Simulation of fire growth in GIS using discrete event hierarchical modular models

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ABSTRACT

The objective of this work is to introduce and illustrate the potential of discrete event, hierarchical modular models for simulation of fire spread in GIS. The knowledge based discrete-event simulation environment (DEVS-Scheme) associates stand-alone discrete event models with spatial locations represented in a GIS data base, and couples those models in a coherent manner. The dynamic models then process the spatially distributed information on fire conditions, and simulate fire growth. The models can receive external updated information, and the fire perimeter can be updated at any moment due to the continuous time nature of the discrete event specifications. In this paper we discuss the limitations of GIS for simulation of fire spread, show how some of those limitations can be overcome, and compare the results obtained by discrete event simulation to an actual fire.

1. INTRODUCTION

Many authors have expressed interest in using GIS for simulation of spatial dynamic ecological processes (Berry 1987; Itami 1988; Costanza *et al.*.1990; Baumans and Sklar 1990), and fire spread has been used as an application topic (Green *et al.* 1989, Vasconcelos and Guertin 1992, Ball and Guertin 1992). Despite their potential, GIS are adapted for rather than designed for simulation, and there are some difficulties when using GIS alone for simulation purposes. GIS systems do not include procedures for handling time, they are designed to process entire arrays of data, and can not easily address varying localized operations.

In this work we suggest that discrete event simulation as implemented in DEVS-Scheme, can provide many of the necessary simulation capabilities, and that DEVS-Scheme can serve as a prototype simulation environment for realistic spatial dynamic modeling in GIS. The methodology presented opens a wide set of possibilities for representing real systems in an object-oriented modular hierarchical manner that can be spatially referenced and thus easily interfaced with any GIS. Moreover, it supports a level of extensibility, and reusability of the models not found in other modeling approaches. DEVS-Scheme can represent reality at several spatio-temporal resolution levels simultaneously, and perform simulations with GIS in a computationally efficient way. Additionally, as illustrated through the fire spread application, it can handle complex spatial interactions at any particular resolution level, and represent them in a GIS.

2. HIERARCHICAL MODULAR DISCRETE EVENT MODELS IN DEVS-SCHEME

The methodology presented is called *knowledge-based simulation* (Zeigler 1990). It integrates discrete event simulation formalisms and artificial intelligence knowledge-representation schemes in DEVS-Scheme. DEVS-Scheme is a knowledge-based, object-oriented simulation environment for modeling and design that facilitates construction of families of models in a form easily reusable by retrieval from a model-base. (Zeigler 1990).

All models in DEVS-Scheme are *hierarchical, modular, object-oriented* models. The term modularity means the description of a model in such a way that it has recognized input and output ports through which all the interaction with the external world is mediated (Zeigler 1990). For a set of component models (objects), a coupled-model can be created by specifying how the input and output ports are connected to each other, and to external ports. The new *coupled-model* is itself a modular model and thus can be used as a component in a yet larger, hierarchically higher level model. Objects can communicate with each other and with higher levels of control, to cause changes in their states, by a process called *message passing*. This process uses couplings as communication channels (Zeigler 1990).

The most basic models from which all others are built by coupling are called *atomic-models*. Atomic models are specified in the dynamic discrete event formalism where the value of the time increment is not fixed and stipulated in advance, but variable and determined individually for each state transition. Since the DEVS formalisms include closure under coupling (Zeigler 1984, 1990) all models created by coupling of atomic-models (couple-models) also are discrete event models. Atomic models are stand-alone modular objects that contain: a set of state and variables and parameters, an internal transition function that computes the next state and state transition time when no messages arrive in the input ports, an external transition function that computes the next state and transition time when an external event arrives in an input port, a time advance function, and an output function which generates an output just before an internal transition takes place.

Two state variables are usually present in atomic models: *phase* and *sigma*. In the absence of external events the model remains in the current *phase* for the time given by *sigma*. When an external event occurs the external transition function places the system in a new phase and sigma thus scheduling it for the next internal transition (Zeigler 1990). The next state is computed on the basis of the present state, the input port and value of the external event, and the time elapsed in the current state.

