Life-Saver: Flood Emergency Simulator

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ABSTRACT

This paper proposes an agent-based simulation system for Dam Break Emergency Plan validation.

The proposed system shows that integrating GIS data with an agent-based approach provides a successful simulation platform for the emergency plan validation process. Possible strategies to emergency plan modeling and representation are discussed, proposing a close relation with the actual workflow followed by the entities responsible for the plan's specification.

The simulation model is mainly concerned with the location-based and location-motivated actions of the involved agents, describing the likely effects of a specific emergency situation response.

The simulator architecture is further described, based on the correspondence between the representation of the plan, and the simulation model. This includes the involving characteristics of the simulation, the simulation engine, the description of the resulting data (for the later evaluation of the emergency plan) and a visualization and interaction component, enabling the dynamic introduction of changes in the scenario progression.

Keywords

Crisis Response, Emergency Plan Validation, Agent-Based Simulation, GIS Integration, Human-Computer Interaction

INTRODUCTION

Project Life-Saver was created in the Portuguese context of Dam Break Emergency Management. In this country, the management of flood emergencies, directly or indirectly caused by dam break or malfunction, is planned through the guidance of specific emergency plans. These plans involve a flood wave propagation study in the downstream valley of the subject area and the development of a warning and information system prepared to face the emergency, as it progresses.

The evaluation of one specific Dam Break Emergency Plan (DBEP) requires the test of very specific natural conditions, associated with flexible access to updateable information and the control of specialized rescue teams. Such operation requires a considerable amount of resources and it is generally not possible to simulate a realistic emergency scenario through physical experimentation. To face this problem, computationally "generated" natural or induced flooding is proposed, as well as a response to the emergency, through simulation using one spatial-temporal representation.

Project Life-Saver aims to develop a system that can effectively validate existing DBEPs through agent-based simulation of all the actors intervening in the situation.

The simulator is justified by the need to concurrently study phenomena with explicit and implicit representation (e.g. flood and inter-related individuals). Agent-based simulation enables interaction and communication between several actors involved in the process. It can also represent situations where individuals have complex and differentiated behaviors, aimed at the study of global emergent consequences as a result of the interaction process (Ferber, 1995).

In Life-Saver, the simulation will be supported by all of the available spatial data from the downstream valley of the Dam. This information is generally organized in a Geographic Information System (GIS) and the simulator is automatically fed with relevant spatial information as needed.

The simulator will be able to define emergency scenarios, which will include available DBEP resources, actors and roles. System dynamics will be visualized in a graphical interface with an emergency scenario representation, while parameters that characterize this dynamics will be registered for later analysis.

Life-Saver includes the development of a prototype of the validation system, tailored to work with the Alqueva Dam Emergency Plan, which also involves another smaller dam, Pedrogão (Santos and Gamboa, 2003). The Portuguese National Civil Engineering Laboratory (LNEC), responsible for the development of the Plan, is a partner in the Project and is responsible for the creation and management of all the data used in this project.

RELATED WORK

Project Life-Saver focuses on several issues that can be systematically grouped into several related but distinct areas. The first area is concerned with modeling and representing all the information provided by the emergency plan, with the aim of simulating the emergency. The DBEP document reflects the actual organization and actions of the real actors involved in the emergency scenario. Although these depend on the reality of the dam, they must also be generalized as much as possible, aimed at an overall simulation structure, which can later be applied in different DBEPs. The second one focuses on the actions themselves. These can be independent of each other, or organized to represent a complex structure that, as a whole, will show global characteristics, emergent from existing interactions. Additionally, the structure of all the concepts involved must take into account the geographically conditioned agent-based nature of the problem. Finally, a visual interface for human-computer interaction is also taken into account.

Although there is a lack of work published on the specific problem of emergency plan simulation, several projects mainly focused on the design and need for crisis management systems, discuss issues related to one or more of the above areas.

The need for such a system is grounded on the difficulty of a DBEP evaluation through a physical drill. The setting of drills tends to be highly costly and time consuming. Also, drills lack most of the realism inherent to a natural disaster, either by greatly differing from its real dimension or by being executed in a state of readiness not compatible with some possible scenarios, adding little benefit to the validation process (Brady, 2003).

