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Challenges in Designing Spatial Decision Support Systems for Evacuation Planning

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ABSTRACT

Nuclear emergency planning and management profoundly depend on computer-aided decision support tools that gather and analyze data on radioactive emissions, meteorology, demography, geography, etc., and provide decision support for prevention/mitigation, response, and recovery. Various technologies are amalgamated to aid this decision-making process. However, complexities arise when attempting to link two streams of technology to achieve a realistic, usable tool that emergency planners can rely on. This discussion aims to identify and analyze the challenges faced in using two technologies - simulation modeling and geographical information systems (GISs) - to design decision support tools for evacuation planning. The issues investigated arise from experience in designing the prototype decision support system CEMPS. The discussion primarily focuses on issues related to the behavioral and decision-making processes of the various players in the evacuation system, logistics, the generation of realistic scenarios for testing contingency plans, the validation of such decision support tools, and future trends in technology and the emergency planning and management process.

KEYWORDS

Evacuation, spatial decision support systems (SDSSs), modeling, simulation, geographic information systems (GISs).

INTRODUCTION

Hardly a day passes without some form of disaster or tragedy hitting the headlines. Indeed, the ever increasing role that humans play in both creation and destruction has provoked grave concern for the continued existence of the human race and the global environment. At the same time, modern science and technology have made great strides, which, in theory at least, have been accomplished for the betterment and safety of human society and the environment in which it lives. It is therefore ironic that many of these achievements are responsible for a considerable proportion of the disasters and human tragedy occurring today. Paradoxically, we often again turn to technology to find solutions to these problems or to prepare better to deal with them when they occur.

Today, nuclear emergency management depends on computer-aided emergency management systems that gather and analyze information and data on radioactive emissions, meteorology, demography, geography, etc., and provide decision support for emergency prevention, mitigation, response, and recovery (e.g., Herrnberger, 1996; Fedra and Reitsma, 1990; Belardo and Wallace, 1981). Most often these systems are designed by amalgamating various technologies that aid the decision-making process. Such technology evolves quickly, which often makes its use attractive but complex. The complexity is intensified when one attempts to link two streams of technology to achieve a realistic, usable design/system. The emergency planning process offers various opportunities for testing such a union.

This paper aims to identify and analyze the challenges faced in using two technologies - simulation modeling and geographical information systems (GISs)[1] - to design decision support tools for evacuation planning. The issues discussed arise from experience in designing the prototype Configurable Evacuation Management and Planning Simulator (CEMPS). The issues primarily focus on the behavioral and decision-making processes of the various players in the evacuation system, logistics, the generation of realistic scenarios for testing contingency plans, and the validation of such computer-based decision support tools. Future trends in technology and the evolution of emergency planning and management processes are also discussed.

INTEGRATING TECHNOLOGIES FOR SPATIAL DECISION SUPPORT

In any problem situation the decision-making process goes through stages of problem definition, identification of alternatives, analysis, and evaluation of alternatives, followed by the prescription of the best alternative. Often such problems involve descriptive information/data with a spatial/geographical dimension. The role that spatial technologies, such as GIS, play in this planning process is discussed by Batty and Densham (1996). Plunkett (1993) describes an example of how a GIS is used in the nuclear emergency preparedness and response process in southern New Jersey (U.S.). Here the GIS is used to plot the radioactive plume dispersion, and users can interact with the GIS to obtain further analysis of the crisis. Spatial technologies are thus widely used in all stages of the emergency management process today.

Conceptually, a spatial decision support system (SDSS) involves linking GIS and analytical/decision models to produce systems especially able to cope with spatial problems. It is designed to aid in the exploration, structuring, and solution of complex spatial problems such as the evacuation process. The aim is to support decision making by employing quantitative approaches with the use of geographic information that is stored in a manipulable form within the GIS. A primary advantage is the consequent ability to display the critical information related to an incident on maps/satellite images/digital terrains in relation to time in emergency response software using spatial technologies (Mondschein, 1994).

A typical SDSS has four components: *analytical tools* enabling data investigation; *decision models* enabling "what-if"/scenario investigations; a *geographic/spatial database*; and a *user interface* providing easy access to decision models, databases, analytical tools, and an attractive and comprehensive display of the output (Densham, 1991). When problems are well-structured and relatively static (e.g., resource allocation), mathematical programing methods can be built into the SDSS. For dynamic situations, such as evacuation, simulation is a popularly used modeling tool (see Fedra and Reitsma, 1990; Zhang and Grant, 1993).

