Video Game-Based Platform To Improve Decision Making During Response To Large Scale Natural Disasters

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Abstract: Decision making during response to large scale disasters is always a daunting task that requires to be conducted as efficient and effective as possible in order to mitigate the social, economic, and political impacts of those disasters in our society. In this context, the presence of incomplete information, and cascading effects, i.e.; one person's decisions affecting the same person or others at a future moment, limits the performance of decision makers. This paper presents a research effort that involves the development of a video game-based online web platform for the Chilean disaster management agency, which includes wildfire and critical physical infrastructure scenarios to assess and improve trainees' decision making. The results obtained by this initiative highlight that trainees improve their decision making performance quickly using a video game based simulator; the expert has a key role in facilitating knowledge transfer using the video game-based experience; experts and trainees have signature decision making performance curves; and that the video game-based simulator is perceived by the response agency as a valid tool to support training of disaster response decision makers. The main conclusion from this research effort is that training based on serious video-games improves decision making under incomplete information and cascading effects.

Keywords: Decision Making, Emergency Management, Serious Video Game

1 INTRODUCTION

During the last decades natural disasters such as earthquakes, floods, forest fires, tsunamis and hurricanes have increased in frequency and intensity (EM-DAT, 2019; Guha-Sapir et al, 2012; Parry et al, 2007; Van Der Vink et al, 1998; Whelchel et al, 2018; Boccard, 2018), which raises the need for efficient work across all stages of an emergency management lifecycle, i.e. mitigation, preparedness, response and recovery. Large-scale disasters are complex, exhibit significant uncertainty often coupled with unpredictable outcomes (Turoff et al, 2008; Moynihan, 2008; Aldunate et al, 2005; Danielsson and Ohlsson, 1999), and usually have large social, political, and economic consequences. Globally, in recent years, large-scale disasters have taken a large toll: earthquake and tsunami in Chile in February 2010 (~ US $30MM) (EMDAT, 2019); wildfire in Chile 2017 (~US $370 MM) (de la Barrera et al, 2018); earthquake and tsunami Japan 2011 (US $ 235MM) (Kim, 2011); flooding in Thailand 2011 (~ US $ 46MM) (World Bank, 2011); Deepwater Horizon oil spill, Gulf of Mexico (~ US $ 60-100 MM) (Robertson and Krauss, 2010); between 2000 and 2012, more than 1.5 billion people have been affected and economic losses are established on the 1.3 trillion dollars, and 1.7 million deaths (UNISDR, 2013). The Impact Forecasting Database indicates that the average cost of natural disaster is $255 billion per year, based on considering 30,000 natural disaster losses from 1900-2015 (Daniell et al, 2016a; Daniell et al, 2016b). Large scale disasters frequently expose that a limiting reason for the performance of response systems is the insufficient organizational capacity and unpreparedness of proper decision-making (Kapucu and Van Wart, 2006). Decision-making is a key skill for large scale emergency response roles like disaster managers, planners, first responders, voluntary agency coordinators, and other political and technical professionals; the impact of their decisions is decisive to mitigate the consequences of those disasters. There is a pressing need for proper education and training of professionals engaged in disaster response systems. Emergency management decision-making have received significant attention from the research community throughout the years (Quarantelli, 1997; Rosenthal and Kouzmin, 1997). Among many others, two factors play a key role in the outcome of this process; uncertainty, derived from limited information about the situation (Cosgrave, 1996; Johnston et al, 1997) that may quickly lead to negative results (Maki, 2013; Quarantelli, 1997, Lipshitz and Strauss, 1997), and cascading effects, where an initial decision triggers subsequent actions with consequences of varying impact (Pescaroli and Alexander, 2015; Stallings, 2006). The complexity of emergency management decision making is increased as this process be conducted usually within a narrow timeframe and its outcomes have determinant consequences for the disaster response effort (Andrzejewska et al, 2013). In this context, where experts already have a hard time making appropriate decisions to manage the response to disasters, there are actors who are not experts, but have to participate in the process, like people from the political arena, community authorities, or disaster response personnel in their early career. Reducing the gap between experts and neophytes involved in large scale disaster decision making, in a standard and systematic manner, is key to contribute to mitigate the impact of those large scale disasters. Experts and neophytes in emergency management decision making are different not only in technical aspects, but also on non-technical skills such as ethical decision-making (Barke and Jenkins-Smith, 1993; Bostrom, 1997; Fisher and Kingma, 2001; Ford and Schmidt, 2000; Daniell et al, 2016a], including the use of non-cautious criteria which generate errors or false alarms, sometimes repeatedly (Simmons and Sutter, 2009). One of the problems faced by research aiming at improving decision making for large scale natural disasters is the environment for experimentation. Research conducted in the real world is difficult due to barriers such as time, cost, safety, and operational limits, and classroom-based instructive preparation is limited due to its lack of realism. Using video game technology to simulate environments for emergency management decision making is a rapidly evolving field (Trybus, 2015). Realistic simulations offer a safe, ethical, and cost-effective alternative to practice and developed decision-making skills in a virtual environment (Williams-Bell et al, 2015). This
article describes a research effort aimed at understanding how to improve decision making for large scale disasters, under the presence of incomplete information and cascading effects, reducing the gap between experts and neophytes using a simulator built on video-game technology. The remainder of this paper is structured as follows: Section 2 exposes the related work; Section 3 presents the video-game based online platform built for this research effort; Section 4 shows the methodology and discusses the experiments; Section 5 provides the results obtained; Section 6 discusses future work; then the conclusions are presented.