A Dam Break scenario can be the triggered by different types of incidents, either natural or human. The disaster can itself cause other specific emergencies, intimately related with its location. The response for the initial disaster situation, whichever its source might be, must take this chain of events into account (Bammidi and Moore, 1994).

The IMACSIM project is concerned with the specific problem of interacting with an ongoing simulation, and the generation of crisis simulations based on previously created scripts. IMACSIM focuses particularly on the hierarchy involved in a crisis situation, with centralized information gathering and a decision-making component (Benjamins and Rothkrantz, 2007).

A study on pandemic influenza (Jenvald *et al,* 2007) explores the necessary workflow for a crisis situation emergency plan definition. The systematic and cyclic nature of the process, the need to explore all the possible scenarios and the constant change of the scenario itself requires regular work to insure that the emergency plan is valid and up to date (Jenvald et al., 2007).

Disaster simulation, along with disaster management is greatly influenced by the geography of the scenario. GIS provides the means to analyze and process geographic data, in order to support geo-referenced simulation environments. Several projects discussed and proposed methods for GIS integration with crisis management systems, as present below.

Disaster management systems like Sahana could greatly improve in functionality and flexibility when supported by a GIS. Either by the creation and update of maps or by querying the geographic information for optimal resource

allocation, GIS can provide a different (spatial) perspective to a crisis situation, widening the possibilities for information use, thus making the system more efficient and effective (Careem, Bitner and Silva, 2007).

GIS offers the possibility to reveal patterns and relationships difficult to extract from a traditional database system. Hormdee et al., discuss GIS integration with a chemical emergency response system and Steinamn proposes a related approach for a nuclear emergency plan support system. (Hormdee, Kanarkard, Adams, Darvey and Taweepworadej, 2006; Steinman, 2002).

Gimblett (2002) describes the current status of GIS integration with Agent-Based Modeling (ABM). While the use of GIS shortens the gap between the resource management operations and the awareness of its geography, it also faces potential pitfalls. These can be related with the functionalities offered by the GIS, such as map projection system and data resolution (Steinman, 2002), but also with the inherently static nature of GIS data (Gimblett, 2002). Capturing the time-dependent nature of an evolving set of events raises the need for cooperation between the GIS and a dynamic simulation environment (either agent-based or cellular automata), to enable the update of the geographic data through the simulation of the spatial evolution of the situation (Gimblett, 2002).

Given the heterogeneous nature of the agents involved, different kinds of behaviors are expected, with different timings. It is also expected that, in most situations, agent behavior is translated into different kinds of inter-agent relationships, inherently localized by nature. A spatially explicit, individual-based modeling approach (Gimblett, 2002) is proposed as the best-suited technique for the simulation issue in a crisis situation.

A relevant aspect of an emergency plan validation system is the presence of a visual interface, to be used for information presentation and human-computer interaction (Benjamins et al, 2007).

Canos et al. (2004) discuss the increasing relevancy of such an interface, using the Valencia (Spain) subway train as a case study. The study explores several sources of information such as text, audio, video, 3D models and animations, proposing a multimedia interface for "handling emergency in the underground metropolitan transportation" (Canos, Alonso and Jaen, 2004).

DAM BREAK EMERGENCY PLAN

A DBEP is constituted by a set of actions intended for execution by the emergency response entities. These entities are previously identified during the plan's specification. This identification, along with the complete scenario characterization – its geography and demography – constitutes the first step of the plan construction process (Santos et al., 2003).

A DBEP model construction follows a specific workflow. This requires an exhaustive characterization of the scenario by the identification of the entities involved in the rescue operation. Also part of the characterization process is the accurate description of the geography of the scenario, using a GIS (Santos et al., 2003; Jenvald et al., 2007).

Additionally to the GIS data and the rescue entities characterization, the DBEP also includes a database with the description of every entity affected by the emergency situation. This database contains the probable initial location and current physical state of the population and follows a standard relational database organization (Santos et al., 2003).