Banz and Newkirk (no date, pp. 22-24) discuss at length the roles of computer simulation in the emergency planning process. In most situations, the greater part of the evacuation process involves vehicles/evacuees traveling along existing roads and would probably be controlled by the local emergency management personnel and/or the police/armed forces. Simulation offers an efficient way of modeling evacuations because it allows the modeler to build-in what is likely to be realistic behavior as opposed to making concessionary assumptions for the sake of easy computation - necessary when using many analytical models. It is crucial to ensure that evacuation plans are based on realistic assumptions.

Evacuation also relies on elements that are geographically referenced on the earth's surface. For instance, evacuees would commence their evacuation from the point (e.g., home, workplace) where they received the warning to evacuate. This is a unique spatial co-ordinate on the earth's surface. As evacuees travel on their evacuation journey they can be tracked continuously using their current spatial location co-ordinate. This information is a powerful asset in observing evacuation behavior, such as route choice of individual evacuees. This asset of spatial referencing data can be made easily accessible via a GIS. Riddle et al. (no date), for example, illustrate a hazardous material evacuation system designed within a GIS that allows the retrieval of information pertaining to a geographic area affected by a hazardous material release that can be used by planners in the management of emergency evacuations.

Batty (1994) discusses the possible contribution GIS can make to visual simulation. He identifies two extremes: one in which the various components of the GIS can be drawn into the modeling process and another in which modeling can take place within the GIS. A combination of the two is often used in the design of an SDSS, where, by using the analytical tools within the GIS, some sort of analytical modeling of the data takes place, while tailor-made decision models within the SDSS are likely to draw on the display and data analysis facilities of the GIS.

A PROTOTYPE SDSS FOR EVACUATION PLANNING

The powerful attributes of both simulation modeling and GIS have been harnessed in the design of the prototype SDSS CEMPS (Configurable Evacuation Management and Planning Simulator). The aim was to produce an interactive planning tool to produce simple scenarios wherein emergency planners are able to watch a simulation proceed and provide limited interaction to obtain information on the progress of the evacuation. CEMPS integrates a tailor-made, dynamic, interactive evacuation simulation model with a GIS to produce a system that is both detailed and general enough to be configured as appropriate. Decision modeling tools have also been included using the impressive built-in capabilities of the GIS system ARC/INFO. The role of the GIS here is to define the terrain, road network, and related geographical elements such as the hazard source and shelters, as well as the population to be evacuated, hence making CEMPS configurable from existing GIS data files. Simulation and link routines have been added to enable dynamic interactive modeling.

CEMPS is an integrated system with four main core components designed for achieving specific design objectives:

- *A traffic simulation model* that uses data from the geographic database and simulates the behavior of individual evacuees on a road network as they journey to a shelter. This component also performs analytical queries regarding current status of such things as congestion on roads and available shelter capacity.
- *A GIS component* that provides dynamic mapping of the simulation as it progresses. This component includes the GIS database, functions that provide convenient and consistent downloading, and GIS-based query and analytical/modeling functions (such as generation of the shortest routes to shelters and evacuation zones), and population and evacuee queries.
- *An integration link* that integrates the traffic model with the GIS by controlling and synchronising parallel tasks and performing communication functions between the GIS and simulation model.
- *A user interface* that employs the interface development facilities provided by the GIS and the OpenWindows programing environment to provide menu, interactive, and display facilities.

