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## GENETIC ALGORITHM BASED SIMULATION–OPTIMIZATION FOR FIGHTING WILDFIRES

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Wildfire is one of the most significant disturbances responsible for reshaping the terrain and changing the ecosystem of a particular region. Its detrimental effects on environment as well as human lives and properties, and growing trend in terms of frequency and intensity of wildfires over the last decade have necessitated the development of efficient forest fire management techniques. During the last three decades, Forest Fire Decision Support Systems (FFDSS) have been developed to help in the decision-making processes during forest fires by providing necessary information on fire detection, their status and behavior, and other aspects of forest fires. However, most of these decision support systems lack the capability of developing intelligent fire suppression strategies based upon current status and predicted behavior of forest fire. This paper presents an approach for development of efficient fireline building strategies via intelligent resource allocation. A Genetic Algorithm based approach has been proposed in this paper for resource allocation and optimum fireline building that minimizes the total damage due to wildland fires. The approach is based on a simulation–optimization technique in which the Genetic Algorithm uses advanced forest fire propagation models based upon Huygens principles for evaluation of cost index of its solutions. Both homogeneous and heterogeneous environmental conditions have been considered. Uncertainties in weather conditions as well as imperfect knowledge about exact vegetation and topographical conditions make exact prediction of wildfires very difficult. The paper incorporates Monte-Carlo simulations

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to develop robust strategies in uncertain conditions. Extensive simulations demonstrate the effectiveness of the proposed approach in efficient resource allocation for fighting complex wildfires in uncertain and dynamic conditions.

*Keywords:* Genetic algorithm; forest fire; simulation–optimization technique.

## 1. Introduction

Forest fires affect human lives and forest ecosystem in many different ways. The short term or immediate effects of fire are consumption of vegetation, removal of wooden debris, and depletion of soil organic matter. It heats soil, threatens human safety, destroys properties, and kills animals unable to avoid excessive heat and smoke. Fire-caused changes in soil productivity and forest structure affect future vegetation development that influences soil loss due to erosion. Fire-caused changes in water temperature and sedimentation rates affect the populations of aquatic organisms. These and other immediate effects of fire continue to shape forests long after any flames have passed. In recent years, in spite of large expenditures and substantial infrastructure dedicated to wildland firefighting, the damage done in terms of acres burnt has risen dramatically and has reached record highs during the last couple of years. This is evident from the fact that during 2004–2008 wildland fires have consumed approximately 41 million acres of land as per the data provided by National Interagency Fire Control [National Interagency Coordination Center (2007)]. The severity of the wildland fires can be judged from the fact that during just a period of two weeks, the October 2007 California wildland fires resulted into approximately 0.5 million acres of burnt land, evacuation of a million people, and had a price tag of over 1 billion dollars. Apart from these short term socio-economic impacts, large wildland fires have smoke-related health impacts, and huge long-term environmental impacts. Mega wildland fires pump a large amount of carbon-dioxide very quickly into the environment which can have tremendous impact on climate. In a study carried out to estimate carbon dioxide (CO<sub>2</sub>) emissions using computer models [Wiedinmyer and Neff (2007)] for October 2007 California fires, it was found that the fires produced 7.9 metric tons of CO<sub>2</sub> in just one week which was equivalent to 25% of monthly CO<sub>2</sub> emissions due to burning of fossil fuels in California.

Impact of forest fires on human lives and properties as well as on environment makes it necessary to effectively manage forest fires. There are overall three aspects of forest fire management; *fire use*, *fire prevention* and *fire suppression* [Stephens and Ruth (2005)]. Fire use is the process in which a naturally or artificially generated forest fire is utilized to manage fuel distribution in the forest by removal of wooden debris and vegetation. Fire prevention includes taking different steps for the prevention of wildfires such as removal of hazardous fuels and generating wide spread consciousness about forest fires. Although fire prevention steps help in damage reduction and in some cases prevention of forest fires (mostly human generated fires), fire suppression is considered as the most important aspect of forest fire management. Lack of total control over removal of hazardous fuels and most

of the forest fires being originated through sources (such as lightning) which are essentially stochastic in nature, *fire suppression* aspect of forest fire management requires special attention.

Fighting a large, active fire is a very challenging task primarily because of the complexity and uncertainties involved in the task. Complexity arises due to a large number of firefighting resources, heterogeneity in types and capabilities of the resources, growing number of homes in proximity to forests, limited logistical access of the fire sites using roads, spatial distribution of the fire, and occurrence of fires simultaneously at multiple locations during high seasons. All the firefighting assets, with their diverse capabilities and constraints, must be managed in real-time so that the entire set of heterogeneous systems operates at the highest possible level of synergy and effectiveness. To compound the complexity, wildland firefighting is time critical in nature and decisions need to be made in an uncertain environment with incomplete/inaccurate information. Uncertainties arise due to the dynamic nature of the task, changing weather conditions, and lack of complete knowledge of fuel and ground conditions. Both the complexity and uncertainty affect the ability to accurately predict the fire growth and use the available resources in an optimal and timely manner.

To help the incident managers in making decisions, Forest Fire Decision Support Systems (FFDSSs) have been developed during the last thirty years which provide valuable information on forest fire behavior, fire detection, and risk assessment. Examples of FFDSS include LANIK [Martell *et al.* (1994)], Spatial Fire Management System (SFMS) of Canada, and FOMFIS [Caballero (1998)] and DEDICS [Ollero *et al.* (1998)] of Europe. LANIK includes an initial attack simulation model that predicts the impact of ground and aerial resources. SFMS incorporates a full implementation of the Canadian Forest Fire Danger Rating System, providing assessments of fire ignition and growth potential, and predicted fire behavior. FOMFIS is aimed at the definition, design, and implementation of a computer based system giving support to the process of planning activities and resource distribution for the preventive operations carried out by the forest firefighting services. The DEDICS system emphasizes more on fire detection, situation awareness, database management, and communication which can support decision making and management. Each of these systems has its own merits and demerits and some were specially developed for some particular scenarios. FFDSSs provide the necessary information for the firefighting incident managers to take appropriate actions for forest fire containment. Recently, Fire and Aviation Management (FAM), a subsidiary of the US Forest Service 2007 [United States Department of Agriculture (2007)], has developed WFDSS (Wildland Fire Decision Support System) tools to help fire managers and agency administrators make decisions regarding strategies and tactics on wildland fires. WFDSS, unlike other fire behavior prediction software such as FARSITE [Finney (1998)], is probabilistic in nature that can incorporate the uncertainty associated with wildfire behavior. A short description of FARSITE is provided in the next section. However, all these decision support systems largely lack

the optimization and intelligent capabilities that can be used for effective decision making and allocation of resources in a dynamic and uncertain environment that characterizes a complex wildfire. Although these FFDSS software have been applied in fire detection, fire behavior prediction, and risk assessment, fire suppression is still mostly performed using thumb rules and the experience of the incident managers. With the advances in the capability to accurately predict fire propagation, the ability to gather and process information for obtaining accurate situational awareness, and the computational optimization methods, it is believed that paradigm shifting methods can be developed to help incident managers in generating strategies for effective wildfire fighting.

Firefighting efforts in wildland areas require different techniques, equipments, and training from the more familiar structural firefighting found in populated areas. There are several methods used by firefighters for fighting complex wildfires which can be broadly categorized into two kinds of strategies: *direct attack* and *indirect attack*. Direct attack is any treatment applied directly to burning fuel such as wetting, smothering, or quenching the fire chemically or by physically separating the burning from the unburned fuel. This strategy includes the utilization of urban and wildland fire engines, aircrafts, and helicopters for applying retardants directly to the burning fuel. In most of the cases, the objective is to build firelines around the fire for suppression. Indirect attack associates with the preparatory suppression tactics used at a distance from the burning fuels. This strategy also involves building firelines via methods such as fuel reduction, backfire generation, and wetting unburned fuels. A fireline is a strip of land cleared of flammable materials like plants and shrubs. After the initial firefighting crews mitigate wildfire propagation rate with the help of fire retardants, firelines are required to be built that can actually contain the forest fire. These may be constructed by physically removing combustible material with tools and equipment. Firelines may also be created by a method called backfire generation which involves creating small, low-intensity fires using drip-torches or flares. When the firefront reaches the fireline, it stops propagating further due to the lack of additional flammable materials. Thus, fireline building strategy is considered to be one of the most basic strategies for the containment of wildland fires.

In real-life wildfire fighting scenarios, a limited number of resources are available and the goal is to use the resources in the best possible manner so that the total damage due to the forest fire is minimized. Optimum resource utilization and allocation is an important part of forest firefighting. Over the years, researchers have worked in different aspects of wildland fires such as modeling of forest fires, fire prediction, fire detection, and risk evaluation. A good amount of research has been performed in the area of forest fire suppression strategies such as in [Chi et al. \[2003\]](#), [Fiorucci et al. \[2004\]](#), [Hu and Sun \[2007\]](#) and [Mees et al. \[1993\]](#). [Fiorucci et al. \[2004\]](#) have put forward a general framework for the formalization of problems relevant to forest fire emergency management through real-time resource assignment. [Hu and Sun \[2007\]](#) have presented a design of fire suppression simulation using a discrete

event agent model based on a discrete cellular space. Finney *et al.* [2009] have performed a generalized mixed-model analysis that provides a first step in explaining the relation between suppression efforts and large fire containment. Mees *et al.* [1993] have provided a mathematical model for the probability of the fireline succeeding in containing a fire. Chi *et al.* [2003] have used the Genetic Algorithm (GA) to construct the best combination of available resources for forest firefighting but optimal fireline building and realistic fire growth models have not been used. In two recent papers, HomChaudhuri *et al.* [2009, 2010] proposed a GA based framework for resource allocation and optimal fireline building for wildfire propagation in homogenous terrain with constant weather and wind conditions and heterogeneous terrain with added uncertainty in weather and wind conditions. Generally the forest fire suppression is carried out using thumb rules and heuristic knowledge of the incident manager, and the current decision support systems lack the application of computational intelligence techniques. Particularly, to the best of our knowledge, computational intelligence techniques in optimal fireline construction haven't been used in literature or in practice.