2 RELATED WORK
Simulations have been used to model complex environments in numerous domains, such as medical (Nestel et al, 2011), military (King et al, 2006), and emergency response (Jenvald and Morin, 2004). One example is the research presented in (Turoff et al, 2008) that argues that the use of simulation and virtual worlds used in gaming-based training (Reuter et al, 2009) is a feasible tool to model many features of emergency response. Also, resource allocation support is a typical problem faced by simulation-based decision making, like the work described in (Campbell and Schroder, 2009), where a simulation environment called RimSim is presented as a tool for decision support that facilitates both planning and training for different decision making roles. Research in military context (Kykesteb and Nählinder, 2011) has used micro-world simulation technology to determine whether simulation training had an effect on team decision-making in regular command-and-control exercises. Although simulations have been widely used in emergency response to facilitate training/learning activities and learning outcomes (Dobson et al, 2001; Granlund, 2001) there are limitations on using these simulations in emergency services, because of the focus on small-scale individual task training, where simulated scenarios may be oversimplified (Stolk et al, 2001). The literature also describes that several simulations widely used in emergency response management share some limitations regarding the degree of fidelity, while provide real-time environments, without immersive 3D modelling (Jenvald et al, 2001). These difficulties suggest that there is a need to explore new technologies and methodological frameworks to improve the learning and knowledge acquisition experiences of disasters and emergency situations. Particularly, the serious video-games environments, is used to simulate situations that are impossible to mimic in real-life for training and research in emergency management. Recent work demonstrate that simulation games are effective tools in the teaching of management techniques and engineering tasks, and have been widely used in experiential learning in general (Despeisse, 2018; Hidayatno et al., 2019; Vij and Sharma, 2018). The work related to video games used for emergency management is growing rapidly (Williams-Bell et al, 2015) and recent literature describes game-based virtual environments used to reinforce the learner engagement (Caroca et al, 2016). Video games are widely used by the Department of Homeland Security DHS, the Department of Defense (DoD) and other government agencies to support training, evaluation, analysis, and technology exploration. Serious games are currently used in the form of immersive simulations, live exercises, scenario based training, red teaming, and war gaming. But, their activity is hampered by the lack of a systematic approach to reliably build games. In particular, there is no simulation that specifically addresses decision making under incomplete information and cascading effects. In general, related literature does not report similar initiative to the one presented in this article; a simulator to evaluate and improve decision making under incomplete information and cascading effects.

3 VIDEO GAME-BASED ONLINE TECHNOLOGY
This section describes the main components of the video game-based platform built for this research effort. These elements correspond to the video game scenarios, a wildfire model, a dynamical system articulating system variables, user roles; where the expert/moderator is a key element for the tool; and the front-end or web interface used by trainees and experts. In the next paragraphs, these elements and the system architecture are presented. The system architecture is essentially a distributed system (see Figure 1) designed to: a) facilitate the integration and management of current and future elements of the system; b) provide a robust and usable online experience to the end users; and c) to facilitate the experimentation phase and further use by the Chilean emergency response agency in conducting training sessions with other technical and political stakeholders involved in the disaster response system. The system architecture was developed on a web-multiplayer architecture using HTML5, Ajax web services, and the video game engine Unity 3D. The wildfire model developed in this work uses a Cellular Automata (CA) as central element. Experts from the Chilean National Forest Protection Agency (CONAF) explore fire propagation dynamics that qualitatively progress in a manner that they consider realistic for every simulated scenario by manipulating parameters CA’s cell transition functions or environmental variables like temperature, humidity, and wind speed and direction.