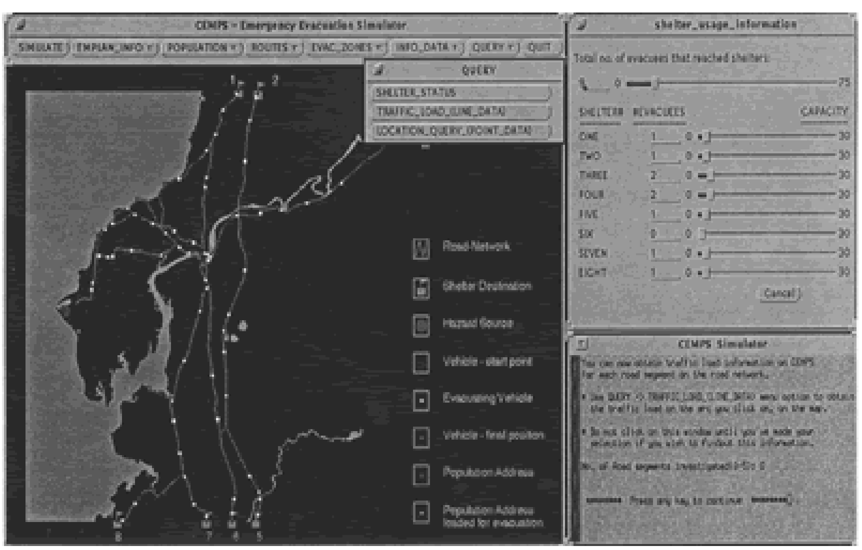

Figure 1. An Example of the CEMPS Display

The details of the design and development of CEMPS can be found in de Silva and Eglese (2000) and Pidd et al.

(1996). The issues and challenges discussed in this paper, while being crucial to the design and development of CEMPS, have significant generic implications for the design of decision support tools for the emergency planning and management process.

DECISION MAKING AND EVACUEE BEHAVIOR

Large-scale evacuations involve the movement of people, voluntarily or involuntarily, to safe places. Understanding the behavior and decision-making process of these people, which is affected by fear, uncertainty, and the speed at which things happen, is crucial to the success of the evacuation. Johnson (1985) discusses a theoretical model designed for evacuation decision making in a nuclear reactor emergency, basing its design on the intended behavior of the population affected by the modeled disaster. The model stresses the influence of *distance* and *direction* on evacuee behavior. The distance from the hazard source and the direction in which the evacuees travel to safe areas determine the behavior of the evacuees in their response pattern and journeys. For instance, the closer a potential evacuee is to a hazard, the more quickly the evacuee is likely to respond to a warning. Furthermore, the evacuee is likely to travel away from the hazard source and its looming radioactive plume. A disaster can trigger varying and extreme forms of human behavior. Studies of evacuee behavior during the Three Mile Island mishap conclude that only a few people used the official shelters and that the majority preferred to find shelter in homes of friends and relatives (Cutter and Barnes, 1982; Sorensen et al., 1987, p. 234). This means that the routes taken by evacuees were determined by their personal destination goals rather than being predefined by the location of official shelters. Thus an evacuation can become a frustrating and messy situation with which emergency planners must be prepared to cope, with some degree of efficiency, in order to avoid costly confusion, damage, injury, or even loss of life.

Two parallel streams of decision making take place during an evacuation: that of the authorities, i.e., the people managing the evacuation operation, such as emergency planners; and that of the individual, i.e., evacuees. The behavioral issues encompass the complications that arise due to the disparity between these two processes. Factors that contribute to the disparity include inadequate information, unclear goals, and poorly defined procedures. Klein (1998, p. 330) discusses the Recognition-Primed Decision (RPD) model that can be used to understand individual decision-making behavior under time pressure, as is the case in evacuation. The model attempts to understand two processes:

1. How do decision makers size up a situation to recognise which course of action makes sense?
2. How do they evaluate that course of action by imagining it?

The disparity issues between authorities and evacuees can be analyzed by applying this model to the decision-making process of these two groups in the evacuation process. An interesting "disaster life-cycle" model that can be used to view human reactions to any type of disaster is discussed by Park (1989) in the context of the lessons drawn from the Three Mile Island incident and the Chernobyl disaster. It is a simple model, which summarizes human reactions to a disaster by examining, in context, activities and priorities at various stages of coping with a disaster and monitoring human adjustment at different time scales. Srinivasan et al. (2000, p. 161) discuss the importance of "programmability" and "structuredness" in decision making when designing a decision support system. Decision making in the evacuation process - indeed, most real-world problem processes - tend to be unstructured and/or nonprogrammable. The challenge then is to model the problem and the decision-making process with minimal abstraction from the real world.

LOGISTICS

Logistical problems in evacuation can arise during the warning process, when transporting and providing accommodation for large numbers of evacuees, or while administering protective measures, etc. (see Lindell et al., 1985; Efrat, 1992). Brandsjö (1988) mentions the enormous procedural difficulties faced during the evacuations associated with the Chernobyl accident. The examples include having to remove large quantities of shoes and clothing from evacuees before they left the area because these contained a high level of radiation and having to find replacement clothing for evacuees, coupled with the lack of trust by the evacuees in the authorities.