In this paper, simulation–optimization technique is used to solve the problem mentioned in the previous section. The general optimization problem includes a set of controllable parameters that optimize a given objective function with a set of constraints. Simulation–optimization technique finds its application where an analytical expression of the objective function is not directly available but can be evaluated via simulation. As mentioned in the previous section, the goal of this paper is to minimize the total damage due to wildfires which can be measured as the total area burned till the fire is completely suppressed. It is very difficult to form an analytical expression of the objective function for this problem that includes both the fire propagation and fire suppression occurring simultaneously. Hence, simulation–optimization technique is thus used in this paper.

Simulation–optimization technique has gained its popularity in the last few decades especially with the advent of higher computing powers. There are several methods available in the literature to carry out the mentioned technique [Fu *et al.* (2005)]. These methods can be broadly classified into gradient-based search methods, statistical methods, response based search methods, heuristic methods, stochastic optimization, and model based method. The gradient based methods make use of the gradients to determine the search direction but works only in continuous domain and requires the cost function to be differentiable. The response surface method [Barton and Meckesheimer (2005)] uses approximate functional relationship between input and output variables via use of methods such as linear regression and neural networks. The primary drawback of this method is that it uses excessive simulation points in one area before exploring the others and thus as the number of input variables increase, the method becomes computationally expensive. Statistical methods include methods such as ranking and selection [Kim and Nelson (2005)] which make use of statistical theory and select the best solution from the competing ones but find their application in discrete domain only where

the candidate solutions are relatively small. Heuristic methods include GA, Tabu search [Glover and Laguna (1997)], simulated annealing, etc. These methods have gained popularity for their ability to handle large search spaces and avoid getting trapped into the local minima.

In this paper, the GA is used to generate the optimum fireline that minimizes the damage due to forest fire and determines the location of the firefighting crews on the landscape from which fire suppression should start as well as the shape of the firelines so that the fire doesn't escape (firefront reaching the firelines before they are built) and the total damage is minimized at the same time. The search space of the location parameters  $(x, y)$  of the crews is the entire terrain or at least a big part of it so that the optimal solution lies within the bounds of terrain in consideration. The search space of the shape parameters of the firelines to be built is the complete domain of the real numbers. Apart from the very large search space, the search space is noisy with discontinuities. Particularly, the search space becomes noisy when uncertainty is added in the forest fire propagation model. Furthermore, it may be noted that an analytical expression establishing the relationship between the decision variables and the cost index (i.e., the total damage due to forest fire) is not available. These reasons justify the use of GA search and optimization technique which has been quite successful in obtaining the global solutions for the complex search problems [Holland (1992)].

The importance of fireline building strategy in wildland fire containment provides the major motivation for using fireline construction as a firefighting strategy in this paper. The major contribution of this paper is the development of the GA based simulation–optimization framework that can utilize the fire propagation models for optimal resource allocation for fighting complex wildfires. Another significant contribution of this paper is that this paper considers both homogenous terrain with constant wind velocity, and heterogeneous terrain (e.g., hilly terrain with slopes) with added uncertainty in wind speed and direction. Uncertainty in weather conditions is a major issue in fighting a large wildfire that influences its own weather in a very unpredictable manner. The incorporation of uncertainty in wind velocity (both rate and direction) in the forest fire propagation model and usage of Monte Carlo simulations lead to a more realistic implementation of the proposed GA based approach and the solutions are expected to be more robust to uncertainties in weather conditions. This paper, in overall, presents an application of the GA into wildfire fighting and demonstrates how the use of such data driven techniques in such application, which has hitherto relied mostly on expert knowledge and heuristics, can result in minimization of damage.

The paper is organized as follows: First, a brief discussion on forest fire propagation model is provided for both homogenous and heterogeneous conditions. Then, the wildfire fighting problem considered in this paper is formulated, which is followed by a description of the proposed GA based simulation–optimization approach. Finally, simulation results are presented followed by discussions and conclusions.

## 2. Fire Propagation Model

In order to develop intelligent resource allocation and optimum fireline building strategies for the minimization of total damage due to wildland fires, a realistic forest fire propagation model is required. It is imperative to model fire growth from a spatio-temporal perspective. Integrating the many aspects of fire behavior (wind, terrain, temperature, humidity, fuel, etc.) is a very challenging task, and a lot of research has been carried out over the last few decades. In this section, fire growth models in both homogenous and heterogeneous terrains are discussed.

### 2.1. Fire propagation in homogenous terrain

Séro-Guillaumea *et al.* [2008] has proposed a general framework of forest fire propagation model. There are a couple of basic approaches to fire growth models, namely cellular and the two dimensional deterministic wave approaches. The cellular or the grid-based approach for fire growth is simulated in a discrete fashion on a regularly structured grid. A well cited example of this modeling methodology was developed by Kourtz and O'Regan [1971] which was based on a Monte Carlo technique. The model enables simulation of a small fire at any time after ignition by predicting the perimeter location and burning area for prescribed fuel and weather conditions. While cellular models are simple and provide necessary insight for conceptual system studies, they need additional mechanisms to incorporate temporal changes such as shifting wind-speed and direction as well as fuel moisture. For example, Karafyllidis and Thanailakis [1997] have developed a model to predict fire growth using cellular automata that can predict fire growth accurately in homogeneous as well as heterogeneous conditions, and can easily incorporate weather conditions and land topography.

Some of the problems associated with cellular models are avoided by the vector or wave approach based on Huygens' Principle [Richards (1990)] for fire growth modeling. This approach is incorporated into the fire growth model *FARSITE* (Fire Area Simulator). *FARSITE* model is widely used by the USDI National Park Service, USDA Forest Service, and other federal and state land management agencies to simulate the spread of wildfires, and it automatically computes wildfire growth and behavior for long time periods under heterogeneous conditions of terrain, fuels, and weather. In this modeling technique, also called Envelop model, each point on the fire-front is considered to be a new source of fire generation and the fire-front is propagated as a continuously expanding fire polygon or ellipse at specified time-steps. The fire polygon is defined by a series of two-dimensional vertices (points with  $X, Y$  coordinates). The number of vertices increases as the fire grows over time (polygon expands). The expansion of the fire polygon is determined by computing the spread rate and direction from each vertex and multiplying by the duration of the time-step. Assuming a uniform fuel distribution, uniform landscape and weather, and constant wind direction, firefronts propagate in an elliptical fashion. Equations

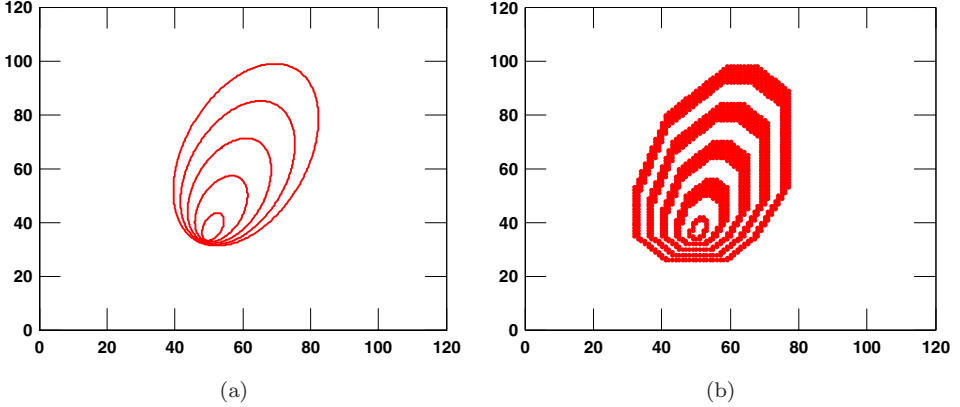


Fig. 1. (Color online) Fire-fronts obtained using the envelop model in homogeneous conditions at different time instants (a) for a continuous case, and (b) in a discrete grid based framework.

governing the Envelop model are provided below:

$$\begin{aligned}
 X_t &= \frac{a^2 \cos \theta (x_s \sin \theta + y_s \cos \theta) - b^2 \sin \theta (x \cos \theta - y_s \sin \theta)}{\sqrt{b^2 (x_s \cos \theta + y_s \sin \theta)^2 - a^2 (x_s \sin \theta - y_s \cos \theta)^2}} + c \sin \theta \\
 Y_t &= \frac{-a^2 \sin \theta (x_s \sin \theta + y_s \cos \theta) - b^2 \cos \theta (x \cos \theta - y_s \sin \theta)}{\sqrt{b^2 (x_s \cos \theta + y_s \sin \theta)^2 - a^2 (x_s \sin \theta - y_s \cos \theta)^2}} + c \cos \theta
 \end{aligned} \tag{1}$$

Here  $X_t$  and  $Y_t$  are the rate differentials and the angle  $\theta$  is the wind direction.  $x_s$  and  $y_s$  are the orientation of the vertex on the firefront in the terms of component differentials. The location of the new fire-front is available by multiplying the rate differentials with the step time. Figure 1 shows the fire-fronts at different time steps using the above model for a continuous environment (Fig. 1a) and a discretized grid-based environment (Fig. 1b).