From the official DBEP document for the Alqueva/Pedrogão Dams (Santos et al., 2003), the Life-Saver team point out a set of concepts and concerns relevant to DBEPs in general, which were used to model the plan in a simulation context.

As any organized operation, the emergency situation response relies on a hierarchy or chain of command. The notion of "chain of command" encompasses a centralized decision-maker entity responsible for issuing commanding actions to all the intervenient entities (Santos et al., 2003).

The individual mobility aspect was considered the main distinguishing characteristic of the entities responsible for the rescue operations. Rescue entities perform a specific set of operations when faced with a concrete situation in a nearby location but, from the plan's perspective, the use of their movement characteristics was found to be completely independent of a specific Dam's scenario. The people affected by the emergency have the expected behavior of evacuating to predetermined safe spots.

SIMULATOR ARCHITECTURE AND IMPLEMENTATION

The validity of a specific DBEP – and every emergency plan in general – is assured by its constant revision, updated data and entity training exercises. Although the complete scenario may present itself as too complex for physical drills, subsets of that scenario may be subject to localized drills.

The availability of a simulation platform for the DBEP provides the planners with a tool to gain perspective on an emergency scenario as a whole and draw conclusions about the plan, make changes, re-test and through an iterative approach, refine the plan to an accepted configuration.

Plan Representation

The plan is constituted by agents, actions and triggers.

The actions being represented are those describing movement in the scenario space. In addition, the time window for a specific rescue operation is provided in the agent's description. For plan validation purposes only actions describing changes in the agent's location are relevant, those being described by the DBEP.

The actions must follow a priority system, providing a way to represent quick response emergency tasks and routine tasks. Priority relationships enable the representation of a complex chain of actions, involving several actors, i.e. cooperation.

For every agent or agent type, the plan must contain: a description of every action and a list of possible relationships between agent and actions.

A trigger is a particular scenario configuration – an event – that is previously identified to be best responded by a specific set of actions. The conditions that describe the event and the corresponding action are provided by the DBEP.

A DBEP can be represented in various forms. The most simple and basic one is the actual source code describing the plan's contents, i.e., every agent's behavior specification.

Some other representation approaches are possible. Given the structured and hierarchical nature of its components, the DBEP can be constructed as a combination of previously determined actions, from the movement of a single agent to a complex situation requiring the movement of several types of previously determined agents. The plan is interpreted as meta-data, fed to the simulation engine, generating the scenario response.

Simulation Platform

The platform chosen to provide support for the simulation model is the Recursive Porus Agent Simulation Toolkit 3 (Repast).

Originally developed by David Sallach, Nick Collier, Tom Howe, Michael North and others at the University of Chicago, Repast is an agent-based modeling and simulation toolkit.

Repast provides an object-oriented platform for agent based simulations. In addition, it includes a fully concurrent discrete event scheduler, supporting both sequential and parallel discrete event operations.

The toolkit is completely flexible in the definition of the agent's characteristics and behaviors. Several solutions for two-dimensional agent environments and visualizations are provided. GIS support is also available. The properties of Agents and Models may be dynamically accessed and changed during execution.

Repast 3 is implemented in several programming languages, following a reference implementation of the core services in Java. Life-Saver uses the Java implementation of the toolkit. (Repast, 2007)

Simulation Environment

The simulation has two main sources of data subject to prior treatment: The geography of the scenario, generally stored in a GIS, and the DBEP.

GIS data follows one of the *de facto* standards currently in use, the ESRI Shapefile (ESRI, 1998). Life-Saver uses the ESRI ArcGIS (ESRI, 2007) suite as a GIS. Every geographic feature in the scenario is represented as a Shapefile. The scenario constituted by all these features can be schematically represented as a set of layers, with

correspondence to the same absolute geographic location and describing each one a specific feature – water, houses, roads, etc.

Although the Shapefile may be the information representation format internal to the GIS, a basic grid representation of the space is required by the simulation platform. Repast accepts raster formats as representations of space. A raster file approximates the information contained in the Shapefile by a grid of values representing some arbitrary property of the geographic space (DeMers, 2002).