A comprehensive discussion of evacuation planning concepts and decision criteria is reported by Lindell et al. (1985, p. 202) for the National Environmental Studies Project of the Atomic Industrial Forum of the U.S. Covering issues relating to both sheltering and evacuation, it identifies factors - such as the radius of the area within which the public is going to be evacuated, delay time between warning and the start of evacuation, speed of evacuation, changing meteorological conditions during evacuation - that need to be addressed in planning evacuation activities. Alternative modes of transport, the identification of facilities requiring special consideration, such as schools and hospitals, protective health measures for the vulnerable population, etc. also need to be investigated.

In planning evacuations, often the consequences of deciding to end the evacuation are overlooked. The same behavior and logistic issues also apply in large part at this stage of the evacuation process. Conflicts can arise between evacuees and public officials about the timing and return of evacuees to the affected region, and there may be procedural difficulties in the return of a large evacuee population to an affected region (Gillespie and Murty, 1991). An overall evacuation plan therefore must include plans for this final aspect of the evacuation process.

IMPROVEMENTS IN SCENARIO GENERATION

Parameters that define an evolving emergency, that provide information on the influence of uncertain forces - such as the effects of weather patterns and wind, road accidents, extreme behavior of individuals, factors affecting route choice behavior, early warning, and the dynamic evolution of the radioactive plume - must necessarily be included in models if the scenarios generated by the simulator are to be improved and expanded. One way of including this type of information (which can be subjective, especially where evacuee behavior assumptions are concerned) is to include a knowledge base that provides the traffic model with expert information input to the simulation as the need arises. A more complex rule base would need to be developed in order to utilize this information in a more intricate scenario generation process. For example, consider the likely situation during an evacuation in which traffic is directed by the police to various shelters according to the available information on traffic congestion, closure of roads, and current shelter capacity. In this scenario the behavior of the evacuee would necessarily be restricted when he/she made judgements regarding route finding on the road network. When the simulator permits persons in evacuating vehicles to select their own routes to a close shelter, as is the case in CEMPS, the model does not reflect the more complex situation in which an evacuation is directed by an external source (e.g., the police). Simulation of this latter case requires additional information on overall congestion and the capacity of nearby shelters, which may not be directly available to an evacuee. This information must be fed into the simulation via an information base, which releases the necessary information in the appropriate format. Providing functions to perform multi-stage/phased evacuations can further enhance the scenario generation process.

Behavior functions, as in the case of the CEMPS traffic simulation model, are designed using various simplifying assumptions. For instance, it is often assumed that evacuees will respond to a warning to evacuate promptly. Realistically, however, this assumption should recognize that there would be delays in responding and embarking on an evacutation. These varying behaviors can be modeled according to a suitable warning-response behavior pattern. Some statistical methods have been employed for this purpose in evacuation models developed in the past (see Hobeika and Jamie, 1985; Stern and Sinuany-Stern, 1989; Sinuany-Stern and Stern, 1993; Southworth, 1991). This initial behavior of evacuees at the start of the evacuation process will determine how the evacuation progresses in the following stages.

The accuracy of predicting evacuee behavior and the detail required for modeling this behavior depends on whether the simulator uses a micro, measo or a macro modeling approach. The micro approach concentrates on simulating the behavior of each evacuating entity, while the macro approach concentrates on using flow equations that grossly average evacuee/entity behavior. The measo approach attempts to strike a balance between the two by averaging behavior among groups of evacuees. The choice among the three approaches very much depends on the trade-offs that must be made in order to maintain realistic computing power when processing large amounts of data. Flexibility for scenario generation increases as the micro approach becomes more and more detailed.

VALIDATING ASSUMPTIONS

A simulator is intended to mimic a real-world system using actual data associated with that system. It uses assumptions that generally simplify the complex behavior of the real-world. These assumptions fall into two categories (Banks et al., 1996, p. 548):

1. *Structural assumptions* that involve simplification and abstraction of issues involving the operation and the processes of the real-world system, and
2. *Data assumptions* that are based on the collection of reliable data and proper analysis of this data.

The CEMPS simulator is intended for use at different levels of detail - whatever the user feels is appropriate. This means that the experimental frame cannot be specified in a straightforward way, which in turn makes validation of structural assumptions very difficult. Thus trade-offs are inevitable if the model is to establish a balance between flexibility for the user and realistic validation of assumptions.