## 2.2. Wind-slope correction

Fire propagation rate and direction is primarily affected by weather and topology of the terrain. There are other factors that have their effect on fire behavior. Those factors include vegetation or fuel distribution and moisture content. However, this paper incorporates just the two factors viz. weather/wind and topology into the fire propagation model. This provides a fairly good overall realistic simulation of forest fire and serves the purpose of this paper which is development of optimization framework that uses such fire propagation models. In a homogenous terrain, the rate and direction of fire propagation is primarily determined by the wind speed and direction. In heterogeneous terrain, the fire propagation rate is higher when fire moves upslope and the rate decreases when fire moves down-slope. The direction of fire propagation is affected by the slope and aspect at each point of the terrain. In order to obtain a more realistic forest fire propagation model, the slope and

wind correction model is required to be incorporated. Sharples [2008] has listed the different wind-slope models available, such as models of McArthur [1966], Rothermel [1972], Albini [1976], Finney [1998], and has proposed a more general framework for such a correction. This framework is briefly described below.

When dealing with heterogeneous terrain, two significant topographic parameters are: *topographic slope* and *topographic aspect*. Topographic slope is defined as the maximum inclination of a terrain surface at a particular point. Considering the terrain modeled as an elevation function  $h(x, y)$ , where  $h(x, y)$  is the elevation at a point  $(x, y)$ , the topographic slope at a point is formally defined as the length of the gradient vector field. The gradient vector field can be obtained by the following equation:

$$\nabla h(x, y) = \left( \frac{\partial h}{\partial x}, \frac{\partial h}{\partial y} \right). \quad (2)$$

And thus, the length of the gradient vector field is given by the norm:

$$\|\nabla h(x, y)\| = \sqrt{\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2}. \quad (3)$$

The topographic slope is typically described by the topographic slope angle  $\gamma_s$ ,

$$\tan \gamma_s = \|\nabla h(x, y)\|.$$

The alignment of topographic slope is known as the *topographic aspect*  $\gamma_a$ . A vector normal to the surface at a particular point can be decomposed into a horizontal component, in the  $x - y$  plane, and a vertical component, perpendicular to the  $x - y$  plane. The direction of the horizontal component defines the topographic aspect, which is expressed as the angle between the horizontal component and the north (positive  $y$ -axis). The topographic aspect direction points down-slope. The topographic aspect in terms of the elevation function  $h(x, y)$  can be expressed as the direction of the negative gradient vector field  $\nabla h(x, y)$ . The aspect angle at a point is shown in Fig. 2.

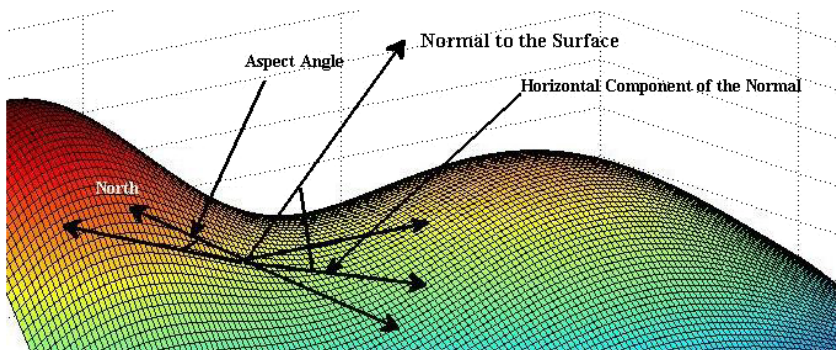


Fig. 2. (Color online) Schematic diagram showing the topographic aspect of the terrain.

The wind-slope correction can be approached using two methods: *scalar* and *vector*. In the scalar method, the rate of fire propagation at a particular point in the terrain is the product of the wind induced rate of spread ( $R_w$ ), and a scalar quantity that is a function of the slope at the given point. In the McArthurs model, the rate of fire propagation at a particular point in the terrain is given by:

$$R(w, \gamma_s) = R_w \exp(0.069\gamma_s). \quad (4)$$

Here  $\gamma_s$  is the slope faced by the firefront at a particular point. The general framework of wind-slope correction in forest fire propagation is proposed in Sharples [2008] and can be expressed by:

$$R(w, \gamma_s) = B_{-\gamma_a} S_{\gamma_s} B_{\gamma_a} R_w. \quad (5)$$

Here  $B_{\gamma_a}$  is the change of basis matrix which facilitates a transformation from cardinal coordinates to the terrain-following coordinates. The *terrain-following*  $\{t, u\}$  coordinates aligns with the upslope and across slope directions. The cardinal coordinates  $\{x, y\}$  are the global coordinates of the terrain where  $y$  direction is towards the north and  $x$  direction is towards the east. Figure 3 shows such a coordinate system. The matrices  $B_{\gamma_a}$  and  $S_{\gamma_s}$  are given by equations:

$$B_{\gamma_a} = \begin{bmatrix} -\cos \gamma_a & \sin \gamma_a \\ -\sin \gamma_a & -\cos \gamma_a \end{bmatrix}. \quad (6)$$

$$S_{\gamma_s} = \begin{bmatrix} 1 & 0 \\ 0 & \sigma \end{bmatrix}. \quad (7)$$

The term  $\sigma$  in Eq. (7) is the scalar factor similar to the one used in Eq. (4). Performing the matrix operation as in Eq. (5), the rate vector of fire propagation at a particular point is available whose magnitude and angle correspond to the rate and direction of forest fire propagation at that point of the heterogeneous terrain. The detailed steps performed in Eq. (5) are as follows: first a coordinate transformation is obtained from cardinal coordinates to the terrain following coordinates ( $B_{\gamma_a}$ ).

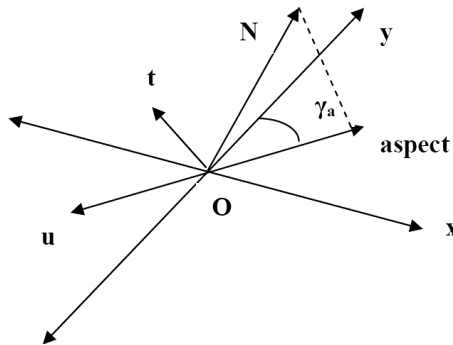


Fig. 3. Schematic diagram showing the cardinal and terrain following coordinate systems.

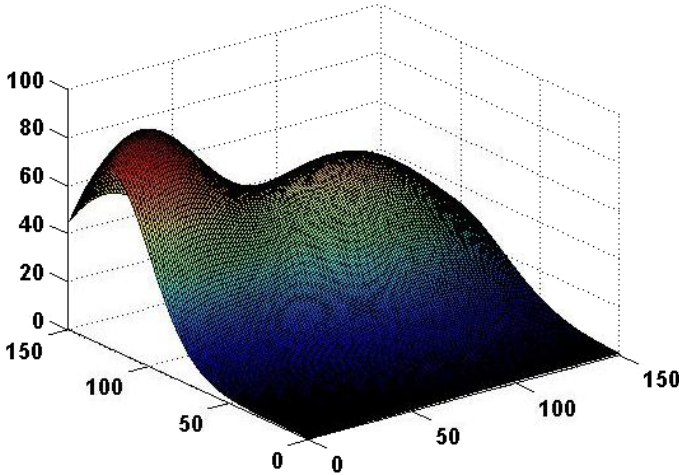


Fig. 4. (Color online) A randomly generated terrain.

The scalar slope-correction relationship ( $S_{\gamma_s}$ ) is applied to the upslope component to the wind induced rate of spread vector. With the multiplication of the vector  $B_{-\gamma_a}$ , the rate of fire propagation vector is obtained in the cardinal coordinates from the terrain following coordinates.

In Fig. 4, an arbitrarily generated terrain is shown that is used in this paper as an example terrain to apply the fire propagation model and verify resource allocation and fireline building strategies generated by the proposed GA based technique. A grid based method is used in the simulation with a grid size of  $3 \times 3$  units. Since most of the forest fire propagating software such as FARSITE and others use raster files to represent the terrain, wind-weather conditions, and other information such as vegetation/fuel distribution, a grid based representation of terrain is more suitable for generation of resource allocation and firefighting strategies. Furthermore, the grid based method facilitates easy integration with Geographic Information Systems (GIS) that are widely used in disaster management.

Figure 5 shows a simulation of forest fire propagation on the mentioned terrain (Fig. 4). Figure 5(a) shows the fire propagation with only wind-slope correction without any uncertainty. The simulated result shows the tendency of the fire rate increase towards the upslope of the terrain. Furthermore, uncertainty has been incorporated in wind direction. Figures 5(b) and 5(c) show the effect of uncertainty in wind direction and wind speed respectively. The wind direction in this simulation is considered to follow a normal distribution with a mean of  $20^\circ$  and a standard deviation of  $3^\circ$  and changes at each time step during the simulation. The rate and direction of fire propagation  $R$  at *each point* of the terrain are calculated using Eq. (5) when  $R_w$  changes in both direction and magnitude since because of uncertainties in wind direction and magnitude.