DEVS knowledge representation scheme, the *system entity structure* (SES), combines *decomposition, coupling* and *taxonomy* (Zeigler 1990). The entities in the SES refer to the conceptual components of reality for which models may reside in the model base. A *multiple entity* represents the set of all members of an entity class and it can generate a composition tree with any number of similar entities. An *experimental frame* (EF) specifies the form of experimentation that is required to obtain answers to questions of interest (Zeigler 1984, 1990). It is a *coupled-model* that generates streams of inputs to the model, monitors the simulation, and processes model output. The experimental frame reflects the objectives one has in experimenting with the model. It specifies a limited set of circumstances under which the model (or models) and the real system are to be observed or subject to experimentation (Zeigler 1984, Vasconcelos and Zeigler 1993).

3. DYNAMIC MODELLING IN GIS WITH DISTRIBUTED DISCRETE EVENT MODELS

DEVS-Scheme and GIS can be linked to generate a powerful spatial dynamic simulation environment for ecological and natural resource management applications. For simulation of fire spread in a cellular space one can envisage a coupled model so that for each cell of the landscape map there may be a corresponding atomic-model. The dynamic models can then process the spatially distributed information available in the GIS data base, and update it through time. The models also can receive external updated information at any moment, due to the continuous time nature of discrete event specifications.

DEVS-Scheme includes capabilities of variable structure (Zeigler *et al.* 1990). This means that a model's initial structure may change as the simulation proceeds, in a way that differs from simulation to simulation, depending on the specific conditions. At any instant, component models can be replicated, introduced in the overall model's structure, and initialized based on spatial and hierarchical position. Additionally, those models that become inactive and are no longer needed may be removed from the entity structure. Variable structure capabilities are used in the fire growth model, where this ability is translated in the possibility of having only models corresponding to active (burning) cells in the model structure. New models are loaded when cells start burning. Conversely, when a cell burns out and its model is no longer needed, it is removed from the model structure and memory is freed up for the functioning of newly ignited cells.

Variable structure models are important for spatial dynamic modelling in GIS because they make it possible to develop representations based on the parallel processing concept in low end workstations (**Figure 1**). There is an efficiency of memory usage when only active models are loaded in memory at any moment (corresponding to a portion of the whole grid). The sequential processor can emulate parallelism by sequentially processing state changes at a given simulation time, only for the subset of loaded models having an event at that instant.