![Figure 1. Simulation engine architecture](image-url)
To obtain a realistic and customizable wildfire model, each cell of the CA was designed having five states: non-flammable, flammable, burning, burnt, and extinguished. To compute a cell’s state we use probabilistic rules based on the state of the surrounding cells, in addition to the cell’s combustion characteristics (flammable/non-flammable) and environmental conditions such as wind direction and speed, humidity, and temperature. A cell’s transition probabilities correspond to change from flammable to burning, from burning to burnt, from burning to extinguished and from extinguished to (re) burning. This last transition is included to simulate auto ignition or re-ignition after fire was wrongly thought being extinguished. Finally, those environmental conditions and the transition probabilities are always available to experts so they could manipulate them to produce what visually was a realistic wildfire dynamics for the areas modeled, which was always achieved. More details of this system component may be found in (Aldunate and San Martin, 2018).

The dynamical system is the element of the simulator that allows to implement nonlinear dynamics and cascading effects. The variables comprising the dynamic system include wildfire combat resources, wildfire combat actions, wildfire propagation (area), coordination unit capability, environment, terrain, general impact (score) and allocation of resources / replenishment (see Figure 2). Each one of these variables is actually comprised of a set of other system variables, such as firefighter and water capacity under fire combat resources. The (optional) use of this dynamical system is defined during the configuration process of a simulation session. If the dynamical system is in operation during a simulation session, sequences of variables’ changes are recorded every time a user’s decision change one variable, and this variable generates changes in other variables. The specific values of the parameters of the dynamical system are defined by the expert for the simulation sessions and the user is not aware of them. Through these parameters, non-linear cascading effects are introduced in the system. The system also keeps log of variables changes throughout the simulation sessions and this log is available further analysis conducted by the expert with the trainees during debriefing sessions. This way the trainees may be fully aware of their actions/decisions and how them generated other actions that in turn impacted further conditions and decisions carried out by him/herself or others during the simulation session. The video game scenarios built correspond to protected areas of the V Region; Valparaiso, in Chile, in close collaboration with CONAF experts. These scenarios correspond to El Yali National Reserve, Campana National Park, Peñuelas Lake including Placilla, and Valparaiso metropolitan area including urban-rural interface. The scenarios aimed at realistic representations of the location modeled (see Figure 3), including main arboreal species, existing grasslands and water bodies. Also, the video game scenarios include different camera perspectives like a 3D first person, inside a helicopter, or fixed aerial view (orthogonal to terrain), which contributes to provide a rich experience and usability to the simulated scenarios.
Regarding user roles implemented in the simulator, this are two: the Expert and the Apprentice. The Expert/Moderator is who creates and controls the simulation scripts; initial conditions, difficulty levels, events occurrence, among others. The Trainee/Apprentice is the person being trained for decision making for complex environments. The Expert is a key player on this research; s/he not only creates the simulation scripts or sessions, but also may optionally participate during the simulation sessions and change the events of the simulation, with or without the Trainees being aware of this, to generate unpredictable events to mimic even more realistically the inhospitable and chaotic environment occurring in large scale natural disasters. By doing this, the Expert may generate or adapt simulation sessions to the skills and challenges the Trainees may poses and face; with more or less incomplete information and cascading effects. The elements that the Expert may manipulate at will during the simulation are the environmental conditions, availability conditions of resources, transport and resources supply conditions, communication problems, frequency of occurrence of types of events per scenario, e.g., start new fires or re-start one that was considered extinguished. The Expert, in his role during the execution of the simulation sessions, has full control how the simulation unfolds being able to change it completely if so s/he thinks it’s needed. The Expert may design and provide any experience to the Trainees, covering the full spectrum from linear and pre-defined to completely no-linear and random scripts. This role is what, in the modest opinion of the researchers behind this work, really constitutes one of the more valuable asset of the technology built, because it has the power to adapt the tool to the Trainee types, the scenarios, the type of emergency, and make the whole simulation experience customizable for varied learning needs.

The user interface contains elements such as Unity Web plugin, which allows immersion in the 3D modeled scenario; a Google Maps component that complements the information available to the user, e.g., location of user in geographical terms, wildfire location and progression, and movement of resources; a YouTube tool, with content managed from the script; shared documents, and chat and video conference channels, to resemble a realistic coordination and command post.

As an appendix effort to the one showed in the previous paragraphs, a system using video game technology was built for the Chilean Public Works agency (Ministerio de Obras Publicas, MOP) to improve knowledge transfer and move towards standardizing a procedure on quick and early safety and structural assessment of Critical Physical Infrastructure (CPI) affected by earthquake. This simulation presents two types of sessions: a) a session where the

Figure 3. Combat wildfire Video game scenarios built: a) El Yali National Reserve; b) Peñuelas Lake; c) La Campana National Park; and d) Greater Valparaíso.