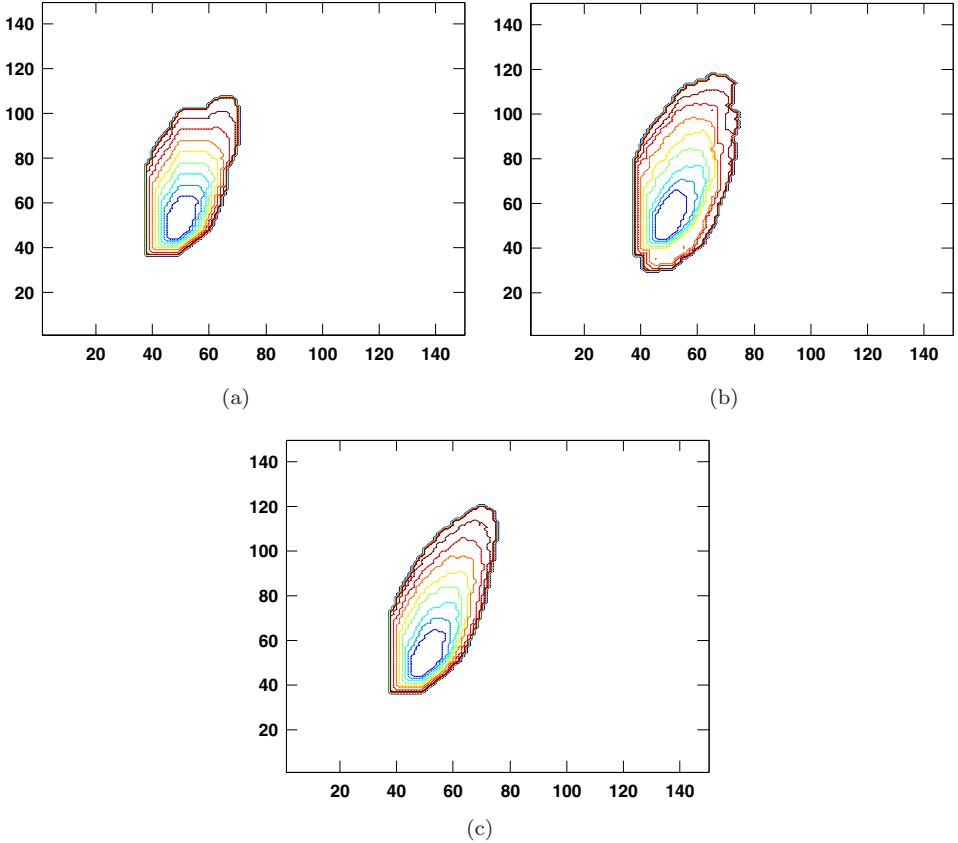


Fig. 5. (Color online) Fire propagation after considering wind and slope correction: (a) only wind-slope correction; (b) wind-slope correction with uncertainty in wind direction; (c) wind-slope correction with uncertainty in wind speed.

### 3. Problem Description

Broadly speaking, the objective of this paper is to develop a framework for optimal decision making for the containment of forest fires. This paper considers fireline construction as the firefighting strategy, and determines allocation of fireline construction resources and shapes of firelines for optimal containment of wildfire. After the initial attack to mitigate the wildfire, firelines are built around the firefront that contains the wildland fire. Firelines, as mentioned earlier, can be considered as a strip of trail or road that is built with the purpose of separating the fire from the fuel so that the forest fire stops from further propagation. The optimization problem is to perform optimum resource allocation and to find the optimal fireline that can be built with the given resources and which minimizes the total burned area and also ensures that fire does not escape. Fire is said to escape when firefront reaches the semi constructed fireline and hence cannot be contained within the fireline.

This paper considers a finite number of firefighting teams who build firelines with specified shapes. The paper considers polynomial curves for the firelines. The optimization problem is to find the initial locations of the firefighting teams in the given terrain from where they would start building the fireline as well as the parameters of the polynomial curves that define the shapes of the firelines. Two cases are considered in this paper: (i) Problem I: a homogeneous case where the terrain and weather conditions remain constant and (ii) Problem II: a heterogeneous case where the terrain has varying slopes and weather (primarily wind) condition changes. In a real world scenario, weather/wind condition is difficult to predict and the uncertainty or noise associated with the wind speed and direction results in inaccurate fire behavior prediction. Fire behavior prediction is also affected by the uncertainty present in terrain and fuel distribution modeling. Thus the optimal fireline to be built should be robust enough to contain the fire under such uncertainties or random effects. This kind of intelligent resource allocation promises better and more robust results in minimization of forest fire damage in a real world scenario.

Mathematically, the optimization problem can be formulated as follows. Consider  $N$  teams of firefighters. Their initial positions on the 2D terrain are given by  $(x_k, y_k)$ ,  $k = 1, 2, 3, \dots, N$ . The team ‘ $k$ ’ builds the fireline given by the function  $y = f_k(x, d_k)$  where  $f_k$  is the function representing the shape, and  $d_k$  is the vector of parameters for the function  $f_k$ . The structures of functions  $f_k$  are assumed to be known a priori. The optimization problem is to determine the initial positions  $(x_k^0, y_k^0)$ , and parameters  $d_k$  of functions  $f_k$  that minimize the following cost index ( $PI$ ):

$$PI = \begin{cases} \text{Area enclosed by curves} \\ y = f_k(x, d_k) k = 1, 2, \dots, N & \text{If fire does not escape the enclosed area} \\ \infty & \text{If fire escapes the enclosed area.} \end{cases} \quad (8)$$

The fire is said to escape when firefront reaches the fireline (represented by the above curves) before the teams finish building their respective lines. For this purpose, a constant rate of fireline construction ‘ $r$ ’ (unit length per unit time) is considered. If a team finishes building its own line, it helps the other team who has not built the line. It may be noted that each team starts from its initial position and finishes at the initial position of the next team. The last team finishes at the starting position of the first team to form the enclosed space. Hence, this introduces the constraint on the shape of the firelines which can be represented by:

$$y_{k+1}^0 = f_k(x_{k+1}^0, d_k) \quad \text{for } k = 1, 2, \dots, N - 1. \quad (9)$$

$$y_1^0 = f_k(x_1^0, d_k) \quad \text{for } k = N. \quad (10)$$

Equation (9) essentially says that the initial position of the  $(k + 1)$ th team lies on the fireline built by the  $k$ th team. Equation (10) says that the initial position of the 1st team lies on the fireline built by the  $N$ th team.

### 4. Approach

This paper proposes a GA based approach to solve the problem specified in the previous section. Because of its ability to provide global solution for complex problems with large search spaces, and its robustness, the GA [Holland (1992)] is chosen for this research. The GA is a search and optimization technique to find the exact or approximate global solutions to an optimization and search problem. The GAs are based on mechanics of natural selection and natural genetics [Goldberg (1989); Miachalewicz (1996); Garg and Kumar (2002)]. They combine survival of the fittest among the candidate solutions with randomized, yet organized, information exchange to form search algorithms with capabilities of natural evolution. The GA starts with a random creation of a population of strings representing candidate solutions and thereafter generates successive populations of strings that improve over generations.

The processes involved in the generation of new populations mainly consist of operations such as reproduction, crossover and mutation. The steps involved in GA can be summarized as follows:

- Step 1: Initialize a population-string of individuals. Each individual string represents a candidate solution.
- Step 2: Evaluate the fitness or loss index of each individual.
- Step 3: Carry out the genetic operations (See Fig. 6) viz. reproduction (selection of sub-population for next generation), crossover (swapping of corresponding parts of strings at a random point for two individuals selected on the basis of their fitness), and mutation (randomly changing the value of strings at randomly selected position of the string).
- Step 4: Test for termination criterion.

The GA operates by finding a solution that minimizes a loss index. A loss index is the measure of goodness or effectiveness of a solution. In the problem considered in this paper, the loss index is the total burned area due to wildland fire and is obtained

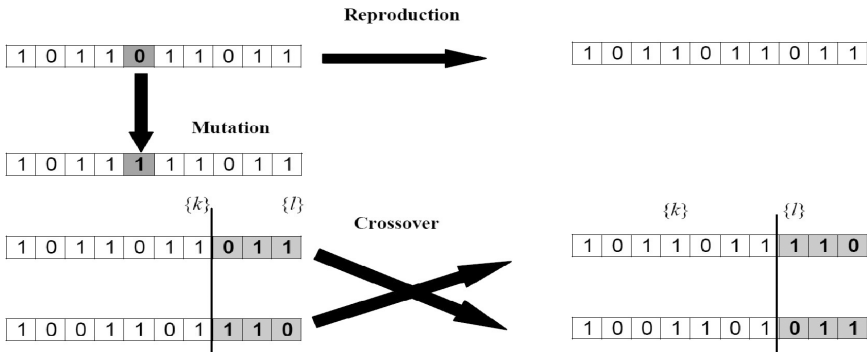


Fig. 6. Schematic diagram showing various GA operations.