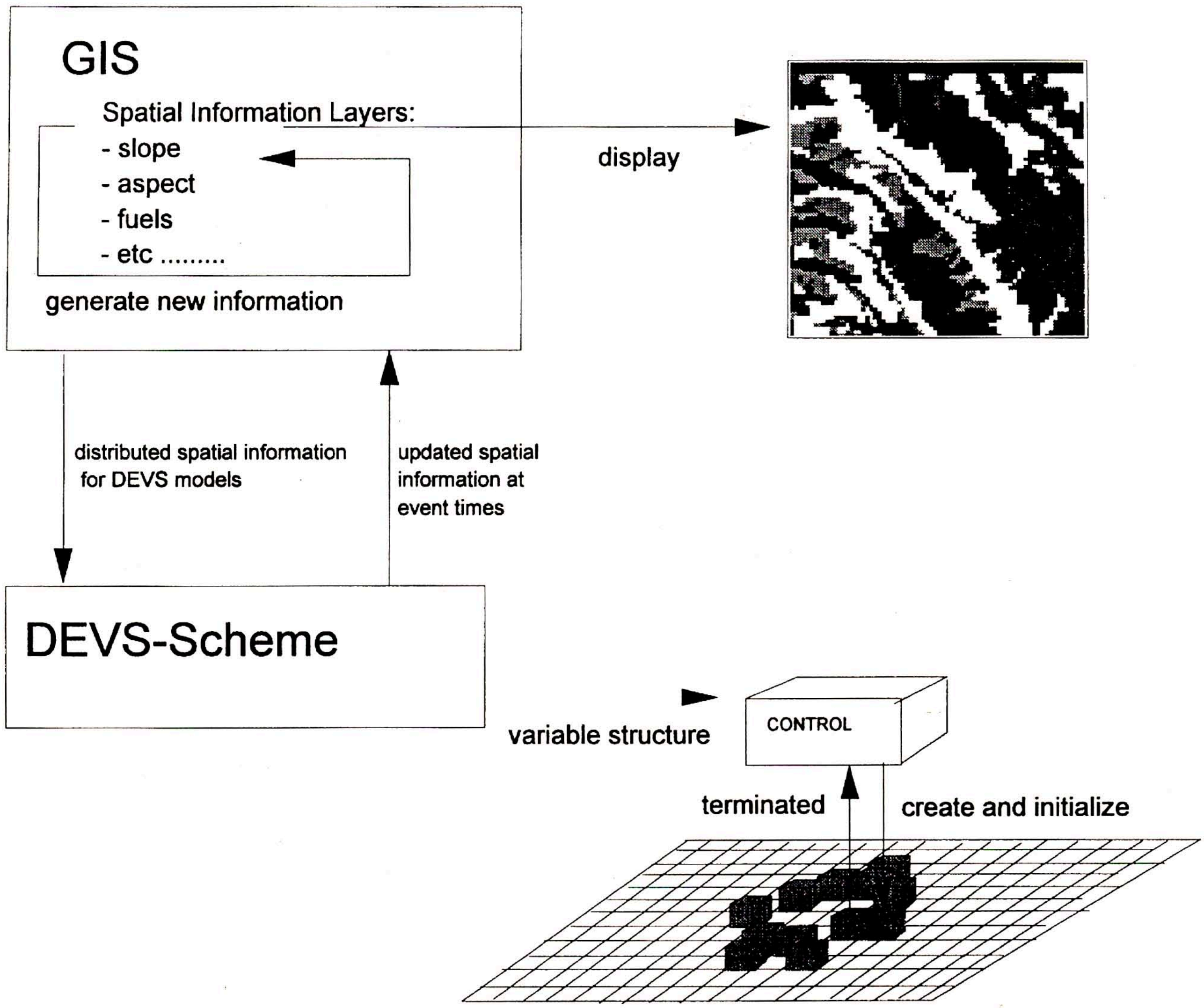


Figure 1- Variable structure and GIS. DEVS variable structure and dynamic modelling capabilities are linked to the spatial data base management and display capabilities of GIS to provide a powerful spatial dynamic modelling environment

4. FIRE SPREAD MODELLING IN GIS

The rate of fire spread can be estimated through Rothermel's rate of spread equation (Rothermel 1972, 1983) for homogeneous conditions of fuel, weather, and topography. However, the great majority of wildland fires occur under heterogeneous conditions both in space and in time. Awareness of the need to account for spatial variability of wildfire behaviour led several authors to use GIS for prediction of distributed fire characteristics (Salazar and Palmer 1987, McKinsey 1988, Salazar and Power 1988, Hamilton *et al.*.. 1989, Holder *et al.* 1990, Vasconcelos and Pereira 1991, Vasconcelos and Guertin 1992, and Ball and Guertin 1992). Here, we briefly focus on some aspects of FIREMAP (Vasconcelos and Pereira 1991, Vasconcelos and Guertin 1992, Ball and Guertin 1992; Pereira and Vasconcelos 1990) because this system incorporates a procedure for simulating fire spread.

FIREMAP implements the connection between Rothermels's rate of spread equation as used in the BEHAVE system (Andrews 1986) and the Map Analysis Package (MAP) GIS (Tomlin 1986). Maps of all fire characteristics calculated by BEHAVE, such as: rate of spread (ROS), direction of maximum spread (DMS), fireline intensity (FLI), among others, may be produced, and fire spread is simulated on a discrete time basis. Within each constant weather time interval, all cells are assumed to burn in the same direction, which can only be updated between time intervals. Additionally, there is a need to manually update the fire perimeter at the end of each time interval, so that only those cells burning in the fire front are kept burning and thus influence the next time period (see Vasconcelos and Guertin 1992 for details).

The application of FIREMAP showed that, despite the adequacy of GIS as a spatio-temporal data base management system, there are important limitations to the implementation of dynamic models in a GIS environment. The main problems relate to the lack of flexibility of GIS spatial operators and to the discrete time nature of the simulations. These limitations impose the assumption of a single rate of spread value associated with each cell and constancy of spread direction during each time interval. Additional limitations are related to the difficulty of using operators applicable only to individual grid cells, and to the lack of flexible rule-based operators.

5. DEVS-GIS MODEL FOR SIMULATION OF FIRE SPREAD

5.1 Conceptualization

For simulation of fire growth in a cellular space, one can envisage the placement of an atomic-model at each burning cell location. Thus there may be a set of spatially referenced atomic-models, corresponding to distributed virtual processors in the raster map grid that use the values of ROS, DMS, and FLI previously computed in the GIS. The coupling of atomic-models in space can then be dynamically managed by an extra atomic-model, a controller.