Figure 4. Simulator User Interface (Sessions).
trainee will approach a sequence of CPI cases affected by earthquakes, previously defined by the expert, and b) a session that allows the expert to assess the trainee’s performance on assessing structural damage on the CPI cases. The assessment of structural stability of CPI affected by an earthquake is based on a traffic light model where green means safe to proceed; yellow means proceed with caution; and red means do not proceed into the CPI for search and rescue operations. This system does not approach the issues of incomplete information or cascading effects, but is a helpful effort to understand where and what type of activities of the response system may be benefited from using video game based simulation environments. The evaluation of this tool conducted by the MOP Agency is presented later in this article. Details of this part of the work may be found in (Aldunate et al, 2016).

4 EXPERIMENTS AND RESULTS
The experimentation to evaluate the impact of the systems developed included a couple of phases. First, the Apprentices used the Simulator to make decisions in sessions without incomplete information and cascading effects. Then, they were asked to participate in similar simulation sessions (VJS), but this time under the presence of Incomplete Information (II) and Cascading Effects (CE). Next, Experts who were different from the ones that created the simulation scripts, participated in the same simulation, including II and CE, that the Apprentices took. The performance of the experts for every scenario modeled was then established as baseline metrics to assess the performance of apprentices. After this, the Experts and Apprentices met to debrief the decisions made by Experts and Apprentices. Finally, after the previous debriefing activity, Apprentices took another simulation session with II and CE to test their skills and improvement.

Figure 5 presents performance curves for Apprentices making decisions with and without Incomplete Information (II) and Cascading Effects (CE) on key variables of the simulated environment.

Figure 5.- Performance curves for Trainees/Apprentices making decision with and without Incomplete Information (II) and Cascading Effects (CE) on some representative critical variables of the simulated environment.

Verbally this aspect highlighted by the Simulator was extremely valuable to become aware or increase awareness of this phenomenon, during debriefing sessions with the experts. The performance of decision making between trainees and experts was compared through performance curves that measured using a Critical Variables Factor, calculated on a 0-100 normalized scale, by aggregating the values of all the critical variables designed for the system. This value was clearly better for the experts. Figure 6 shows performance curves for some representative critical variables and they clearly depict a smoother nature for experts than for apprentices. Analyzing this evidence with experts, it was realized that changes in
decision making through the simulation sessions were mostly handled in an incremental manner by the Experts, while there are more radical changes in decisions made by Apprentices. Experts in decision making during response to disasters described that this is consistent with the fact that they are always trying to anticipate the negative consequences of their decisions, and tend to be more cautious about their decision under II and CE. Also, the experts agree on that they tend to have a global picture, a systemic view, of the disaster scenario and maintain implicit awareness of the relationship between critical variables at all times during the response to large scale disasters.

Figure 6. Performance curves from decision making between a) expert and b) apprentices, before learning/debriefing sessions. Experts curves are clearly smoother than apprentices curves. Curves for more sensitive critical variables show more radical changes, derived from late or not well conducted decisions, and more negative values for the case of apprentices. Plot in c) shows how apprentices improved when retaking simulation sessions after debriefing/learning sessions. G1: Environmental conditions; G2: Physical damage; G3: Resources; G4: Disaster impact.

After experts and apprentices met to debrief on decision making conducted under II and CE, specifically analyzing their performance curves, as shown in Figures 5 and 6, the apprentices were asked to go through other simulations sessions involving similar situations as the ones presented in the first round of experimentation. The performance curves obtained for the apprentices this time were better, as shown in Figures 5.c and 6.c, demonstrating learning from the apprentices. This learning outcome is also captured by a survey conducted with the apprentices at the end of experimentation, see Figure 7, where the benefit perceived by the apprentices regarding knowledge acquisition on issues impacting decision making during response to large scale disasters, using video game-based simulator and an enhance role of experts, is evident. Figure 7 shows the perception of awareness of knowledge increment between the apprentices that participated in the experimentation (SVG-Serious Video Games) v/s apprentices that were part of a control group (No-SVG).
Finally, a qualitative evaluation of the simulators built for this research effort was conducted by subject matter experts from the Chilean agencies involved in response to large scale natural disasters; ONEMI, CONAF, and MOP. The survey questions belonged to four main categories under which they were grouped: functionality; usability; quality; and performance. Every question was graded using a 1-5 scale, where every represented the following: 1-very negative; 2-negative; 3-regulate; 4-positive; 5-very positive. Then, the group category was obtained by averaging the questions in each category.