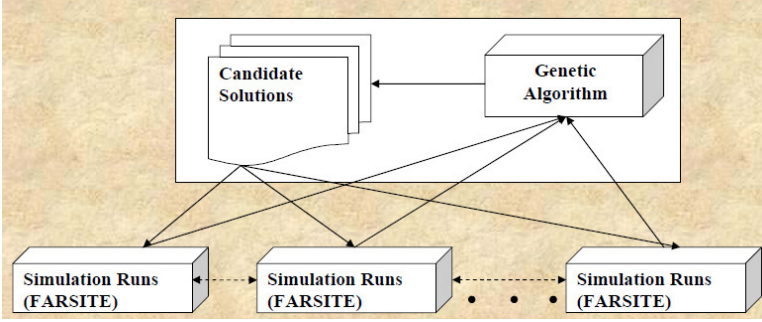


Fig. 7. Schematic representation of the GA based simulation–optimization technique.

using Eq. (8). Since the loss index for the GA (the total area burned due to fire after fireline building is complete) cannot be explicitly represented as a function of the parameters, simulation–optimization technique (Fig. 7) is used to evaluate the performance of each solution of the GA. In the proposed simulation–optimization technique, the forest fire progress is simulated with the help of fire propagation models when the fireline is built concurrently. A population of solutions that have different parameters representing different strategies of the firefighting agents are generated by the GA and their performances are evaluated when the wildfire is propagated concurrently. The fitness value of each solution is sent back to the GA where new populations are generated with the loss index information of the previous generation. After a number of generations, the optimal solution is provided by the GA which minimizes the loss index.

To obtain the optimal fireline for the containment of the forest fire, the GA based approach should provide: (i) the initial locations of the firefighting teams from which fireline building will start; and (ii) the parameters of the polynomial shapes that define the firelines to be built. Considering quadratic polynomial, the equations for the firelines are given by:

$$y = a_k x^2 + b_k x + c_k, \quad (11)$$

where  $k = 1, \dots, N$  represent the  $N$  firelines to be built by the  $N$  firefighting teams.

To obtain an overall closed shape using  $N$  different quadratic shaped firelines built by  $N$  different crews, each crew should move from its assigned starting point in the terrain to the starting point of the next crew. This constraint is represented by Eqs. (9) and (10). The equation governing such fireline is given below in which the firefighting agents building the fireline ‘ $k$ ’ move from point  $(x_k^0, y_k^0)$  to  $(x_{k+1}^0, y_{k+1}^0)$ :

$$y = y_k^0 + a_k(x^2 - (x_k^0)^2) + b_k(x - x_k^0), \quad (12)$$

where  $x_k^0 \leq x \leq x_{k+1}^0$  considering  $x_k^0 < x_{k+1}^0$  without loss of generality. It may be noted that the locations  $(x_k^0, y_k^0)$  and  $(x_{k+1}^0, y_{k+1}^0)$  are determined by the GA. Furthermore, if GA provides the parameter  $b_k$ , the other parameter  $a_k$  of the fireline

can be computed simply using the constraint given by Eqs. (9) and (10) and is given by:

$$a_k = \frac{(y_{k+1}^0 - y_k^0) - b_k(x_{k+1}^0 - x_k^0)}{(x_{k+1}^0)^2 - (x_k^0)^2}. \tag{13}$$

The initial locations of the firefighting teams in the terrain,  $(x_k^0, y_k^0)$ , along with the parameter  $b_k$  of each of the firelines given by Eq. (12) are the required parameters to be optimized by the GA, where  $k = 1$  to  $N$ . When the locations and the parameters  $b_k$  are available, the parameter  $a_k$  ( $k = 1$  to  $N$ ) can be computed as shown in Eq. (13). Thus given a number of finite firefighting teams  $N$  there are  $3N$  parameters to be determined by the GA. Table 1 shows parameters to be determined by the GA for a given number of firefighting teams  $N$ .

Now, as the firelines are built from one point to another, some combinations of the points as initial and final points for firelines will result in the intersection of two firelines which would represent a practically wrong solution. Hence, concepts from the Traveling Salesman Problem (TSP) [[Dorigo and Gambardella \(1997\)](#)] are introduced here to obtain the proper order of the points so that all the points are touched with no intersection of two or more firelines. In this case, a TSP algorithm can be used to obtain the proper sequence of the points so that an intersection of lines is avoided.

Both Figs. 8 and 9 show an example with four firefighting crews. The location of the firefighting crews (1, 2, 3 and 4) generated by GA. Figure 8 shows the incorrect traveling order with a sequence 1–2–3–4–1. The intersection between the generated firelines signifies an impractical solution. Figure 9 shows the correct order, 1–3–2–4–1, after applying the traveling salesman algorithm that negates the possibility of intersection of generated firelines.

Table 1. Sample solution.

Team 1	Team 2	Team 3	...	Team $N$
$x_1, y_1, b_1$	$x_2, y_2, b_2$	$x_3, y_3, b_3$	...	$x_N, y_N, b_N$

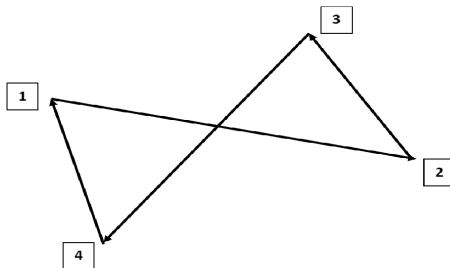


Fig. 8. Incorrect traveling order.

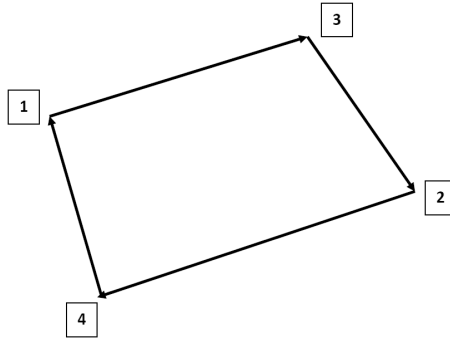


Fig. 9. Correct traveling order.

## 5. Simulation Results

In this paper, a grid based approach for terrain representation is considered where the whole terrain is divided into grids of size  $3 \times 3$  units. Whenever the firefront touches a particular grid, that grid is considered to be on fire and acts as the source of fire propagation in the next time step according to the Huygens's principle of wave propagation. Using  $N$  quadratic function shaped firelines with different parameters, a lot of flexibility on the overall fireline shape is added for the forest fire suppression. Since fire propagation rate is not uniform in all directions, such flexibility in overall fireline shape is expected to give better results than a fixed shape, such as an ellipse or circle, of the overall fireline. In this problem,  $N$  firefighting teams are assumed to be working at a constant rate and when any team finishes its assigned task of fireline building, it helps the next team to complete its assigned task and hence their combined rate of fireline production increases. In this case, GA has  $3N$  parameters to optimize which consist of the initial locations  $(x_k^0, y_k^0)$  of the  $N$  firefighting teams and the parameters  $b_k$  in Eq. (12) for the  $N$  firelines ( $k = 1$  to  $N$ ). A sample solution of the GA will look like Eq. (14),

$$\text{sample solution} = [x_1 \cdots x_N y_1 \cdots y_N b_1 \cdots b_N]. \quad (14)$$

In Equation (14),  $(x_1, y_1) \cdots (x_N, y_N)$  are the initial locations of the  $N$  firefighting resources from where fireline building would start and  $b_1 \cdots b_N$  are the parameters determining the shape of the firelines.

A moderate grid size of  $3 \times 3$  square units is chosen in this paper for the simulation purpose which provides a fairly good resolution of the solution as well as manageable search space. In each iteration, a TSP algorithm is utilized to obtain the proper order of the teams' locations as explained in the previous section. Simulation of fire propagation model is used to compute the cost index of each candidate solution using Eq. (8). Once loss indices of all solutions are obtained, the GA operations are used to generate populations in subsequent generations and eventually obtain the optimal solution.

During the execution of various operations, the GA often generates solutions that do not satisfy some constraints of the problem or are unacceptable from a practical point of view. Keeping those solutions in the pool of populations leads to unnecessary computations and sometimes wrong solutions. This paper addresses the above issue by associating a very high cost index value to those solutions. For example, in the problem considered in this paper, the GA generated solutions are considered unacceptable if the initial firefighting agent locations and the firelines that are yet to be built are on grids which are already on fire.

As described in Sec. 3, this paper addresses two problem cases. First is Problem I in which fire propagation is considered in a homogenous terrain (flat terrain without any slope) with constant weather and wind conditions. The second is Problem II in which fire is allowed to propagate in an arbitrarily generated terrain (Fig. 4) with varying slopes and with added uncertainty in the wind speed and direction. This gives a more realistic simulation of wildfires in uncertain and dynamic scenarios.

Since the search space for the GA is large for both the problems, 300 generations and a population size of 301 is used. The mutation probability is generally considered low for most of the problems and is taken as 0.0077 and the crossover probability of 0.77 is considered. Steady state GA is used with a steady state population size of 31. In steady state GA, a certain percentage of the population selected by their fitness is retained into the next generation without being altered. This saves computation time since the objective function evaluation is computationally intensive. The fire is assumed to start at time  $t = 0$  and the fire suppression effort starts at  $t = 4$  units of time. The fireline building rate of each firefighting agents are considered same and is considered to be 12 grids per time step. The results obtained from extensive simulation studies are provided below.

**Problem I.** In this problem, a homogenous terrain and constant wind and weather condition is considered. The wind direction is assumed to be constant at  $20^\circ$  with the positive y-axis. The results obtained using different numbers of firefighting groups are shown below.