Since the time to burn in each cell is known, based on rate of spread and cell size, it is possible to generate the time segment, *burning time* corresponding to the phase *burning* for each cell. Moreover, given an ignition cell, it is possible to compute the time a fire takes to cross the boundaries of several consecutive cells, by generating a time advance function based on the rates of spread of those cells. The crossing of a boundary can then be envisaged as an internal event generated after the cell remained in phase *burning* from *ignition-time* to (*ignition-time* + *burning-time*).

If there is a wind shift while a cell is burning, the fire rate of spread and direction of maximum spread (DMS) change with it. This means that the burning cell now burns at a different rate, and thus the remainder of the burnable area takes a different time to consume than that initially calculated. The time a cell is in phase *burning* can be updated by computing the proportion of the cell burned before the wind shift based on the elapsed time and previous burning time. The time to burn can then be reset to the time it takes to consume the remainder of the cell at the new rate. This is the proportion left to burn multiplied by the burning time under the new conditions.

The above description for fire in a cell, can be encoded in an atomic model CELL, that has phases *passive, burning,* and *burned* with corresponding sigmas of *infinite, burning-time, infinite*. In order to represent fire spread it is necessary to specify how the directions of spread are coded in a grid space and how the varying burning rates in the discrete cells of the landscape are linked to produce a total burn. The eight rates of spread (for the eight primary directions), of which one corresponds to the rate of maximum spread are converted to burning time.

The scheme shown in **Figure 2** facilitates encoding of contagion directions. We can envisage the letters as repre-

