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Emergency Management Respecting System's Complexity: The Case of Fire in a Metro Railway System

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ABSTRACT
The present paper describes the approach adopted for the re-design of an Emergency Rescue Plan (ERP) for a Metro Railway System. Beginning by discussing the limitations of traditional ERPs and commenting on the factors that lead to a misapprehension of system's complexity, we proceed with a theoretical consideration of those elements of complexity science that was the basis of our approach. Finally, we present an example demonstrating the way that the developed model and simulation can be used to conceive and evaluate alternative ERPs.

Keywords
Metro Systems, Emergency Rescue Plans, Bottom-Up Modelling, Complex Adaptive Systems, Agent-based simulation

INTRODUCTION

The problem of fire in a metro railway tunnel is probably the worst scenario that might take place in a metro system. The released thermal energy of the fire and the toxic smoke pose serious threats to the lives of the passengers (Gann *et al*., 1994). Thus, in critical situations like this, the train will have to be evacuated, as soon as possible. An effective Emergency Rescue Plan (ERP) should facilitate the evacuation of the train, and enable the cooperation and coordination among the human agents involved.

Traditional ERPs: Complicated sketches of normative actions

Traditional ERPs aim at providing guidance to all human agents involved in the confrontation of the incident, in terms of providing a set of requisite actions that must be performed. They have the form of a "rulebook" containing written procedures, and describing conditions that need to be met and remedies for the situation described (Kotsiopoulos, 1999). Each procedure is a solution to a predefined scenario (e.g. if a train is derailed, agent *A* should do actions *A1, A2* and *A3*, agent *B* should do actions *B1, B2*, etc.) unfolded both in time and space (e.g. the driver is in the train, while the traffic regulator is in the control room; the driver should first contact the traffic regulator and then the passengers). This leads to a set of prescriptions, interconnected in time and space, forming a complicated sketch of normative actions, providing the human agents with the "one best way" to act.

The problem: Misapprehension of Complexity

Up to date experience, stemming from field surveys and literature review indicates a number of strong limitations, which render the application of traditional ERPs at least problematic. There are situations, especially in minor frequent incidents, where these plans do work adequately. Not always however, are they able to provide the adequate solution for an emergency (especially in infrequent events, like the fire in the metro), with negative up to catastrophic effects on the system's safety (Rasmussen, 1997). These limitations have their origins on the misapprehension of system's complexity along with multiple side effects, stemming from corporate policies, organizational philosophies and ambiguous beliefs in system design. Consequently, traditional ERPs do not always meet their scope because of the following reasons:

- A common fallacy, which has an impact on such designs, is the belief of predictability of system's dynamics. Traditional ERPs are built on the assumption that the system evolves on a predictable manner. This is not the case in a complex system, where the system evolves in a non-deterministic and thus non-predictable manner. As a consequence, traditional designs pay limited consideration of the generating mechanisms of system's complexity. As we shall see in the next section, system's behaviour is characterised by the mechanisms of emergence and self-organisation. Thus, during the evolution of an incident, novel situations might arise, which macroscopically seem unpredictable, while they are just the product of the interaction of the system with its environment. Not considering these mechanisms leads to oversimplifications, regarding the human agents' behaviour. This leads though to the depreciation of the ecological character of the system. Humans are considered as passive receptors of actions carried out by the metro personnel. However, passengers should not be considered external to the system and are active part of it. They act on it, affect and get affected by it (i.e. if the fire is such that the way towards the nearest station is considered inappropriate, passengers will move towards the other direction, jeopardising the efficiency of the ventilation system, which normally should be set, sending the smoke towards that direction!).