Considering four firefighting teams, the red curve in Fig. 10(a) shows the initial firefront from when the fireline building starts. The small blue circles show the initial locations of the four firefighting crews obtained by the best solution from the GA. Figure 10(b) shows the fireline constructed at the end of one time step as discussed in the previous section. Figure 11 shows the completed fireline (blue curve) and the final firefront (red curve). It is seen that more priority is given to the head of the firefront since rate of fire spread is highest in this direction. Figure 12 shows how the cost index of the best solution converges to the optimal value as the generation in the GA increases. The GA uses randomness in its search operation and the solution points get more optimal as generation progresses and converges to the optimal solution. For a problem with large search space, enough number of generations should be considered for the GA to reach its optimal solution. To demonstrate that the proposed method is consistent in obtaining optimal solutions,

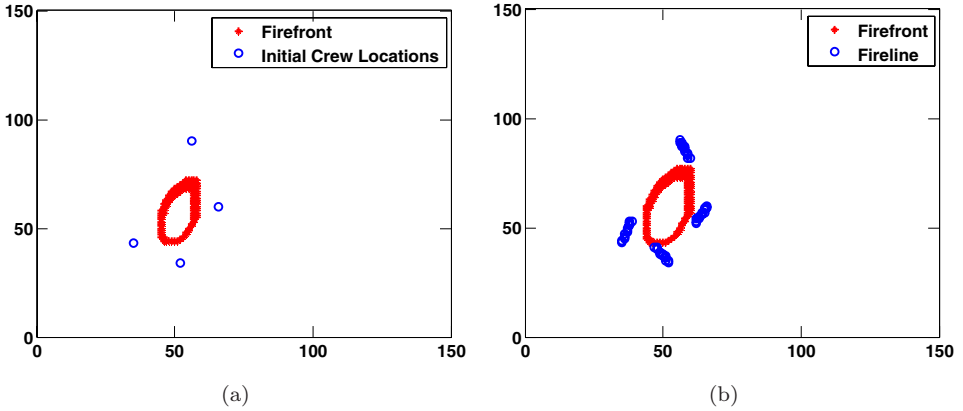


Fig. 10. (Color online) (a) Initial firefront and firefighting crew location and (b) fireline construction effort after one time step.

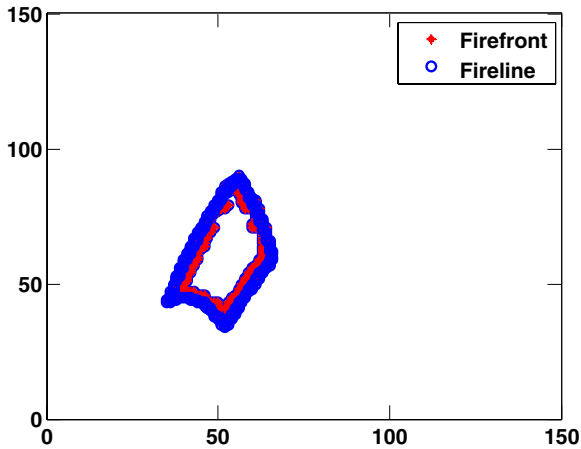


Fig. 11. (Color online) Completed fireline and the final firefront.

we carried extensive simulations and present here the results for 10 simulations with four resources (firefighting teams). The performance of GA for these 10 runs is showed in Fig. 13. It can be seen from this figure that for all the simulation runs, the GA converges to the optimal solution demonstrating the consistency of the proposed method.

Furthermore, the proposed method was applied to different number of firefighting teams to demonstrate the applicability and scalability of the technique. Considering five firefighting teams, the results obtained are shown in Figs. 14 and 15. Figure 14(a) shows the initial firefighting crew locations from the best solution obtained by the GA from which the fireline building should start while Fig. 14(b) shows the completed fireline and firefront. Figure 15, like Fig. 12, shows how the

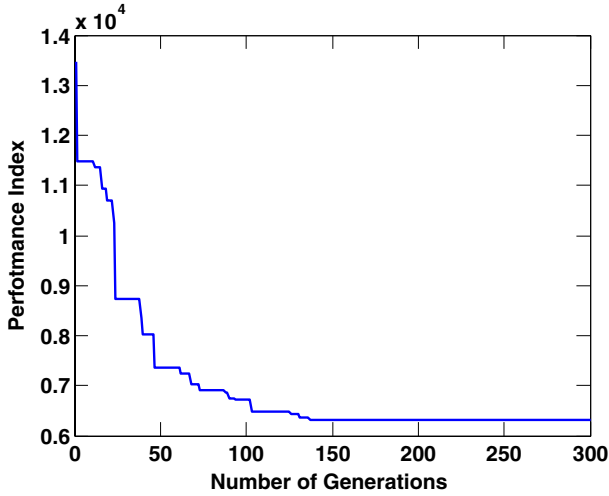


Fig. 12. (Color online) Cost index of the best solution in the generation plotted against the number of generations with four firefighting teams.

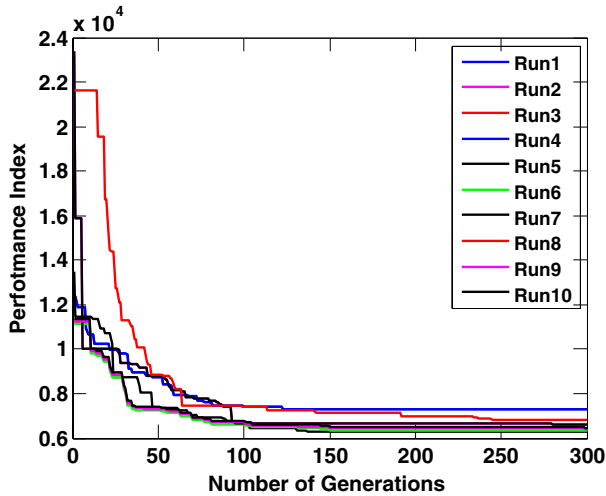


Fig. 13. (Color online) Cost index of the best solution in the generation plotted against the number of generations for 10 different simulations with four firefighting teams.

GA converges to optimum solution with the number of generations when five fire-fighting crews are considered. Figure 16 shows the performance of the firefighting teams when six and seven resources are considered. The cost index considered is the total area burned and it is clearly observable in Fig. 16 that lesser area is burned when using six or seven resources than five or four resources, which is expected.

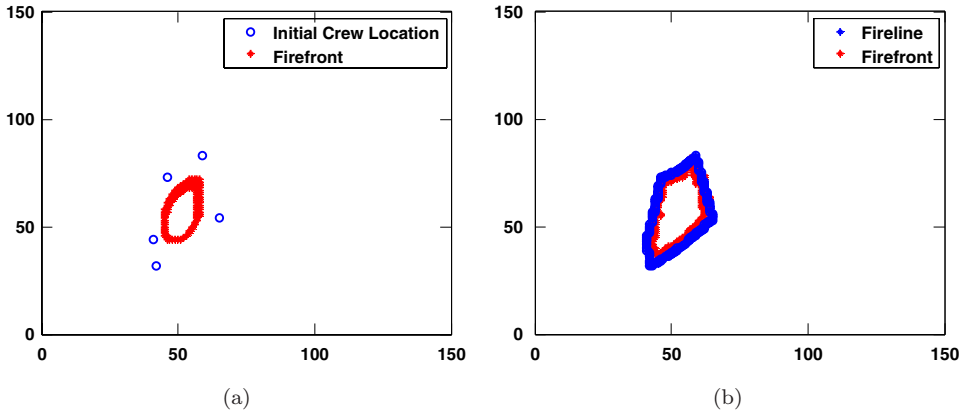


Fig. 14. (Color online) Initial and final state of firefront progression and fireline construction for five firefighting teams (a) initial firefront and firefighting crew location and (b) completed fireline.

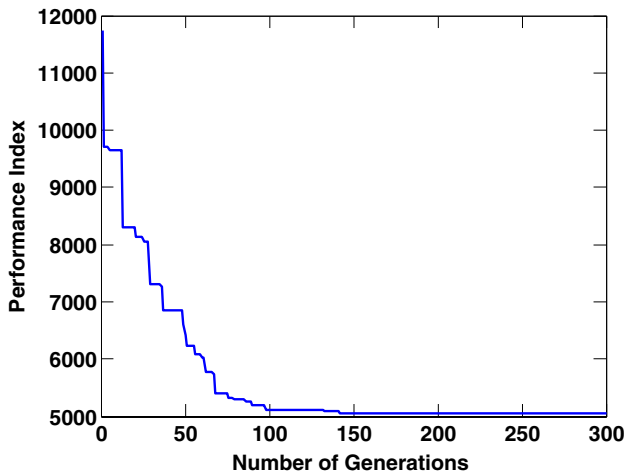


Fig. 15. (Color online) Cost index of the best solution in the generation plotted against the number of generations for five firefighting teams.