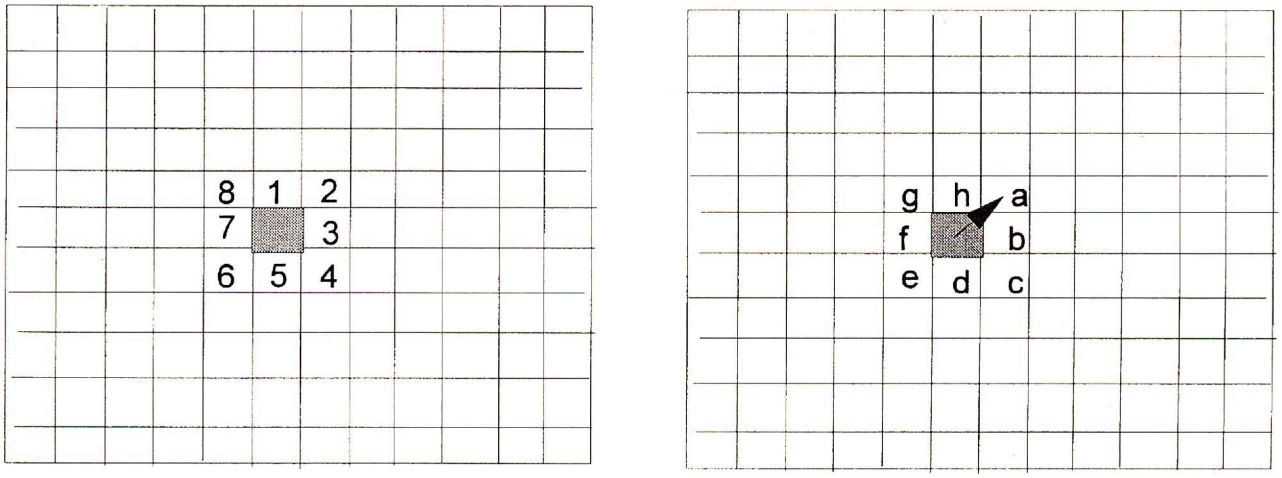


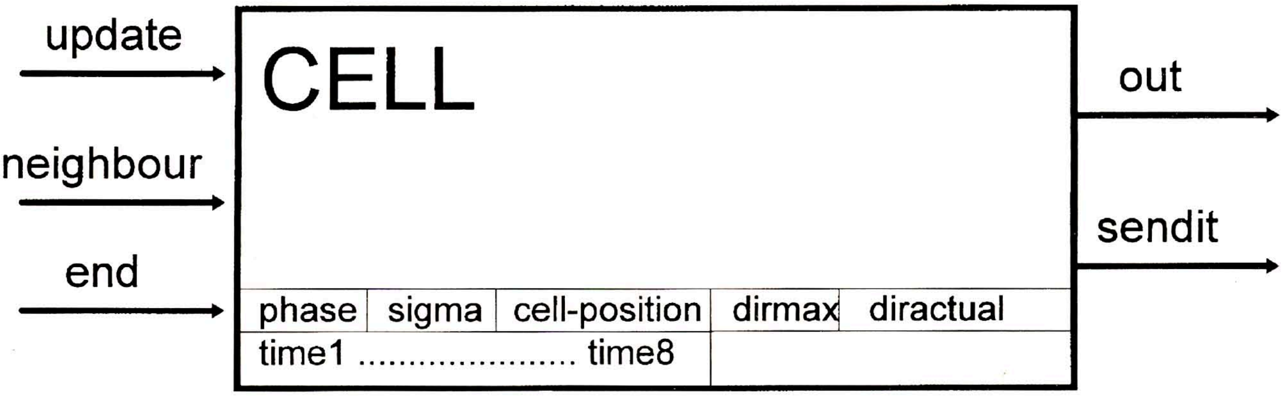
*Figure 2 - The cells numbered 1 to 8 represent the fixed directions to which a cell can spread. The letters represent relative directions and associated rates of spread. Direction **a** always corresponds to DMS and, if a cell is burning in that dire ction it is burning at its maximum rate. Conversely, a cell burning in direction **e** is burning at its slowest rate. The set of relative directions varies from cell to cell and is given by direction of maximum spread in degrees clockwise from uphill.*

senting classes of rates of spread where the letters always represent the spread rate corresponding to a fixed angle from DMS, which varies with time from cell to cell. When the time for a cell to burn has elapsed, its neigbours can be ignited, and those that are not already burning will start burning at a rate dependent on the respective directions of contagion and direction of maximum spread. Each cell can set itself to burn at a rate and direction dependent on the information received from the ignition cell and its own spread conditions.

5.2 GENERAL MODEL DESIGN

This model of fire spread in a cellular space is designed so that for each cell of the landscape map there may be a corresponding atomic-model CELL. Since this model uses the variable structure capabilities of DEVS-Scheme, only active, burning cells need to have a corresponding model CELL. When a new cell becomes ignited, a new model CELL is incorporated in the model's structure and loaded in memory, and when it burns out that model CELL is removed. The number of models CELL at any one moment depends on the position of the source CELLs, elapsed simulation time, and fire spread conditions. The set of CELLs, present at any time, is controlled by another atomic model CO-CELLS that manages the couplings for message passing from burning CELLs to neighboring ignitable CELLs at event times. These models are coupled to form a kernel model of the type controlled-models (Zeigler 1990).

In the fire growth model, the models in the system entity structure refer to cells in raster GIS, corresponding to parcels of land. The system entity structure may generate a composition tree with any number of atomic-models CELL depending on the array size and simulation objectives. The experimental frame (EF) is a coupled model



STATE VARIABLES: phase, sigma,
cell-position, dirmax, diractual, time,..., time8

EXTERNAL TRANSITION FUNCTION :
case port is 'neighbour
    parse content-value
        depending on cell-position, time?, dirmax
            set sigma to one of precomputed time?
            set phase to 'burning
case port is 'update
    compute % left-to-burn from elapsed time
    set dirmax to new dirmax
    set time1,..., time8 to new values
    set sigma to time? x 5 left-to-burn
case port is énd
    passivate

INTERNAL TRANSITION FUNCTION
case phase is 'burning
    set phase to 'burned
    set sigma to 'infinity

OUTPUT FUNCTION
case phase is passive
    output 'cell-position 'ignited
case phase is burning
    output cell-position 'burned

*Figure 3 - The model CELL was designed to function in a grid where it receives and sends information from and to its immediate neighbours (a 3 * 3 window centred at each cell) through CO-CELLS. The pseudo-code and the box diagram show how the behaviour of a cell (explained above) is formalized as an atomic-model*