- A normative and centralized plan, can probably work adequately in a lot of situations. However, when the situation is critical and the amount of information to be managed is large and constantly changing, the centre can be overloaded and lead to sub-optimal decisions. Furthermore, if the centre fails the whole system fails, leading to catastrophic results. On the contrary, there is evidence that a complex system can be managed more effectively in a decentralised manner (i.e. agents have a higher degree of autonomy), which is compliant with the way that behaviour is created. (Chisholm, 1992; Resnick, 1994).
- Contradictory design perspectives. In a complex system, a minor event may have large-scale effects. Therefore, designing for every possible anticipated scenario, increases the problem space and thus the set of required prescriptions. Inevitably, in traditional designs, when trying to deal with this, contradictions (and often overlaps) intrude within the design and they are usually revealed in the actual situation (either directly or as latent failures).

For the reasons mentioned above, it is likely that the prescribed system, will not effectively cope with the dynamics of its environment. Therefore, a different approach is required, which would be more efficient in providing the human agents with the means to cope with the system's complexity.

The alternative: Design for Adaptation

Design for adaptation has been proposed during the recent years (e.g. Rasmussen, 1997, 2000; Rasmussen *et al*., 1994; Vicente, 1999; Woods, 1999) and involves the exploitation of human adaptation, by making visible to the humans the constraints and affordances of the work system, instead of providing them "the one best way of acting". Or as it has been repeatedly proposed, "let workers finish up the design" (Vicente, 1999).

By exploiting human adaptation, we are getting away from the single path towards the solution, moving to a wider set of solutions, which are created, chosen and applied by the agents ad hoc. In this way, the ERP will not be static, but instead will behave dynamically, changing its internal configuration according to the changes posed by the environment. In other words, it will also evolve according to the evolution of the system, giving thus the opportunity to the agents of the system to effectively fill the time and space gaps that were not anticipated by the designers (Rasmussen, 2000).

Adopting this approach, the designer has to answer questions such as:

- which are the gaps that must be filled and which must be left free to be filled by the human agents?
- which is the optimum width for each gap to be filled by the human agents?
- how can we evaluate the effectiveness and efficiency of the alternative design solutions?

To answer such questions, appropriate analysis and modelling of the system are required. In the present study, the complexity paradigm and related formalisms have been adopted for modelling the metro system. As it will be shown, this paradigm allows the development of a computational model useful for both the search of effective alternative ERPs respecting system's complexity, as well as the evaluation of alternative design solutions.

THE COMPLEXITY PARADIGM

It is has been formulated from the time of Aristotle (384–322 B.C.), that in nature "the sum is less that the whole". By this phrase Aristotle attempted to explain the way that the world functions, using the notion of purposeful objects acting as wholes, as opposed to the other dominating view of Democritus (470-400 B.C.), according to which the world is built by atoms and voids around them. These two contradictory views of the world, gave rise to the two dominating methods in modern science, that is, holism and reductionism, respectively (e.g. Checkland, 1984).

Holism, enriched by metaphors from biology and ecology, led to the development of systemic thinking and later on the development of the so-called science of complexity. According to this, the world is built from wholes (i.e. systems), which interact with their environment, aiming at the survivor of their individual parts (i.e. agents). Evolution is driven by the change of their structure, that is, by adapting to the changes posed to them (e.g. Holland, 1992). Thus, the central notion in generated complexity is the modification of the structure and not of the content of the system.

COMPLEX ADAPTIVE SYSTEMS

The study of complex adaptive systems (CAS) has been recently granted with much attention. Based on the notion of complexity and having roots in many disciplines (e.g., biology, non-linear systems, artificial intelligence), CAS theory offers a formal way to describe the behaviour of a complex system, within a dynamic environment (Holland, 1992; Bernon *et al*., 2001; Railsback, 2001). Its focus is on the interplay between the system and its environment as well as in the co-evolution of both the system and the environment (Choi *et al*., 2001).