A comparison of the GA with respect to the Particle Swarm Optimization (PSO) is carried out to evaluate the performance of the GA in terms of two criteria: optimality of the solution and the processing time. The comparison is performed for the case with four firefighting teams and the other conditions of the simulation remain the same as in GA. For a fair comparison with the GA (with 301 population size and 300 generations), 301 particles with 300 iterations are considered for the PSO. It is found that the computation time for both the GA and the PSO are of the same order (PSO being slightly faster) but PSO with 301 particles and 300 iterations obtained a solution which is far from the global solution. Both the GA and

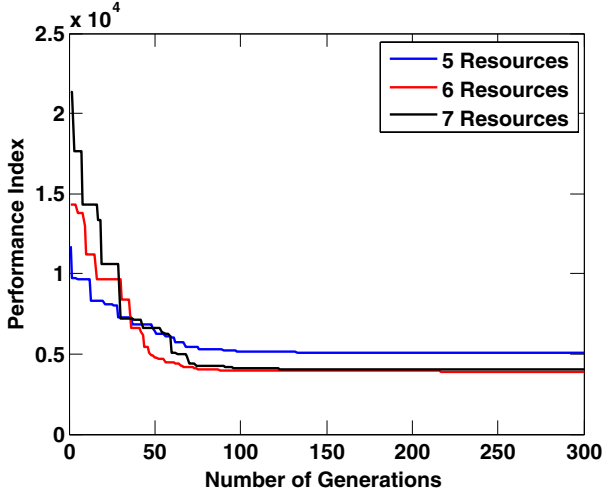


Fig. 16. (Color online) Cost index of the best solution in the generation plotted against the number of generations for five, six, and seven firefighting teams.

Table 2. Comparison of GA and PSO.

	GA	PSO
Computation time (seconds)	106,733	72,959
Cost index of optimal solution (Units)	6,318	12,330

the PSO algorithms were run for three different times for the above case. Table 2 shows the best solution obtained in the three runs. It may be noted that the PSO can provide more optimal results as the numbers of particles and iterations are increased. However, this would result in high computational time. For example, using 500 particles and 400 iterations, the solution obtained by PSO is 8901 but it takes 169915 seconds of computation time.

**Problem II.** In this problem, heterogeneous terrain and changing weather-wind conditions are considered. Along with wind-slope correction to the fire propagation model, uncertainty is added to the wind speed and direction and the final rate of propagation and direction of the forest fire. The source of uncertainty can be noisy wind speed and direction predictions, or uncertainty in terrain modeling or imperfect knowledge about the fuel distribution. Though no heterogeneous fuel distribution is considered, the uncertainty added to the final rate of spread and direction of fire propagation compensates for heterogeneous and uncertain fuel distribution. The wind direction is sampled from a normal distribution with a mean of  $20^\circ$  and a standard deviation of  $10^\circ$ , i.e., wind direction changes in each time step based upon sampling from the above normal distribution. The wind speed is also considered to be normally distributed with a mean of 15 miles/hr and a standard

deviation of 3 miles/hr. Wind speed, final rate and direction of forest fire propagation changes from one point to another in the considered terrain at a particular time instant and also changes with time.

Each GA generated solution is used in the fire propagation model to generate the firelines and the firefronts concurrently and hence to evaluate the performance of each solution. It may be noted that a solution may work for one instance of simulation run but may not work for another because of the added uncertainty. To alleviate this problem and to ensure that a solution should work satisfactorily for any scenario that may result in an uncertain and dynamic condition, the paper uses a Monte Carlo based approach. For each solution, the fire propagation model is run for 50 different scenarios. The cost index value for the solution is considered to be the worst of the cost index obtained from individual scenarios. This ensures that the GA generated solution is robust enough to entirely contain all the different shapes of the firefronts that may result due to varying wind-slope, weather, or terrain conditions. Figure 17 shows the initial state (Fig. 17(a)) and the final state (Fig. 17(b)) of firefront progression and fireline construction for the optimal solution obtained when four firefighting teams are considered. Figure 18 shows the evolution of the best cost index in the generation as the number of generation progresses. Clearly, the area burned for Problem II is more than Problem I. This is because of the fact that GA in Problem II gives a conservative solution to the problem so that the generated optimum fireline can handle uncertainties in fire behavior. The obtained optimum solution is thus robust enough to handle different possibilities arising due to uncertainties associated with forest fire propagation. Similarly considering five firefighting teams, Fig. 19(a) shows the initial locations of the firefighting crews and Fig. 19(b) shows the completed fireline and firefront. Figure 20 shows the evolution of best cost index in the generation as the number of generation progresses for five firefighting teams.

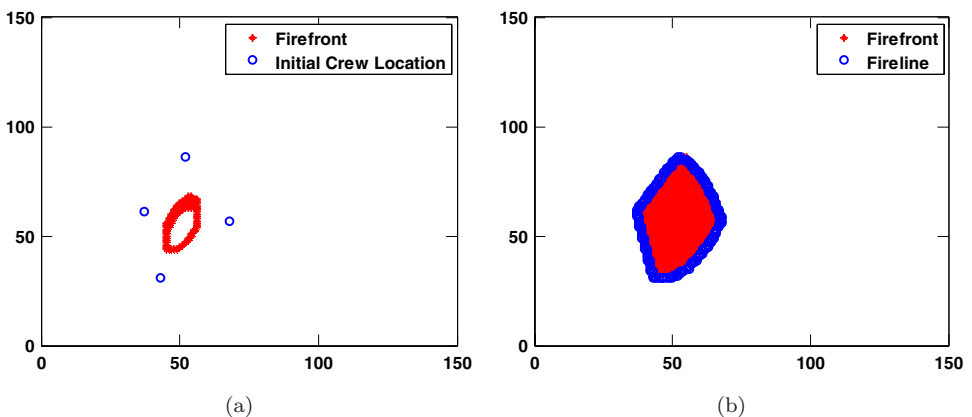


Fig. 17. (Color online) Initial and final state of firefront progression and fireline construction for four firefighting teams (a) initial firefront and firefighting crew location (b) completed fireline.

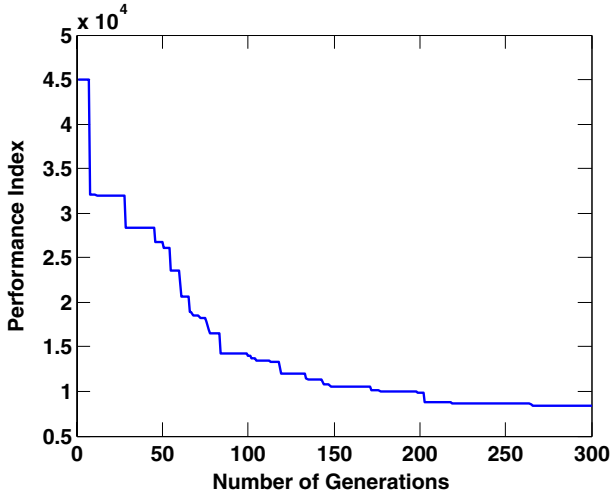


Fig. 18. (Color online) Cost index of the best solution in the generation plotted against the number of generations for four firefighting teams.

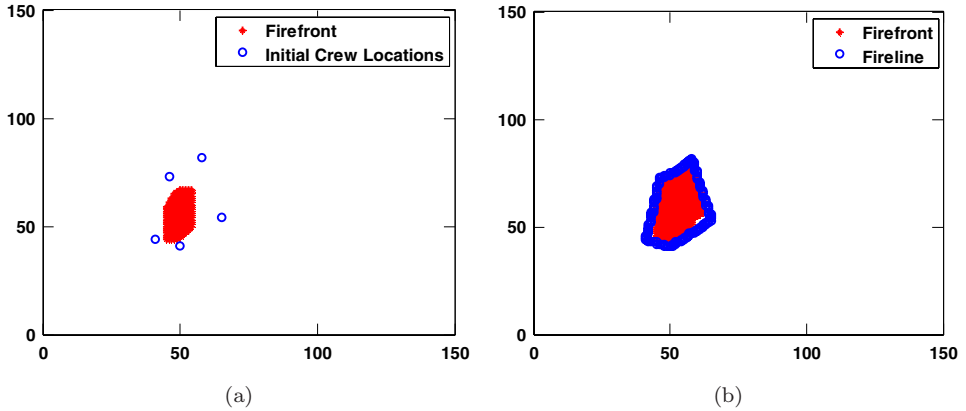


Fig. 19. (Color online) Initial and final state of firefront progression and fireline construction for five firefighting teams (a) initial firefront and firefighting crew location and (b) completed fireline.

### 6. Discussions and Future Research Directions

The GA generates a population of several solutions that gets evaluated in each generation via simulation of the fire propagation model. All these calculations make the proposed GA based simulation–optimization technique computationally extensive. In-spite of this, real time applicability of this technique is not of much concern because of time scale in which wildfires are fought and also due to the fact that the proposed technique can be easily adapted to facilitate parallel computations. As mentioned before, fighting a large forest fire involves a large number of resources. A

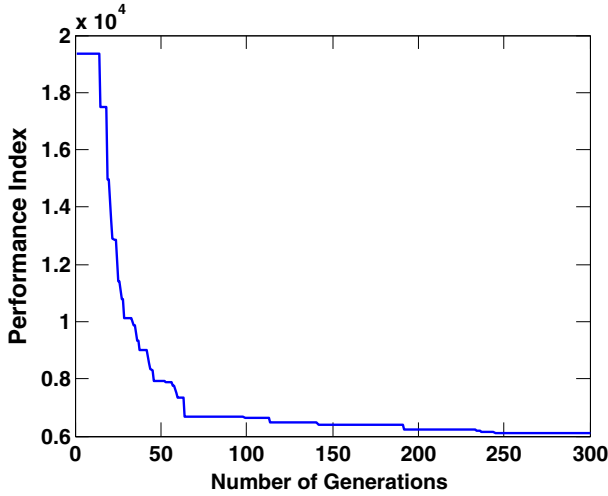


Fig. 20. (Color online) Cost index of the best solution in the generation plotted against the number of generations for five firefighting teams.