The validation of structural assumptions can proceed in several ways. The extent to which evacuee movement is modeled accurately depends on the framework defined for the simulation experiment. Assumptions are typically made regarding speed of movement of evacuating traffic and behavior of evacuating vehicles on the road network. The simulated times needed to move evacuating vehicles between two known points on a road network under defined traffic conditions could be compared with those found in real-life. It may be necessary to observe a very large number of vehicle movements on a road network before relying on the data for such comparison. Similarly, the effect of stochastic occurrences, such as, vehicle breakdowns and accidents, as well as control interventions, such as the closure of roads or lanes, could be compared with the effects that these would have in the real-world system. Such comparisons would involve complex, time-consuming operations, but would nevertheless help build confidence in the model. Balci and Sargent (1984) and Miser and Quade (1988) discuss the problems associated with such validation in relation to large-scale military simulations.

The data assumptions, in general, are based on the collection of reliable data and the proper analysis of this data. The data used in this research are those relating to the Heysham nuclear power station and its environs in the northwest of England and have been obtained from reliable geographical data sources. They are static data relating to the spatial location of each data point. The data is geo-referenced using standard formats and conventions, and thus, in this sense, validated in relation to their geographical situation. However, the data that need proper validation and analysis are those that relate to the dynamic behavior of the elements in the system, such as those relating to the behavior of the evacuating vehicles on the road network in relation to time and the growing emergency, those relating to evacuee behavior following warning (which would affect the time evacuees begin their evacuation journey), etc. However it is very difficult to obtain historical data on previous similar incidents.

VALIDATING THE SDSS

Validating a spatial decision support system is by no means a straightforward process, and there is no clear-cut formula that is generally applicable. Should the SDSS deal with decision making for situations that occur frequently, there is the possibility of comparing the consequences of instances of decisions taken without the aid of the SDSS with those that have been taken with the aid of the SDSS. Such a comparison can be carried out using a suitable approach such as a Turing test (see Norlen, 1972, for a description of the testing procedure). The purpose of the Turing test is to find out to what extent it is possible to discriminate between the model and the modeled. The testing process in this instance is made simpler because the data and information required for the analysis and experimentation are likely to be readily available. Clearly any SDSS validation procedure should include at the least a validation of the output and of any underlying models.

In an SDSS dealing with complex problem situations that are unique or occur rarely, which is the case with emergency situations, validation of its output and underlying models becomes extremely difficult. Again, historical data are not easy to come by and are often nonexistent or incomplete. Often with respect to politically or socially sensitive problems, such as nuclear disasters, public access to historical data on the resulting disaster management activities is heavily restricted. This is especially true for recent events. One method that can be used in these situations is to conduct a comparative study of existing decision support tools that are applicable and evaluate the performance of the SDSS in relation to them. This, however, is not a satisfactory method of validation, since the other tools that are compared with the SDSS may not have the exact same output functions or decision support goals as the examined SDSS.

According to Norlen (1972, p. 172) validating a simulation model involves estimating how well the model matches its specifications. This is a difficult task, and many suggestions have been made concerning various approaches to model validation. In the case of the CEMPS simulation model, standard validating methods such as the three-step approach described by Law and Kelto (1991, p. 759) and Banks et al. (1996), which encompasses maintaining contact with the potential decision makers throughout the design stage with the aim of developing a model that seems reasonable to the user, using historical data for experimentation, and finally evaluating the output, cannot be applied in whole, largely due to the lack of historical data and validated experiment data on regional evacuations. Ideally, in order to investigate the input-output transformation of an evacuation simulator, there should exist several sets of different case-study data so that one is able to obtain a reasonable range of output for investigating the efficiency of the system. Obviously, this approach can be severely hampered by lack of access to historical data. It is also not appropriate to cite output statistics such as run-time in minutes, because these can depend on factors such as the scenario being investigated, the degree of detail required, the computer hardware and operating system that are used, etc. According to Zeigler (1976, p. 435) the only way models can be validated is by comparing them against specified experimental frames that place the model in the context of its intended use. He also observes that a simulation model that has general validity does not exist. Furthermore, Paul and Hlupic (1994) argue that since the real world is dynamic, so would be its problems and systems. Thus, they conclude that models cannot be validated against the real-world system they represent, again because the real world is not static. These viewpoints underscore the difficulty of validating any simulation model.

THE FUTURE . . .

Much research is currently taking place in the development of complex emergency planning and management systems that could handle a disaster that would, to site one example, affect the whole of Europe. Of particular interest is the RODOS (Real Time Online Decision Support) project involving major research institutions of several nations of Europe (Ehrhardt, 1997; Dutton et al., 1999). This project is a result of the lessons learned from Chernobyl and involves developing a decision support system for off-site emergency management that would be broadly applicable across Europe. Another aim is to provide greater transparency in the decision process by facilitating improved communication among countries for monitoring data, predicting consequences, etc., in the event of a future accident that may affect Europe.