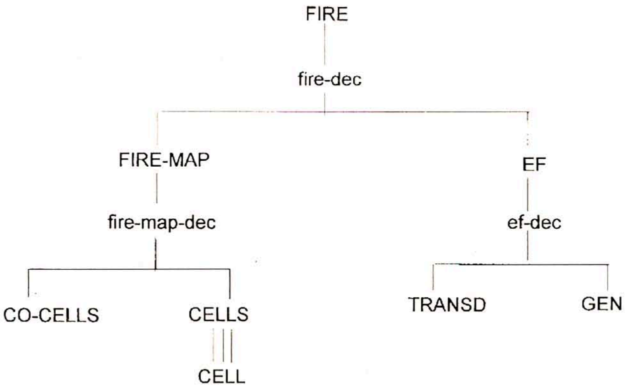


Figure 4 - The system entity structure (SES) for the fire growth model. This SES can be unfolded to generate several different models with different numbers and arrangements of components. The extension "dec" denotes a decomposition of an entity. The three vertical lines denote a multiple entity

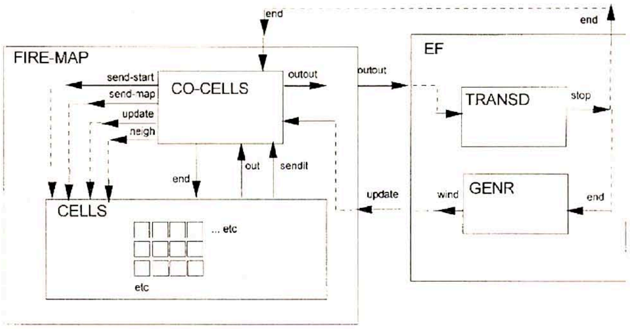


Figure 5 - Complete box diagram for the fire growth model in DEVS

with components TRANSD and GENERATOR. EF receives messages from CO-CELLS whenever a CELL of a map undergoes a state transition and TRANSD updates and displays the map with the new landscape state. The model GENR produces the times for weather updates and sends a message to CO-CELLS, which in turn passes it on to all map CELLs with the new values of spread rates and DMS (read from the GIS database) corresponding to updated weather conditions.

6. APPLICATION

6.1 The data base

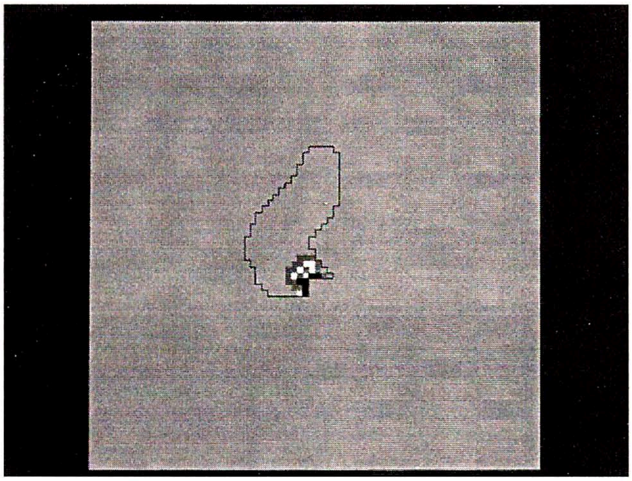
The data used to illustrate the concepts introduced above are from the Ivins Canyon fire, that took place in mid-June of 1988. Ivins Canyon is located in the Spotted Mountain, White Mountains Range, in east-central Arizona and is described in Vasconcelos and Guertin (1992). Briefly, it consists of the following digitized overlays: topography, stream channels, timber type, harvested areas, and fire contours, for an area of nine square miles at a scale of 1:12000. The digitized vector files were rasterized to a grid of 75 rows by 76 columns, with a cell size of 1 acre on the ground (208 ft x 208 ft).

Weather data gathered at the fire camp, were used to generate a set of weather-related map overlays. These were input into the FIREMAP system, together with topography and vegetation data overlays, for calculation of the fire ROS, DMS, and FLI (Vasconcelos and Guertin 1992). It should be noted that the weather information was gathered in a standard procedure designed to collect support information for fire fighting. The data were not collected with this kind of study in mind, and some adjustments had to be made to use it in the simulations. The weather data were not available with one hour periodicity. There were measurements taken with both shorter time intervals and longer time intervals. Consequently, averages of the prevailing weather conditions within each our were used in the simulation.