large number of resources drastically increases the search space and the number of parameters to be optimized by GA. Extensive simulations carried out using a different number of firefighting teams demonstrates that the proposed method is easily applicable to a varying number of resources. However, to carry out optimization in a large search space using a GA, the number of generations and population size have to be increased. These result in even more computations. To alleviate this problem, the future work includes use of distributed GA to facilitate parallel computation. This is a technique in which the complete parameter string is divided into sub-strings, and the GA operations are carried out in the populations of sub-strings. A designed interaction between the populations of sub-strings ensures that the global cost index is optimized. Another direction for future work is reinforcement learning for obtaining optimal resource allocation policy. The availability of high-fidelity simulation environment provides a good motivation of applying reinforcement learning techniques. The drawback of this method is scalability which can be overcome by implementing the reinforcement learning in a distributed manner. Another aspect of the proposed method is that it carries out the resource allocation using a completely data driven method. Wildland firefighting, on the other hand, has hitherto been carried out using expert knowledge and heuristic rules. In fact, a method that systematically combines heuristic knowledge of a firefighter with data driven techniques will have much enhanced capabilities. For example, in the proposed method, the search space of the GA can be drastically reduced and solutions can be achieved much faster if heuristic knowledge of a firefighter is incorporated. Also, real world wildfire fighting is carried out on rough terrain that poses constraints on deployment and movement of firefighting teams. These constraints can be easily incorporated

in the proposed method. One of the future directions for research is to integrate the proposed method with Geographical Information Systems that will provide detailed information about the topography of the region.

## 7. Conclusions

In this paper, a GA based simulation–optimization framework for generating intelligent wildfire fighting strategies has been developed for an efficient containment of complex wildland fires in both homogenous and heterogeneous conditions as well as in uncertain environment. The optimization framework uses the fire propagation model to evaluate the strategies and guide its search direction to obtain the best strategy for fireline construction that minimizes the total burnt area. One of the major contributions of this paper is to apply the GA based simulation–optimization technique to a wildfire fighting scenario where wind-terrain conditions and hence the fire behavior is uncertain, and demonstrate that such techniques can be used to arrive at better resource utilization decisions. Ability to handle uncertainties become very important in fighting complex wildfires since weather conditions are difficult to predict as well as knowledge about terrain and vegetation is often imperfect. To incorporate heterogeneity in the terrain, the fire propagation model used has been modified to incorporate wind-slope correction. Furthermore, uncertainties in wind direction and speed have been incorporated to obtain robust firefighting strategies. The proposed Monte Carlo based GA approach is shown to effectively handle the uncertainty in the fire behavior. The proposed strategy has been verified via extensive simulations carried out using different numbers of firefighting teams/resources available. This preliminary study demonstrates that the availability of accurate fire propagation models, new technologies to gather and process information, and accurate weather prediction models can be used with simulation–optimization techniques as proposed in this paper for more efficient and robust decision making in complex wildfires.

## References

- Albini, F. A. [1976] “Combining wind and slope effects on spread rate,” *Unpublished Memo to RC Rothermel* **19**, 1–76.
- Barton, R. and Meckesheimer, M. [2006] “Metamodel-based simulation optimization,” *Handbooks of Operations Research and Management Science* **13**, 535–574.
- Caballero, D. [1998] “FOMFIS: A computer based system for forest fire prevention planning,” *Proc. 3rd Int. Conf. Forest Fire Research*, 2643–2652.
- Chi, S.-D., Lim, Y.-H., Lee, J.-K., Lee, J.-S., Hwang, S.-C. and Song, B.-H. [2003] “A simulation based decision support system for forest fire fighting,” *Lect. Notes Comput. Sci.* **2829**, 487–498.
- Dorigo, M. and Gambardella, L. M. [1997] “Ant colony system: A cooperative learning approach to the traveling salesman problem,” *IEEE Trans. Evol. Comput.* **1**, 53–66.
- Finney, M. A., Grenfell, I. C. and Mchugh, C. W. [2009] “Modeling containment of large wildfires using generalized linear mixed–model analysis,” *Forest Sci.* **55**, 249–255.

- [Finney, M. A. \[1998\] “FARSITE: Fire area simulator-model development and evaluation,” United States Department of Agriculture. Rocky Mountain Research Paper RMRS-RP-4 revised.](#)
- [Fiorucci, P., Gaetani, F., Minciardi, R., Sacil, R. and Trasforini, E. \[2004\] “Dynamic resource allocation for forest fire risk management,” \*Proc. 15th Int. Workshop on Database and Expert Systems Applications\*, 603–607.](#)
- [Fu, M. C., Glover, F. W. and April, J. \[2005\] “Simulation optimization: A review, new developments, and applications,” \*Proc. Winter Simulation Conference\*, 83–95.](#)
- [Garg, D. and Kumar, M. \[2002\] “Optimization techniques applied to multiple manipulators for path planning and torque minimization,” \*J. Eng. Appl. Artif. Intell.\* \*\*15\*\*, 241–252.](#)
- [Glover, F. and Laguna, M. \[1997\] \*TabuSearch\* \(Kluwer Academic, Boston\).](#)
- [Goldberg, D. \[1989\] \*Genetic Algorithms in Search Optimization & Machine Learning\* \(Addison Wesley Longman Inc, Boston\).](#)
- [Holland, J. H. \[1992\] “Genetic algorithms,” \*Sci. Am.\* \*\*267\*\*, 66–72.](#)
- [HomChaudhuri, B., Zhao, S., Kumar, M. and Cohen, K. \[2009\] “Generation of optimal fire-line for fighting wildland fires using Genetic Algorithm,” \*Proc. ASME 2009 Dynamic Systems and Control Conference\*, DSCC2009–2707. Hollywood, California, USA.](#)
- [HomChaudhuri, B., Kumar, M. and Cohen, K. \[2010\] “Optimal fireline generation for wildfire fighting in uncertain and heterogeneous environment,” \*Proc. 2010 American Control Conference\*, 5638–5643.](#)
- [Hu, X. and Sun, Y. \[2007\] “Agent based modeling and simulation of wildland fire suppression,” \*Proc. 2007 Winter Simulation Conf.\*, 1275–1283.](#)
- [Karafyllidis, I. and Thanailakis, A. \[1997\] “A model for predicting forest fire spreading using cellular automata,” \*Ecol. Model.\* \*\*99\*\*\(1\), 87–97.](#)
- [Kim, S. H. and Nelson, B. L. \[2005\] “Selecting the best system,” in \*Handbooks in Operations Research and Management Science\* \(Elsevier, Amsterdam\), 501–534.](#)
- [Kourtz, P. and O’Regan, W. G. \[1971\] “A model for a small forest fire to simulate burned and burning areas for use in a detection model,” \*Forest. Sci.\* \*\*17\*\*, 163–169.](#)
- [Martell, D. L., Boychuk, D., MacLellan, J. I., Sarkowicz, B. M. and Saporta, R. \[1994\] “Decision analysis of the level of forest fire protection in Ontario,” \*Proc. 1994 Symposium on Systems Analysis in Forest Resources\*, 138–149.](#)
- [McArthur, A. G. \[1966\] “Weather and grassland fire behavior,” Department of National Development. \*Forestry and Timber Bureau Leaflet\*, \*\*100\*\*, 1–23.](#)
- [Mees, R., Strauss, D. and Chase, R. \[1993\] “Modeling wildland fire containment with uncertain flame length and fireline width,” \*Int. J. Wildland Fire\* \*\*3\*\*, 179–185.](#)
- [Miachalewicz, Z. \[1996\] \*Genetic Algorithms + Data Structure = Evolution Programs\* \(Springer Verlag, New York\).](#)
- [National Interagency Coordination Center and Wildland Fire Summary and Statistics \[2007\] National Interagency Fire Center.](#)
- [Ollero, A., Martinez-de dios, J. R. and Arrue, B. C. \[1998\] “Integrated systems for early forest-fire detection,” \*3rd Int. Conf. Forest Fire Research 14th Conf. Fire and Forest Meteorology\*, Vol. 2, pp. 1977–1988.](#)
- [Richards, G. D. \[1990\] “An elliptical growth model of forest firefronts and its numerical solution,” \*Int. J. Numer. Meth. Eng.\* \*\*30\*\* 1163–1179.](#)
- [Rothermel, R. C. \[1972\] “A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service,” Intermountain Research Station, Research Paper INT-115 \(Ogden, UT\).](#)
- [Séro-Guillaume, O., Ramezania, S., Margeritc, J. and Calogineb, D. \[2008\] “On large scale fire propagation models,” \*Int. J. Therm. Sci.\* \*\*47\*\*, 680–694.](#)

- Sharples, J. J. [2008] "Review of formal methodologies for wind-slope correction of wildfire rate of spread," *Int. J. Wildland Fires* **17**, 179–193.
- Stephens, S. L. and Ruth, L. W. [2005] "Federal forest-fire policy in the United States," *Ecol. Appl.* **15**, 532–542.
- United States Department of Agriculture [2007] Fire and Aviation Management Fiscal Year 2007 in Review, FS-9031 2008.
- Wiedinmyer, C. and Neff, J. C. [2007] "Estimates of CO<sub>2</sub> from fires in the United States: Implications for carbon management," *Carbon Bal. Manag.* **2**, 1–10.