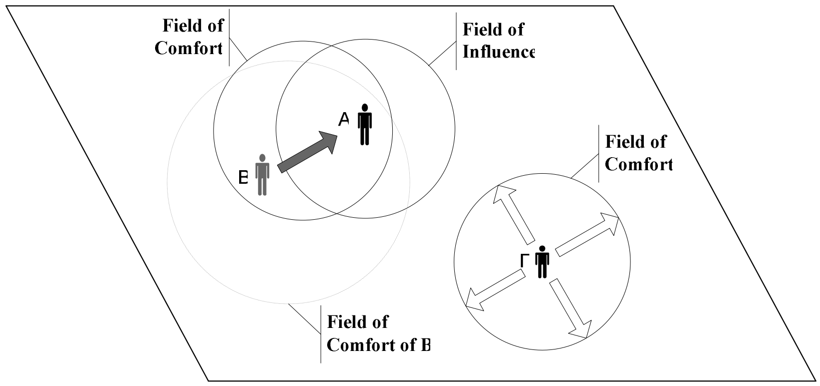

Figure 2: The Joint Field of Influence

3.4 Modelling Environmental Changes

The environmental changes interfere with the crowd's behaviour and alter the balance between physical and psychological influence. The degree up to which this happens depends on the nature of the hazard. For example, in the case of a metro fire, it can be considered that the passengers will avoid its source at all times; furthermore, there will be preference for cells with less smoke, but only over a given threshold of inhaled smoke. In the general case however, a formula about the prioritisation between crowd-specific rules and event-specific rules, has to be defined for the rule-based model of passenger behaviour.

4 Epilogue

A previous simplified version of the crowd behaviour model described above has been used in an agent-based simulation of an evacuation process in a metro railway system in Athens, Greece (Zarboutis & Marmaras, 2002, 2004). The metro on fire was modelled as a Complex Adaptive System, comprising four interacting and co-evolving subsystems: (i) the fire and the released smoke, (ii) the passengers, (iii) the technological system, and (iv) the metro personnel. Leaving many variables open concerning the passengers (e.g. number of passengers, demographic characteristics), the personnel (e.g. time to activate ventilation, ventilation mode) and the environment (e.g. diffusion rate of smoke, fire propagation rate), the simulation provides an appropriate cognitive tool supporting the search for the design of efficient rescue plans or personnel's interventions. More specifically, it provides a dynamic representation of the designer's problem space, enabling him (i) to apprehend the critical dependencies and invariants of the system under consideration, (ii) to conceive the features that should characterise the designed plans for emergency rescue, and (iii) to assess their efficiency.

Agent-based modelling of crowd behaviour during emergency evacuations seems to provide a promising tool for the design of efficient interventions in safety critical situations, especially in cases of large enclosures, such as long tunnels or stadiums, where the crowd mind is responsible to a large extent for the psychomotor behaviour of individuals. However, the domains and the cases of application should be multiplied in order to improve both the models and the techniques of their implementation /simulation.

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