One specific component of the geographic information is the flood progression. The GIS represents it as a layer, no different from other Shapefiles. As real-time wave and flood simulation are not realistic for DBEP validation (because of the computational overhead involved), data from hydraulic simulations was extracted as a discrete succession of characterized points, representing the wave or flood state in a specific geographic location at a specific time. That information is then subject to interpolation and used to approximate the real wave and flood hydraulic simulation during DBEP validation. The realism of this interpolation is directly dependent on the resolution of the discrete succession. The hydraulic data can be collected before the plan validation because emergency response cannot and does not intend to change the wave and flood progression. It is an evacuation problem, conditioned and paced by those hydraulic factors (Santos et al., 2003).

The structure of the entity database follows a predetermined schema to avoid the loss of generalization. This database is available for query during the simulation execution time.

The simulation environment is also prepared for the existence of a visualization and interaction system. This system is external to the simulation process at its core, but the possibility to control most of the parameterization, entity and partial scenario state changes, as well as the time step, is offered. This implies the existence of a generic communication layer attached to the simulation engine. A layer of web-services was designed to accomplish these tasks.

Simulation Engine

The engine is designed for the specific problem of DBEP validation and it is independent of any specific scenario. As an agent-based simulation engine, it requires the identification of the simulation space and the involved agents.

The simulation space is represented as a stack of overlaying spaces. A space is a direct representation of a layer from the GIS (Feature Space). The Feature Space represents only a specific layer.

The spaces can be one of three types: static spaces, representing static geographic features not subject to changes by the scenario progression, like the terrain; segmented spaces, representing features composed by segments subject to state changes, like roads and bridges; dynamic spaces, representing continuously changing features, like a wave or flood.

Every agent can collect information related to its position from each Feature Space. This is accomplished through a special space where the agents can move around (Agent Space) and a stack-like organization of all the other spaces. A specific position in the Agent Space corresponds to a set of values from the stacked Feature Spaces corresponding to the same position in each space. Agents either move freely or are bound to a specific Feature Space (Static, Segmented or Dynamic) and its actions must respect that constrain.

The agent types were extracted from the DBEP modeling process. The simplest plan requires at least the following three types of agents: the Walker Agent, the Driver Agent and the Commander Agent.

The Commander Agent is a location free agent. It has no spatial representation and exists outside the scenario. The Commander Agent action consists on identifying scenario events, creating actions for the other types of agent and recording the actions and states of those agents, if required.

The Walker Agent moves freely in the Agent Space. Although the values from the Feature Spaces can condition its state, they do not explicitly constrain the agent's movements.

A Driver Agent is bound to a road representation on a Feature Space – specifically, a Segmented Space – that will constrain its movements to the road extension.

Emergency response agents can be of any type. The people subject to the rescue operations are considered to be Walker Agents.

Every agent follows a set of actions. The emergency response agent's actions follow a priority system that differentiates between Simple Actions and Commander Actions. Every Commander Action has a higher priority than the Simple Actions. This enables a clear differentiation between routine operations and time-dependent rescue operations. The Commander Action may also act upon lower level actions, reorganizing the actions of an agent.

Agents and spaces are also characterized by a state property that indicates its current condition, e.g., segments in a Segmented Space may or may not be usable; Agents may or may not be considered active.

States may vary according to the scenario necessities and constrains. A full description of the possible states for every agent or space must be provided in the respective characterization.

The events occurring in the scenario can be induced by the human-computer interaction system in real time. Agent state and Space state may be available for direct change from the external interface.

An overview of the proposed architecture is shown in Figure 1.