Another joint European project that also includes the design of tools for evacuation management is the MEMbrain project (Quasar Consultants, 1993, p. 9; 1997). This project involves the development of an integrated software platform for emergency management that incorporates several components, including a geographical information system (GIS) and a decision support system (DSS) that will aid public protection and emergency management.

Interesting developments have also taken place recently in devising globally accessible, networked decision support tools for emergency planners using the Internet. One such development is PREMIS, the Pacific Regional Emergency Management Information System designed to aid civil defence emergency management activities within the state of Hawaii in the U.S. (Hawaii State Civil Defence, 1997). The interesting feature of this system is that it is driven by a GIS called the Integrated Emergency Management Information System (IEMIS)/Integrated Baseline System (IBS). IEMIS supports mapping functions while IBS supports computer-based modeling, including response of transportation networks in evacuations, radiation dose rates, etc.

Implications of Developments in Related Technologies

When discussing the trends for the future of SDSSs in general, the potential of parallel advancements in computer technology that will have a profound effect on SDSSs (such as expert systems technology/knowledge-based decision support architecture, Global Positioning Systems (GPSs), etc.) cannot be ignored. The design of an intelligent SDSS by coupling a GIS with an expert system is discussed by Zhu and Healey (1992). Spatial decision making is based on two streams: one quantitative, which includes data analysis and modeling, and one qualitative, which includes experience, intuition, judgement, and specialist expertise. Current GIS systems focus on providing quantitative information and largely ignore the qualitative aspects of the process. The inclusion of expert systems, which perform decision-making tasks by reasoning, using rules defined by experts in the area, would greatly aid qualitative spatial decision making within GISs, and thus SDSSs.

Not only do such advancements affect the future of GIS, they also have a profound effect on traffic simulation models. Ritchie (1990) discusses an artificial-intelligence-based solution that provides decision support to traffic management systems. Such systems focus on multi-user access and processing applications. Technology, such as GPS, which enables the identification of locations on the surface of the earth to a great degree of accuracy via satellite technology, makes it possible for GIS to perform real-time operations to a great degree of spatial accuracy. These advanced technologies, which have already been introduced to the real-time emergency management processes, will have a profound effect on the way SDSSs are designed in the future.

Global Networks

Many attempts are also being made to bring together emergency planning activities and resources available around the world through modern technologies so that disaster managers can not only draw on the efforts of local emergency planners but also on expertise and information from all over the globe to prepare their emergency plans. One such major effort is the GEMINI project (Global Emergency Management Information Network Initiative), which has directed its efforts not only to develop a global networked system to rapidly access resources and exchange information around the world but also to define standards for information and establish global protocols (Anderson, 1995). Building beyond the GEMINI project, the GDIN (Global Disaster Information Network) initiative, which aims to improve the effectiveness and interoperability of global systems for sharing natural disaster information - especially maps and data generated by remote and land-based sensors - has been initiated with the collaboration of all players in the emergency planning and management arena, such as, national governments, international organisations, NGOs, academia, corporate partners, etc. Thus the future of emergency planning clearly will involve a global approach with enormous reliance on technology.

CONCLUSION

This paper has highlighted and discussed challenges encountered in using and merging technologies to design an SDSS for evacuation planning. In this process several issues are focal:

- The realistic modeling of evacuee behavior,
- The decision-making process that takes place during an evacuation,
- Logistical issues,
- The generation of realistic scenarios,
- The validation of assumptions made in SDSS design, and
- The validation of the SDSS.

These issues are discussed via lessons learned in developing the prototype SDSS CEMPS, while generic issues are discussed in light of using simulation and GIS technology for designing such systems for emergency planning. Developments in both technology and the approach to emergency planning have also been addressed, and implications for the future of emergency planning and management outlined.

As technology evolves, so will the challenges; thus, it is critical to successfully tackle the fundamental issues discussed here so that new and evolving technologies are able to aid the decision-making process in disaster management while improving the integrity and reliability of the outcome.

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REFERENCES

Anderson, P.A. June 1995. "Global Emergency Management Information Network Initiative (GEMINI), Progress Report." Presented at the Halifax Summit and posted on the World Wide Web (WWW): http://hoshi.cic.sfu.ca/~g7/progressG7.html.