Evolution in a CAS

Evolution in a CAS can be described by a set of three interacting elements, namely the system's internal mechanisms, the environment and the co-evolution (Kauffman, 1996; Choi *et al.*, 2001). The internal mechanisms describe the structure of the system in terms of agents that colonize the system, its dimensionality (i.e., the degree of autonomous behaviour), their interactions and the way that collective behaviour is unfolded and shaped (i.e., emergence and control). The environment is considered external to CAS. It is held responsible for providing the changes upon which the system has to adapt, in order to survive in the dynamic and unpredictable environment. Finally, the way that the system evolves over time is described by the notion of co-evolution. According to this, the system reacts to environmental changes by altering its borders (i.e., adding or removing interactions among agents, excluding or including agents). Thus the system is both reacting and creating its environment. The latter provides the stimuli to the system at its border and the CAS in turn, reacts to these changes by altering its internal structure (i.e., adapting to the environmental changes). In this way system and environment co-evolve in a non-random way.

Emergence & Self-Organisation

The system comprises many independent interacting agents, who perform partial actions, with respect to the common goal of the system (Bernon *et al.*, 2001). These interactions, which might take place in various levels of organisation in the structure of the system, may be either direct or indirect (Bonabeau *et al.*, 1997). In the former case, agents interact through the exchange of information and/or materials and/or energy. In this way, they alter their individual behaviours and systemic behaviour is altered accordingly. The indirect interactions of the agents take place through the modification of their immediate environment, affecting thus implicitly their relative movements in the problem space, which they seek to adapt.

Hierarchical Control

Complex adaptive systems are hierarchical, comprising multiple levels of organisation, on which the behaviour of the system emerges. System behaviour thus, is unfolded bottom-up and simultaneously is constrained top-down. This means that individual agents interact with each other at the basic level. The product of their interactions is evident at an upper level –the level of emergence. The emergent properties have to be meaningful at that level and this is assured by the imposition of constraints top-down, at the interactions at the lower level (e.g. Checkland, 1984).

Modelling Issues: Filling the gaps

One of the basic characteristics of Complex Adaptive Systems is that there is not any known algorithmic solution describing their evolution (Bernon *et al.*, 2001). This is in compliance with the inexistence of the "one best way" described earlier. The system is non-deterministic and thus the search for generic macroscopic laws describing its behaviour is impossible. This means that pure reductionistic top-down approaches are insufficient of representing its behaviour. In the words of Simon (1996) "the re-assembly of the individual parts does not produce the system, nor is it able to explain its behaviour".

To gain a full image of systemic behaviour, we need analysis in both directions, top-down and bottom-up. Top-down analysis can give us data that match the representation of the interactions of the system. They have to be supplemented though, by bottom-up observations, leading to data that determine the emergent behaviour of the system and its adaptation to the dynamic changes of its environment (Naveh, 2001). In other words, to adequately analyse the collective behaviour of a complex system, we have to place the observer, both inside and outside the system, aiming at the identification on both the elements that generate complexity (top-down) and on the mechanisms that determine the way that this complexity unfolds (bottom-up) in the various levels of emergence.

STUDYING A COMPLEX ADAPTIVE SYSTEM

Studying a complex adaptive system is an iterative process that involves analysis (top-down and bottom-up), modelling and simulation of the system. Especially the latter (i.e. simulation) and more specifically agent-based simulation, is the primary tool for the analysis of a complex system, as it is the only probable method for representing and studying the system bottom-up. By representing the system in that fashion, we aim at gaining insight at those properties that are not evident in the top-down analysis but determine its behaviour (e.g. Axelrod, 1997; Railsback, 2001).

Simulation of the CAS

In such models, agents can modify their behaviours, adapt to the environment and act on it. The environment changes accordingly and creates the stimuli that are posed to the agents. Agents have an individual identity, autonomous behaviour and are considered as part of an ecology in which they belong, act and react. In each iteration of the simulation, agents' actions are determined ad hoc, based on the temporal and spatial dynamics of the model, as they have been formed in the previous iteration. Thus, based on the built-in rules that describe their interactions, agents plan their next moves.

Analysis and Experimentation

The execution of the model provides us with a tool for experimentation, through the analysis of the simulated data. By performing an inductive analysis (i.e. looking for patterns in the simulated data) we can enrich our understanding of the fundamental processes that create the behaviour of the system (Axelrod, 1997; Railsback, 2001). Running the model under different work settings, we are able to test and experiment with the specific properties of the element that we want to intervene (like the dimensionality of its agents, as we shall see later), testing thus the intervention's efficiency in coping with the different work settings posed to the system.