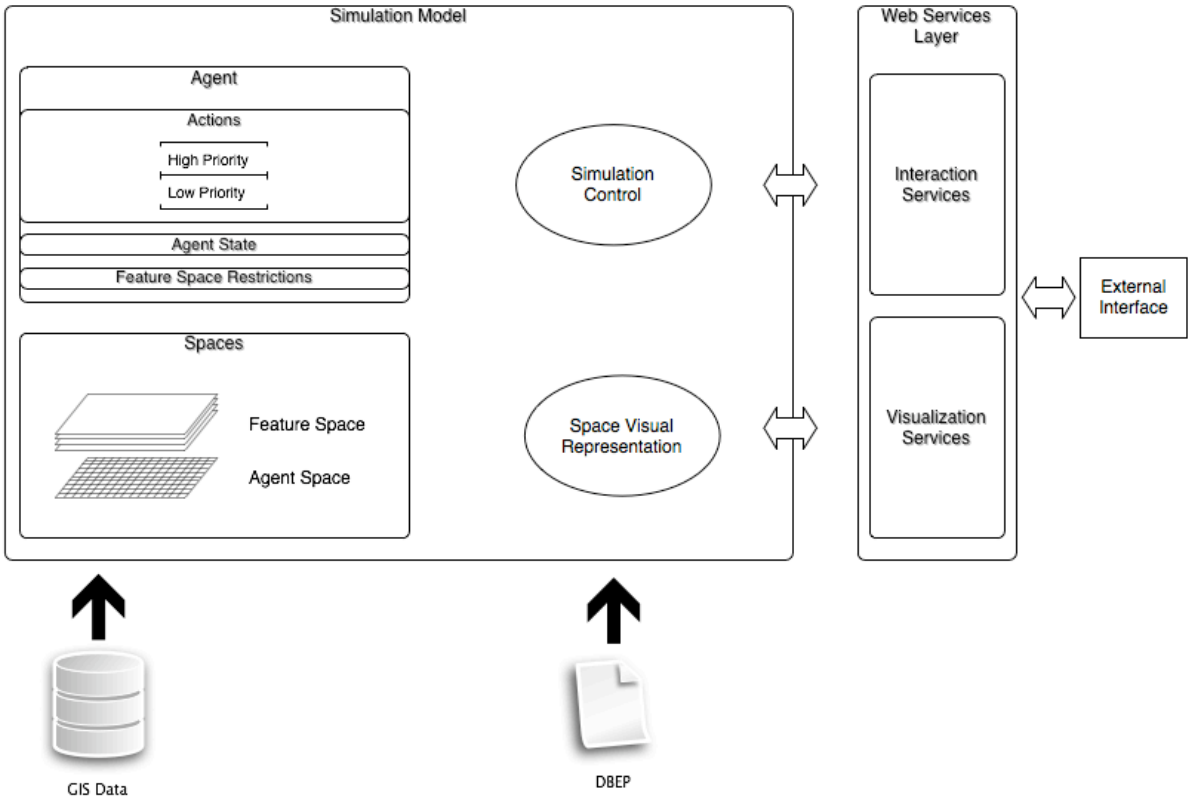

Figure 1. General Architecture

Resulting data

The DBEP validation status is measured by the analysis of a set of indexes built on the collected information.

The choice of what information is to be collected for statistical analysis is transparent to the simulation engine operation. This task will constitute the action of one Commander Agent, modeled to follow and record the actions and state of a specific group of agents as the simulation evolves.

Some indexes can be useful to be instantly available during the simulation execution. Repast provides modules that allow the plot of dynamic data, and the external interfaces should provide similar functionality.

Finally, all the statistic raw data is outputted to a predetermined location, being it a file system location or a database for further analysis.

INTERFACES

The entire dam break scenario will be visualized in a graphical and multimedia environment. The interaction and visualization of the emergency situation are very important aspects of the simulation. The interface must be an accurate tool to get detailed information and change the course of the running simulation, in order to help the decision makers understand the main events that are happening,

The interface features a full-fledged three-dimensional terrain representing the valley, the dam and the artificial lake, with all the agents deployed on the terrain. There will be visual representations of the Walker Agent and the Driver Agent. Additionally there are several layers of information that can be shown and hidden at any time. These layers include the roads, building locations, flooding areas, road blocks, bridges and any information that can be loaded from an ArcGIS shapefile. Roads are in fact representations of the Segmented Space.