Balci O. and R.G. Sargent. 1984. "A Bibliography on the Credibility, Assessment and Validation of Simulation and Mathematical Models." *Simuletter 15* (3); 15-27.

Banks, J., J.S. Carson II, and B.L. Nelson. 1996. *Discrete-Event System Simulation*. Second Edition. Upper Saddle River, New Jersey: Prentice Hall.

Banz, G. and R.T. Newkirk. No date. "The Roles of Computer Simulation in Emergency Planning." *Emergency Preparedness Digest*.

Batty, M. and P. Densham. 1996. "Decision Support, GIS and Urban Planning." *Sistema Terra V* (1): 72-76.

Batty, M. 1994. "Using GIS for Visual Simulation Modeling." *GIS World 7* (10): 46-48.

Belardo, S. and W.A. Wallace. 1981. "The Design and Test of a Microcomputer Based Decision Support System for Disaster Management." Pages 152-164 in *DSS-81 Transactions - Proceedings of the International Conference on Decision Support Systems*, June 8-10, 1981, Young, D. and P.G.W. Keen (eds.).

Brandsjö, K. 1988. "Nuclear Accidents - Chernobyl, a Warning." *Disaster Management 1* (2): 36-41.

Carver, S. 1996. "Where to Dispose of Britain's Radioactive Waste." WWW: http://www.ccg.leeds.ac.uk/mce/.

Cutter, S. and K. Barnes. 1982. "Evacuation Behavior and Three Mile Island." *Disasters 6* (2): 116-124.

Densham, P. 1991. "Spatial Decision Support Systems." Pages 403-412 in *Geographical Information Systems: Principles and Applications*, Volume 1. Maguire, D.J., M.F. Goodchild and D.W. Rhind (eds.). Longman, UK.

Efrat, E. 1992. "The Geography of a Population Mass-escape from the Tel Aviv Area During the Gulf War." *The Geographical Journal 158* (2): 199-206.

Ehrhardt, J., J. Brown, S. French, G.N. Kelly, T. Mikkelsen, and H. Muller. 1997. "RODOS: Decision-making Support for Off-site Emergency Management After Nuclear Accidents." *Kerntechnik 62* (2-3): 122-128.

Fedra, K. and R.F. Reitsma. 1990. "Decision Support and Geographical Information Systems." In *Geographical Information Systems for Urban and Regional Planning, Research Report: RR-90-009.* Laxenburg, Austria: ACA, International Institute for Applied Systems Analysis (IIASA).

Gatrell, A.C., J.D. Mitchell, H.N. Gibson, and P. Diggle. 1991. "Test for Spatial Clustering in Epidemiology: With Special Reference to Motor Neurone Desease." Research Report No. 19. Lancaster University, Lancaster U.K.: North West Regional Research Laboratory.

Gillespie, D.F. and S.A. Murty. 1991. "Setting Boundaries for Research on Organizational Capacity to Evacuate." *International Journal of Mass Emergencies and Disasters 9* (2): 201-218.

Hawaii State Civil Defence. 1997. "Section 3: Pacific Regional Emergency Management Information System (PREMIS) Baseline." WWW: http://scd.hawaii.gov/pdc/premis.htm.

Herrnberger, V. 1996. "Radiological Emergency Management." WWW: http://www.psi.ch/~beer/rem_home.html.

Hobeika, A.G. and B. Jamie. 1985. "MASSVAC: A Model for Calculating Evacuation Times Under Natural Disaster." Pages 23-28 in *Emergency Planning*,*Proceedings of the Conference on Emergency Planning, January 1985, San Diego, California*. Carroll, J.M. (ed.). Simulation Series 15. La Jolla, California: Society for Computer Simulation.

Johnson, J.H. 1985. "A Model of Evacuation Decision Making in a Nuclear Reactor Emergency." *The Geographical Review 75*: 405-418.

Klein, G. 1998. *Sources of Power: How People Make Decisions*. Cambridge, Massachusettes: MIT Press.

Law, A.M. and W.D. Kelto. 1991. *Simulation Modeling & Analysis*. Second Edition. New York: McGraw-Hill.

Lindell, M.K., P.A. Bolton, R.W. Perry, G.A. Stoetzel, J.B. Martin, and C.B. Flynn. 1985. *Planning Concepts and Decision Criteria for Sheltering and Evacuation in a Nuclear Power Plant Emergency*. National Environmental Studies Project, AIF/NESP-031. U.S.: Atomic Industrial Forum, Inc.