6.2 Simulation and results

The simulation of the Ivins Canyon fire is done for a period of four hours, on June 11, 1988 from 15:00 to 19:00 p.m. The weather data are updated hourly and new sets of ROS, FLI, and DMS are computed hourly. The simulations start from a source line that corresponds to a portion of the perimeter of the previously burned polygon (from 13:00 to 15:00 p.m.) lying in the direction of fire spread, and away from the burned area. Another limitation of this study relates to the manner in which the areas already burned are handled. Since the simulations start with a source line that is considered the fire front, it has been decided that the area lying behind it (burned area to the South) should be excluded from the simulation. This results in the blocky appearance of the simulations at the bottom of the simulated burned area. Additionally, there is the limitation of not having fire contours for comparison of the simulated fire progression with real fire progression. There is only one contour corresponding t the total area burned in the four hour period.

The results displayed in **Figures 6,7 and 8** show that the simulated and the real fire have a similar overall shape, and that in the early stages the simulated fire closely follows the path of the real fire. However, at the end of the simulation time there is a marked overprediction of burned area near the source of the fire.



Time = 35.6

Figure 6 - Illustration of how fire spread progresses at the beginning of the simulation. Cell state transitions times are not synchronized, nor do they happen at regular time intervals. Dark gray are burning cells, white represents burned out cells, light gray is the study area, and black is the fire source cells

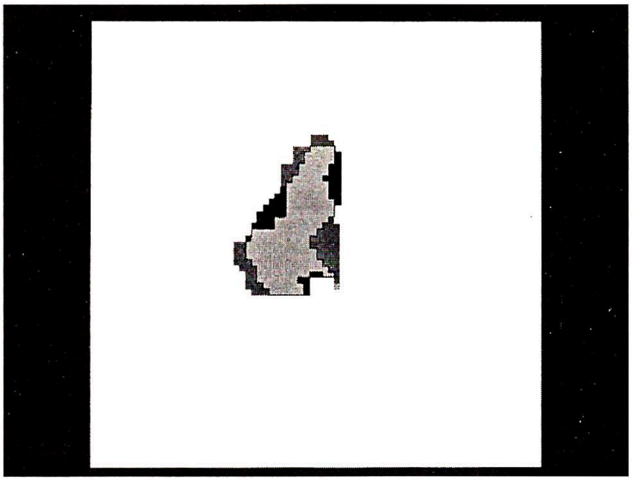
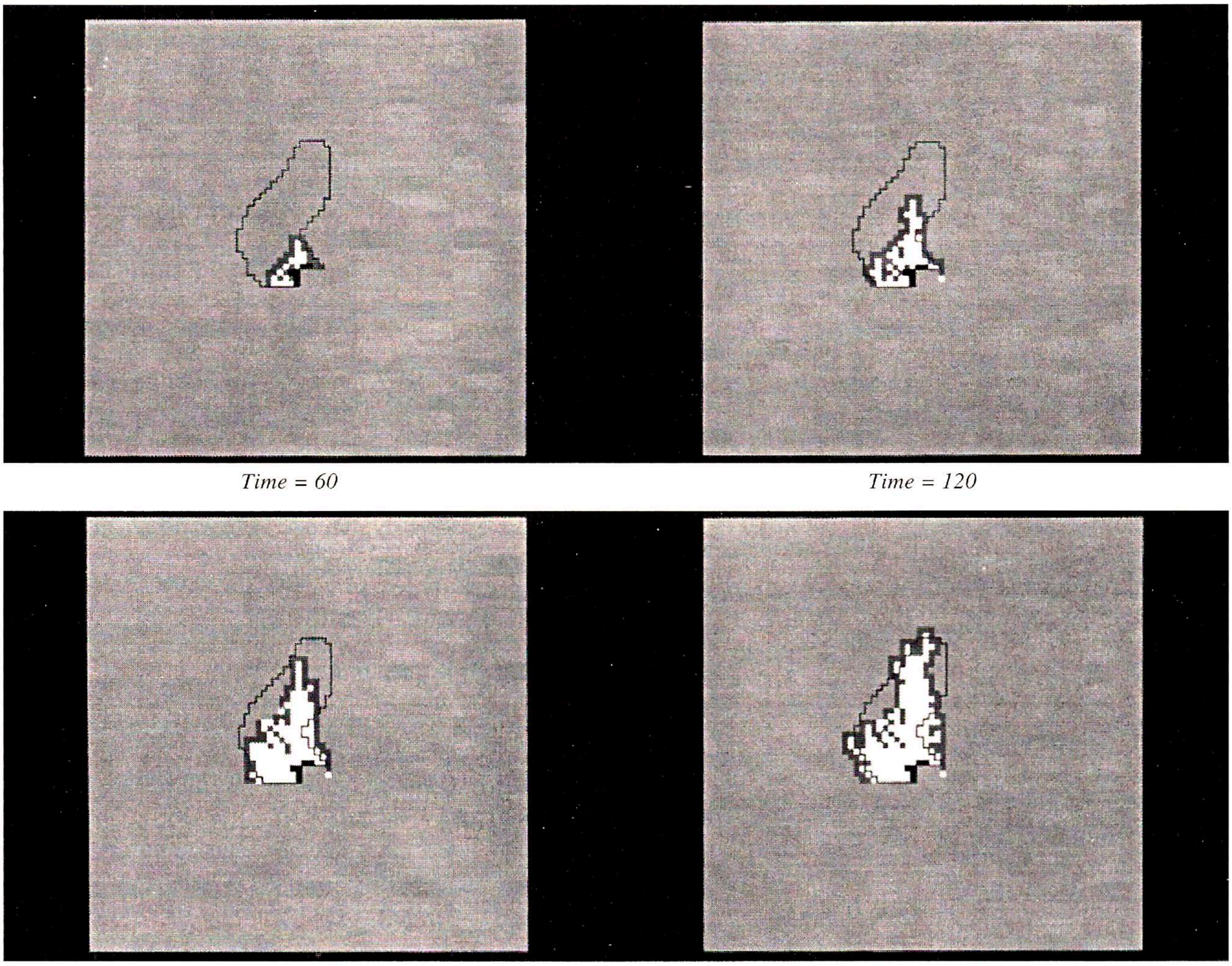