METRO AS COMPLEX ADAPTIVE SYSTEM (mCAS)

In this section we present the way we went about to model and simulate the metro – when on fire - as a complex adaptive system.

The Metro System was modeled as consisting of three interacting elements, namely:

- The Railway System (RS). The RS consists of the infrastructure (e.g. tunnels, lines, stations, the control room, etc.), the rolling stock (i.e. the trains), artefacts (telecommunication system, power system, signalling system, automatic train protection, etc.), the metro personnel (i.e. controllers, regulators, administrators) and the external services involved in the incident (fire brigade, paramedics, police etc.).
- The Group of Passengers (GoP). As members of that group are considered all the individuals that will be present in the area of the incident and do not belong in the previous system. They are untrained and constitute the target group of all the evacuation efforts.
- The Fire (Fi). The fire is the event that renders the situation critical. It propagates dynamically and affects both the RS and the GoP. It has specific properties that describe its dynamics, like the thermal energy released, the concentration of smoke mounted in the tunnel, the thermal conductivity, etc. (Cheng *et al*., 2001; Xue *et al.*, 2001).

Features of the simulated model

The simulated model of the evacuation of a metro train on fire, was developed in a simple agent-based simulation tool, NetLogo 1.0. The problem space was divided in a grid of "patches", each representing the spatial unit in the tunnel, having the size of an average person. The modelled parameters are of two types, namely:

- Parameters describing the conditions of the environment. Each patch was modelled as being colonised or not, being on fire or not, having a quantity of smoke mounted, being occupied or not, belonging in one of the RS's elements (e.g. a patch may belong to the train, the lanes, the sidewalks), etc.
- Parameters describing the behaviour of the human agents. Two classes of human agents with specific properties were created, namely, the passengers and the metro personnel (with the provision to include the firemen and the paramedics). These properties have the form of rules and determine the way that agents act, the way they interact with each other, and the way that they solve possible conflicts ad hoc, during the execution of the simulation.

The Metro Personnel class

The metro personnel were modelled at the level of a number of critical actions modifying properties of the environmental conditions. The critical actions modelled were derived from an existing ERP, and are the following:

- Determine the optimal evacuation direction and provide the passengers with that information.
- Open the train gates.
- Cut-off the electric power from the line.
- Set the ventilation system on to remove the smoke, and regulate its direction..

The effect of these actions to the other elements of the model is strongly dependent on the temporal point of their execution and by their temporal sequence. These two variables were left open at the simulation, in order to experiment with them.

The Passengers class

Passengers were modelled at the level of a number of properties (e.g. age, alive or dead) and abilities (e.g. walking/running speed, visibility range, resistance to smoke inhalation). In the simulated model, these abilities are represented by a set of individual parameters and by a set of simple rules, describing ways of interactions and conflict resolution.

The GoP is created by an number of individual passengers. Each passenger's behaviour depends on the combination of her/is properties and abilities (e.g. elder persons were modelled as being able to move slower than younger ones). The characteristics of the total population (i.e. total number of passengers and distribution among ages), were left open, for experimentation, giving us the option of creating different populations.

Examples of rules that generate passengers' behaviour are:

- Move only if the space around you is free, following the shortest route.
- Move towards the nearest gate. If it is closed, wait (till a given threshold of patience, if it exceeds, open manually the closest door the fire). Otherwise exit the train.
- When exit the train, head to the sidewalks and then to a station
- If you are near the fire, move to the opposite direction.
- If the atmosphere is heavy, move towards the direction less charged with smoke.
- Follow the instructions of the metro personnel, if available on time.
- Don't stay isolated from the others. If alone, head to the nearest passenger(s).