Miser, H.J. and E.S. Quade. 1988. "Validation." Pages 527-565 in *Handbook of Systems Analysis: Craft Issues and Procedural Choices*, Miser, H.J. and E.S. Quade (eds.). Chichester, U.K.: John Wiley and Sons.

Mondschein, L.G. 1994. "The Role of Spatial Information Systems in Environmental Emergency Management." *Journal of the American Society for Information Science 45* (9): 678-685.

Norlen, U. 1972. *Simulation Model Building: A Statistical Approach to Modeling in the Social Sciences with the Simulation Method*. Uppsala, Sweden: Almqvist & Wiksell Informationsindustri AB.

Park, C.C. 1989. "The Disaster Life Cycle and Human Adjustments: Lessons from Three Mile Island and Chernobyl." Chapter 13 (pp. 193-205) in *Population and Disaster*, Clarke, J.I., P. Curson, S.L. Kayastha and P. Nag (eds.). Oxford, U.K.: Institute of British Geographers and Basil Blackwell Ltd.

Paul, R.J. and V. Hlupic. 1994. "The CASM Environment Revisited." Pages 641-648 in *Proceedings of the 1994 Winter Simulation Conference*, Tew, J.D., S. Manivannan, D.A. Sadowski, and A.F. Seila (eds.). San Diego, California: Society for Computer Simulation.

Pidd, M., F.N. de Silva, and R.W. Eglese. 1996. "A Simulation Model for Emergency Evacuation." *European Journal of Operational Research 90* (3): 413-419.

Plunkett, B. 1993. Pages 151-155 in *Proceedings of the Thirteenth Annual ESRI User Conference*, May 1993. Redlands, California: Environmental Systems Research Institute.

Quasar Consultants (A/S). 1993. "Accident Development and Evacuation Management - Quasar's Work-packages in MEMbrain." Oslo, Norway: Quasar Consultants (A/S).

__________. 1997. "MEMbrain." WWW: http://www.quasar.no.

Riddle, D.A., M.A. DePenning, and W.T. McDowell. No date. "Utilizing GIS in Emergency Management: A Hazardous Material Evacuation Model." Working Paper.

Ritchie, S.G. 1990. "A Knowledge-based Decision Support Architecture for Advanced Traffic Management." *Transportation Research 24A* (1): 27-37.

de Silva, F.N., and R.W. Eglese. 2000. "Integrating Simulation Modeling and GIS: Spatial Decision Support Systems for Evacuation Planning." *Journal of the Operational Research Society 51* (4) (Special Issue on Progress in Simulation

Research): 423-430.

Sinuany-Stern, Z. and E. Stern. 1993. "Simulating the Evacuation of a Small City: the Effects of Traffic Factors." Working Paper. Negev, Israel: Ben-Gurion University of the Negev.

Sorensen, J.H., B.M. Vogt, and D.S. Mileti. 1987. *Evacuation: An Assessment of Planning and Research*. Oak Ridge National Laboratory Report ORNL-6376 (Federal Emergency Management Agency Publication RR-9). Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Southworth, F. 1991. *Regional Evacuation Modeling: A State-of-the-Art Review*. Oak Ridge National Laboratory Report ORNL/TM-11740. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Srinivasan, A., D. Sundaram, and J. Davis. 2000. *Implementing Decision Support Systems: Methods, Techniques and Tools*. Information Systems Series. Maindenhead, U.K.: McGraw-Hill.

Stern, E. and Z. Sinuany-Stern. 1989. "A Behavioral-based Simulation Model for Urban Evacuation." *Papers of the Regional Science Association 66*: 87-103.

Zeigler, B.P. 1976. *Theory of Modeling and Simulation*. New York: John Wiley and Sons.

Zhang, M. and P.W. Grant. 1993. Pages 107-114 in *Proceedings of the Thirteenth Annual ESRI User Conference*, May 1993. Redlands, California: Environmental Systems Research Institute.

Zhu, X. and R. Healey. 1992. "Towards Intelligent Spatial Decision Support. Integrating Geographical Information Systems and Expert Systems." Pages 877-886 in *Proceedings of the GIS/LIS '92 Annual Conference*, Volume 2. San Jose, California.

NOTES

1. A GIS is able to store spatially referenced data and information and provide sophisticated mapping and display facilities. Many contemporary GISs come with built-in analysis tools in addition to their data storage, manipulation and representation tools.

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