Figure 8 - Comparison of predicted and actual burned areas. Light gray represents correct prediction of burned cells. Dark gray represents overpredictions, black represents underpredictions, and white is the study area background. Black cells in the base of the fire are the source cells



Time = 60 *Time = 120*

Time = 180 *Time = 240*

Figure 7 - Simulation results after one, two, three, and four hours. Dark gray represents burning cells, white represents burned out cells, light gray is the study area, and black is the fire source cells

7. DISCUSSION

The results indicate that the DEVS model may be used to realistically simulate fire growth. The problems found in many earlier GIS-based simulations of fire spread, related to the lack of flexibility of the operators and to the discrete time nature of the simulations, are overcome. The DEVS model provides the flexibility for using several rates of spread in the same cell. Under a constant weather scenario, a cell may burn at different rates and in different directions depending on its position relative to the spreading fire. Additionally, each cell may burn in a direction that is different from that of its neighbours. A DEVS-GIS environment will also facilitate linkage with models for other dynamic processes relevant to fire growth modeling, such as models for surface winds over mountainous terrain.

Since the DEVS model uses a continuous time base, there is no need to use discrete time steps. Thus, instead of displaying maps of burned areas at fixed time intervals that show the patch of cells burned during that time step, maps are displayed at event times without loss of information on when the cells become ignited. The overpredictions near the source of the fire may be related to the failure to incorporate a procedure to extinguish cells. Even though the cells that burn out in reality may correspond to low rates of spread in the model, they still keep the ability of igniting their neighbours. The neighbours may in turn, burn well and propagate the fire through a path that in reality terminates in a burned cell. There are also possible sources of error that are not related to the simulation process, originating from data collection and in the ROS, DMS and FLI predictions using Rothermel's equation.

Currently, the fire model assumes that all the boundaries of a cell are reached simultaneously, and thus there may be errors associated with the fact that all neighbours of a burning cell get ignited simultaneously. An approach to contagion including different ignition times for the different neighbours of a burning cell may be easily implemented. One can calculate the different times a cell takes to reach each of its boundaries based on knowledge of the burning direction and rates of spread. Thus the model cell can have events scheduled at the times of contagion in the faster directions and reduce the respective elapsed times from the time of the slower direction. The cell is considered as burned out when the last boundary is reached. This approach may be best suited in lower resolution data bases with large cells, and lose significance as resolution increases.

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