At every temporal point of the evolving situation, each individual passenger follows one or more of these rules. The rules are initially prioritised (e.g. always avoid the fire, even if you are getting away from the nearest station). However, they are not applied independently of the other elements of the whole system. Their prioritisation changes dynamically, depending on the interactions of the individual with the other system's elements and on their respective evolution at a given time.

Co-Evolution in the Metro System

At every point in time and space, each passenger is standing on a patch. Evolution is generated by the application of the rules, which dynamically lead to a possible set of passengers' actions, depending on the environmental conditions of a single patch and on the individual characteristics of the agent on it.

Therefore, each individual passenger identifies the environmental conditions of the patch s/he colonises (i.e. mounted smoke, on fire? is it on the train? etc.), assesses the distance from its target point, detects the presence or not of other agents on hers/his neighbouring patches as well as the smoke concentration. Accordingly, s/he plans a set of alternative moves (i.e. those that the rules allow her/him) and performs the optimal move based on criteria set by the rules (e.g. if on sidewalk, go towards the direction which you are told to).

Thus, at each iteration of the simulation, the collective behaviour of the passengers is continuously updated, through modifications in the structure of both the system and its immediate environment. Environmental parameters change (e.g. the fire propagates, the smoke concentration changes), the individual status of the agents change (e.g. a passenger might lose hers/his life, acting then as a physical constraint for the others), and the application of rules determines the actions of each individual accordingly. In this manner, behaviour was modelled as unfolding bottom-up, through the co-evolution of the three elements of the whole system.

Efficiency of an ERP for a Metro System

The efficiency of an ERP can be assessed by the degree of which it enables the passengers to save themselves, upon the initiation of the fire. It is measured thus, in terms of the equal number of human loses, per situation studied.

In our model, passengers were assumed to lose their lives upon the following conditions:

- Smoke inhalation above a critical - lethal - value, as a function of how long a person is exposed to the smoke and of the concentration of the smoke present (Gann *et al.*, 1994).
- Electrocution, upon touching the power lines, when charged.
- Fire Burning, upon a contact with the fire.

The side effects of the fire (e.g. injuries from falls or stepovers, heat etc.) were not considered in the actual version of the model.

AN EXAMPLE: OPENING THE TRAIN DOORS

During the design of an Emergency Rescue Plan, many decisions have to be taken, regarding the confrontation of the dynamics of the system's environment. Such decisions involve both temporal dimensions (e.g. when should the doors be opened, before or after the power is off?) and spatial dimensions (should the power always be cut-off from the control room, or is it preferable to cut it off locally from the closest station?). To demonstrate the use of the developed model of the metro system, we simulated three alternative scenarios dealing with the sequence of the actions related to the opening of the train doors, and evaluated their efficiency. The scenarios studied are:

1. The train driver opens all the doors 5 minutes after the initiation of the fire.
2. The train driver opens all the doors after the power has been cut-off, that is, 8 minutes after the initiation of the fire.
3. The train driver opens all the doors after the power is off and after the ventilation system has been set on, that is, after 13 minutes of the initiation of the fire.

The time values of these scenarios have been assessed considering the actual technical and organisational constraints of the studied metro system.

The interest of studying these scenarios lies on their contradictory perspectives, regarding the potential efficiency of the ERP, as:

- Opening the doors before the power has been cut-off, jeopardises the electrocution of passengers that step on the power lines. On the other hand, opening the doors as soon as possible, minimises the risks created by the smoke and the fire.
- Opening the doors, after having the power cut-off, minimises the risk of electrocution, but the evacuation is taking place in a more hazardous ambience, because of the smoke and fire propagation.
- Waiting for the ventilation to be set on, could possibly offer a better ambience. On the other hand, the prolonged residence of the passengers in the train, while the fire propagates, might create panic, leading to probable uncontrolled passenger behaviour.