The emergency visualization interface will look as close as possible to a RTS game (Real-Time Strategy game). The Computer games (McGrath, Ryan and Hill, 2005) thread of research provides good insights on ways to visually represent emergency situations and interact with them. In a RTS game the world is seen from above, the units work as agents with limited artificial intelligence and information about each unit or building can be retrieved by clicking on them. Many RTS games have sound alerts and provide several shortcuts that enable a quick response by the user to any emergency.

The physical interaction with the system is another important aspect. The menus and user interface are designed to maintain its usability with different hardware interaction devices. The main interaction interface is the Interactive White-Board (IWB), although the mouse and digitizer pen are also being studied, as well as multi-touch devices. The IWB enables an easy touch-screen interaction, while showing the results to an audience.

All these features are created in a visualization module that is completely independent from the simulation. In the future, each module can be independently modified and improved. Additionally there is a controller module that sets up and runs the simulation. All the communication between the modules is accomplished through web services. The controller starts the simulation. The positions of the agents are sent to all the visualization modules. These modules register themselves in the simulation and wait for changes.

ALQUEVA CASE STUDY

Life-Saver was initially motivated by the need to validate the DBEP proposed for the Alqueva dam, Portugal. The planning efforts are shared by LNEC – partner in this project – and the civil protection entities responsible for the dam area and potential flood areas. The Alqueva dam is placed in the Guadiana River, about 150 km north of its base level, at Vila Real de Santo António. It constitutes the largest dam and artificial lake in Europe. In a catastrophe scenario, i.e., the collapse of the dam's wall, there is a set of events which can be predicted.

The emergency scenarios, regardless of its cause, require the same basic approach from the emergency response entities. First of all, there is a formation of a wave, starting from the position of the dam. The wave is expected to reduce in strength, while it progresses through the valley, eventually becoming a flood hazard. According to studies on the wave, the civil protection infrastructure can only initiate evacuation operations after the first 30 minutes of flooding. This leaves every person placed in the territory reached by the wave before that time with the initiative of escaping to predetermined safe spots. Sirens are placed in the valley to alert the populations in the case of emergency.