**Figure 7.** Apprentices perception of knowledge acquisition with and without video game-based Simulator.

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<tr>
<th>Nº</th>
<th>Question</th>
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<tr>
<td>3</td>
<td>How aware are you about how incomplete information may effect emergency management?</td>
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<tr>
<td>6</td>
<td>How aware are you about how cascading effects may impact emergency management?</td>
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<tr>
<td>7</td>
<td>How aware are you regarding strengthening decision making conducted under incomplete information situations?</td>
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<td>8</td>
<td>How aware are you about how incomplete information may effect emergency management?</td>
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<tr>
<td>9</td>
<td>How aware are you about specific actions that the emergency coordinator can perform to coordinate appropriately the response?</td>
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<tr>
<td>14</td>
<td>How aware are you about the roles that have to: a) leads situational assessment, b) scaling request for help, and c) resources allocations?</td>
</tr>
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**Figure 8.- Evaluation of video game-based technology developed in this research effort.** CONAF and ONEMI experts evaluated the Simulator for Decision Making under Incomplete Information and cascading Effects, while MOP experts evaluated the Simulator to Quickly and Safely Assess Structural Stability of Critical Physical Infrastructure.
It can be appreciated in Figure 8 that the evaluation from the Chilean agencies mainly involved in response to disasters was very positive. This positive evaluation not only validates the approach of using video game technology to build an immersive virtual laboratory to develop standard skills for response to large scale natural disasters, but also presents a venue to improve response protocols in general and explore what-if organizational, operational, and coordination and communication strategies.

5 FUTURE WORK

Further research includes the development and understanding of the impact of elements such as mobile and replay capabilities. It is expected that a mobile extension would allow to explore learning strategies to improve decision making, while that a replay capability means that the entire apprentice’s session could be used for pedagogical debrief between the expert and the trainee, as well for other audiences. The latter would not only provide awareness of what the apprentice is doing right and wrong, but also how is that s/he is doing so. During the development of this work it became clear to the researchers that in order to work towards a public policy involving video game-based technology some standardized characteristics should be pursued, such as the development of a valid scenario profile editor with a comprehensive disaster library, involving community members. There are many other factors involved in decision making during response to disasters that could benefit from an video game-based immersive laboratory. For example, memorization (information management), context change (ability to change tasks operating in stressful disaster situations), performance (according to roles), adaptation under uncertainty (reactions and responses of staff to specific complex situations, crisis and depression), common ground and adherence to protocols, coordination, among others. Finally, further work may also include studies and research to expand this research effort to other areas; other types of disasters, such as floods, tsunamis, or mining operations. This will allow to work towards increased awareness and development of skills to fight different types of disasters.

6 CONCLUSIONS

This paper presents a research effort to understand and improve decision making during large-scale natural disasters, especially when the natural disaster generates an environment is complex/dynamic, inhospitable, chaotic, with significant incomplete information and non-linear consequences of decisions and actions. In particular, in this work it has been explored how video game technology may effective and efficiently improve decision making of participants that are not experts in the field. In this context, effective decision-making is possible when participants receive timely and accurate information thoroughly analyzed and properly exposed to them by experts. In this context, the decision making simulator presented in this article plays a key role to facilitate the knowledge transfer and acquisition process. The main conclusion from this research effort is that training based on serious video-games improves decision making under incomplete information and cascading effects. The related literature exposes that decision making skills taught and trained with traditional classroom and drills are improved, but there are concerns regarding that retention may be poor for skills that are not applied in practice. The cognitive and technical skills exhibited by emergency response experts are much more difficult to quantify and teach through traditional methods. This gap on performance for non-expert roles (e.g., political authorities of the community) who are involved on disaster response gets even larger under the presence of incomplete information and cascading effects. This work demonstrates that a video game-based immersive simulator improves awareness of problems and potential solutions during response to disasters, and this approach is more effective than traditional methods for training on this aspects. A video game-based simulator enables the creation, customization, and reuse of disaster scenarios, as well as the ability to support multiple participants, without the economic, legal, operational, political, and technical limitations of traditional training and knowledge transfer methods. This work also shows that the role of the subject matter expert is fundamental and critical for the effectiveness of the technology developed. This is the key element that allows the development of personalized experiences for the apprentices, while tailoring the learning process to have them acquiring the necessary skills to improve their decision making during response to disasters. Ultimately, the outcome of this research effort is perceived by the government agencies involved in emergency management as an opportunity to standardize and improve the learning process of the stakeholders participating in response to disasters.

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