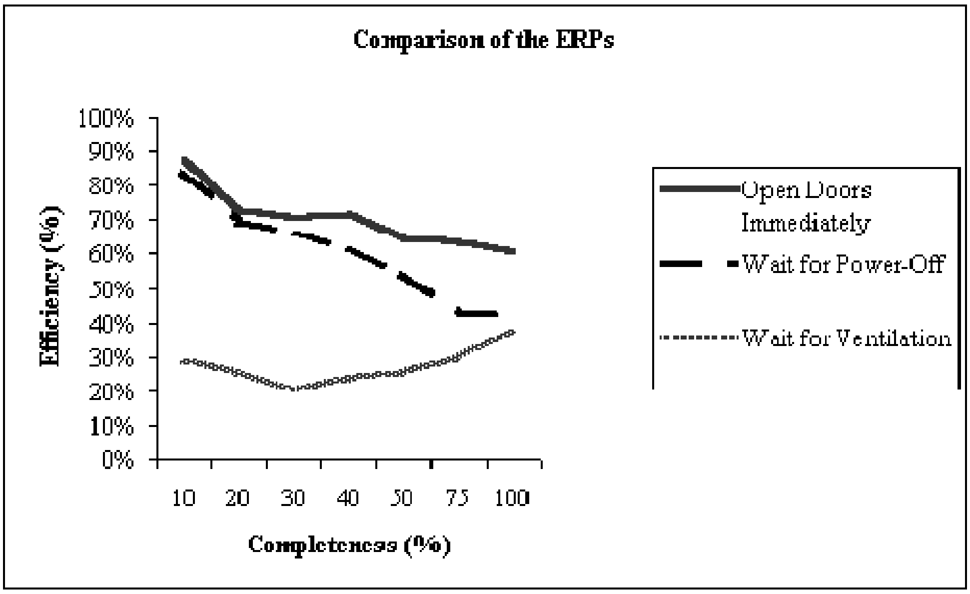

Figure 1: Comparison of three ERPs

The simulation has been run under the following assumptions:

- The train is stalled between two stations.
- The train driver is alive, opens the doors and provides instructions to the passengers regarding the evacuation direction.
- The fire is initiated at the front car.
- The passengers are assumed to be at least five minutes patient, before making use of the manual handles to open the train doors.
- The fire propagates randomly in the train.
- The smoke release rate is constant.
- The smoke is evenly diffused in the tunnel.
- The ventilation system removes the smoke on a constant velocity.

Preliminary Results

Running the simulation for the three scenarios and varying the number of passengers in the train (i.e. completeness), we get the results shown in Figure 1.
The following conclusions could be drawn, regarding the efficiency of the scenarios examined:

- Opening the doors as soon as possible is the most efficient scenario, for every degree of train's completeness.
- Waiting for the power to be cut-off from the line, did not seemed to improve the overall performance of the plan. On the contrary, the loses that were avoided due to a probable electrocution, were less than those due to the prolonged residence in the train.
- The worst scenario appears to be when the doors open after the ventilation has been set on. This could be due to the fact that the fire and the smoke tested propagate with such a velocity that the ventilation system can not create a safe ambience for the passengers, or at least safer than that in the previous scenarios (ventilation must not work with velocities greater than 11 m/sec, because that would pose serious difficulties in the movement of many passengers in the tunnel, Cheng *et al.*, 2001). Furthermore, several passengers ran out of patience and opened the doors. Therefore, they were exposed to the risks of the previous scenario.

CONCLUSIONS AND FURTHER WORK

Designing a plan for the confrontation of fire in a metro system, is a process that needs to take into consideration the dynamics not only of the environment (e.g. fire), but also of the passengers and of the personnel of the system. The co-evolution between system and environment is what determines the behaviour of the system. To capture the way that behaviour is unfolded, the complex adaptive system's formalism can be used. In this manner, the system can be modelled in a bottom-up fashion, with respect to the way that its complexity is generated and perceived by the agents of the system. Simulation of this model can act as a means for conceive and evaluate alternative ERP's designs.
Further work has been planned, in the following two directions:

- Enhancement of the simulation model.
- Development of alternative ERPs and test of their efficiency.

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