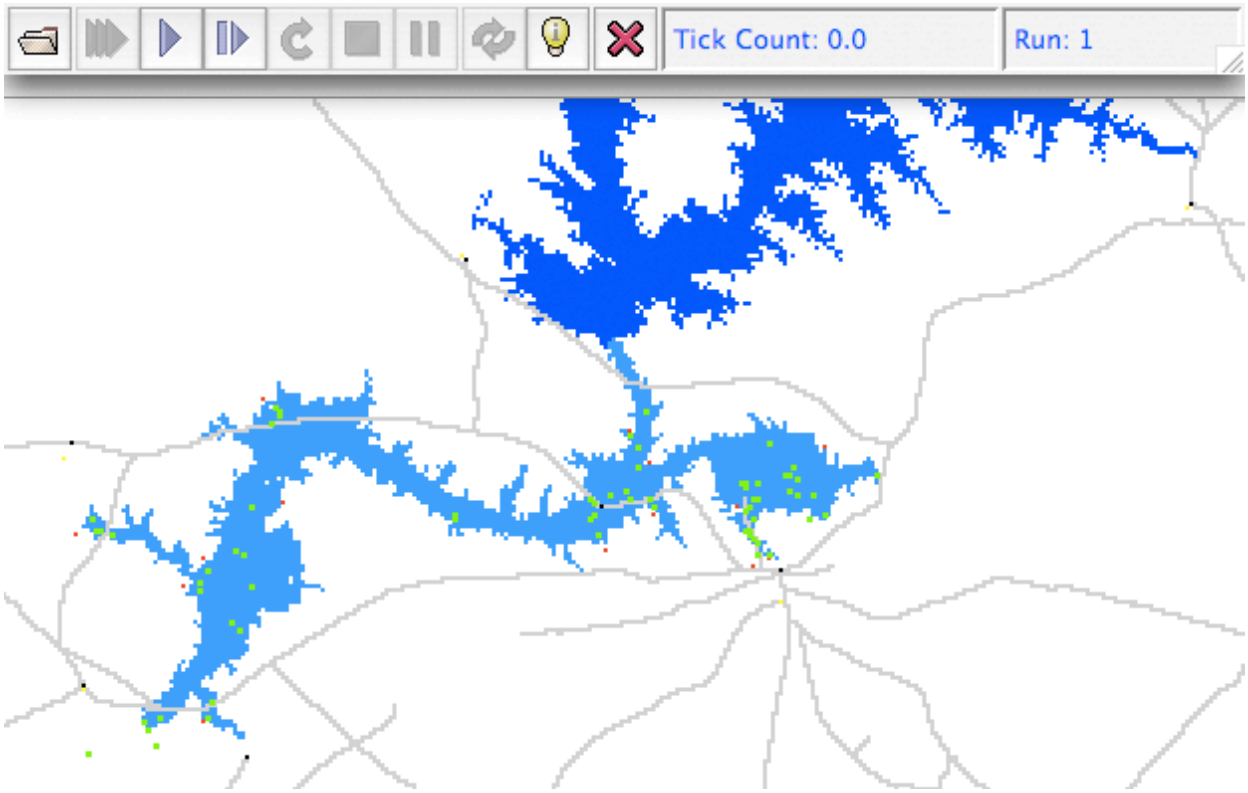

Figure 2. Repast visualization and controls.

After this first period of time, the civil protection will conduct rescue operations in order to evacuate all the potentially dangerous areas (Santos et al., 2003). Life-Saver currently uses the first stage as a test scenario. This encompasses the self-evacuation of the affected populations and the subsequent support from the civil protection. The actions expected from the rescue entities are the gathering and organization of the surviving population. This test scenario makes use of all the functionality provided by the simulation engine. People are represented by Walker Agents moving towards the safe spots and the Civil Protection entities are mainly represented by Driver Agents, moving through the passable road segments. The Commander Agent coordinates the necessary gathering operations as the scenario evolves.

Simulator tests are executed through the implementation of the case-study. The data produced by LNEC was processed as described in the Plan Representation section, using a direct source code representation of each agent's behavior, and the simulator is now capable of generating response based on several scenarios contemplated.

The GIS data was processed to extract the raster representation of each geographic feature. An ArcGis Model was constructed to automate the necessary workflow. The entity database is not complete, but the data available covers the area targeted by the selected scenario.

Repast includes a visualization module for the simulation space. Agents and spaces are represented as a two dimensional grid. Each position of the grid represents an agent or a geographic feature, and is displayed with a specific color, as shown in Figure 2. The external interface provides a realistic representation of the scenario, simulation parameterization and control operations (Figure 3).

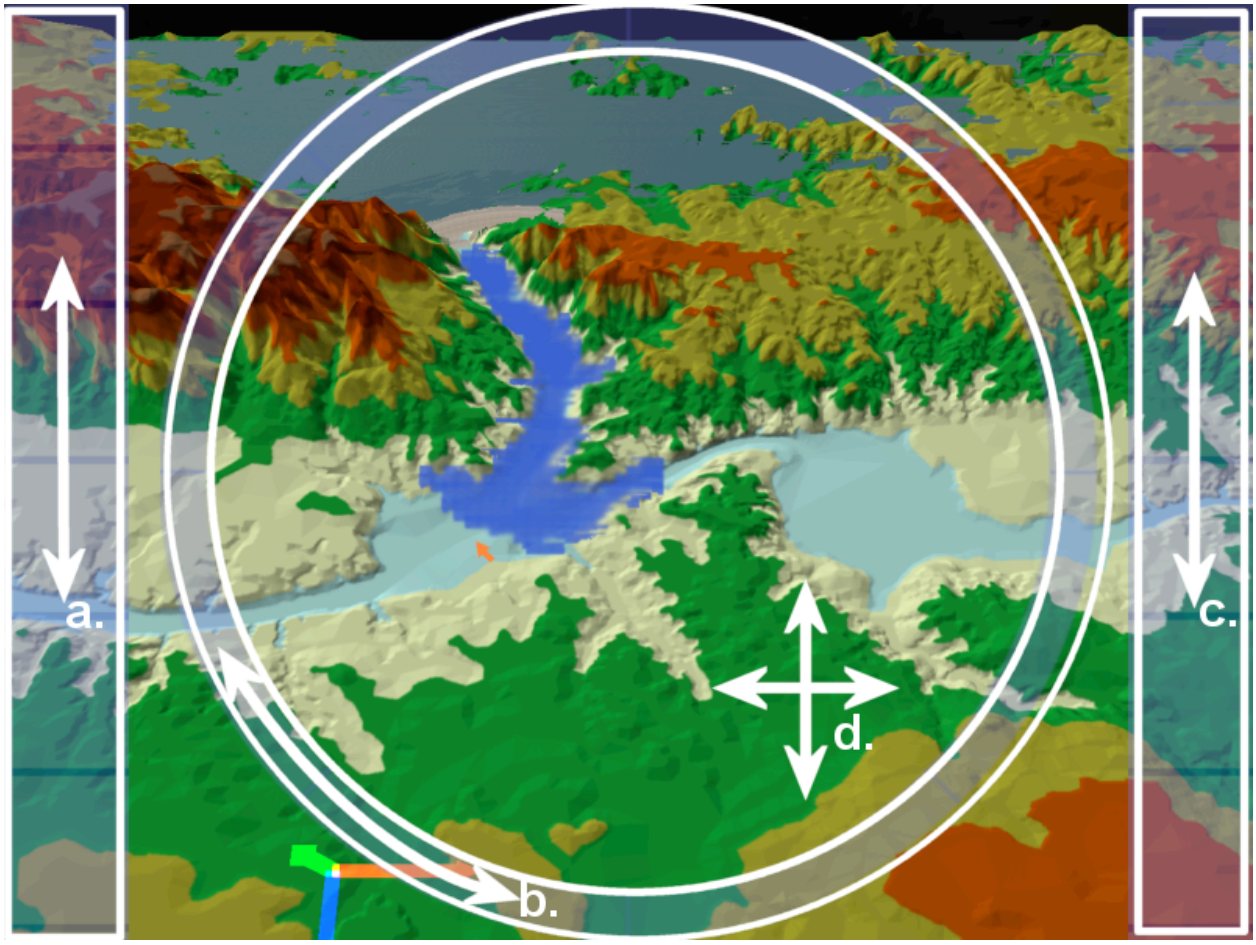

Figure 3. Visual interface: a) zooming b) rotating c) tilting d) moving.

Currently, the case study tailored simulator is under evaluation of its validation capacity by the project team, including the creators of the Alqueva DBEP at LNEC.

CONCLUSIONS AND FURTHER WORK

This paper presented an agent-based simulation system for emergency plan validation, focused on the specific problem of dam break emergency response.

The time-consuming, elevated cost and low reliability attached to the physical drill of a specific emergency plan adds little value to the validation process and calls for the need of a simulation system to perform the validation task. The emergency plan validation process is iterative by nature, requiring synergy between the modeling task and the simulation task. Changes of characteristics in a specific scenario also require the constant updateability of the respective plan. All these aspects reiterate the need for a generic and low cost simulation approach.

The authors propose an approach to the problem by modeling a simulator based on the emergency plan construction strategies followed by the responsible entities. Life-Saver simulation engine is focused on the geo-referenced actions and interactions between the different actors, i.e. all the actions performed by the agents are location-based or location motivated.

Life-Saver integrates GIS data with agent-based simulation, providing an environment for geographically explicit scenario simulation.

The proposed visualization interface adds a realistic display of the simulation progression, facilitating the interaction and the understanding of the emergency scenario.

The design of the simulation engine is aimed at a generic emergency scenario, independent of its characteristics. Generalizing a geographically bound simulation space presents a challenge for the future of the project. It is also important to increase the degree of interaction between the simulation and the external viewer, offering more control over the state of the features, widening the possibilities for different scenario evolutions.

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