AARMS Vol. 15, No. 1 (2016) 85–92. **10.32565/aarms.2016.1.8**

The Examination of the Economical Effectiveness of Forest Fire Suppression by Using Theoretical Fire Spread Models

Ágoston RESTÁS[1]

It is commonly known that firefighting is very expensive solution; therefore it isn't useless to study it by the criteria of efficiency. But the meaning of efficiency for fire managers can be different from the meaning of efficiency for economists. From an economic viewpoint, it is stricter than from a technical view. Method: this research used geometric aspects of the fire spread created rectangular and concentric circles models and used basic mathematic calculations and logical conclusions. Results and discussion: The rectangular model shows the criteria of economic efficiency of firefighting. Moreover, the results from rectangular model can be transferred also to the section of concentric circles model. Based on the concentric circle model we can define both the economic efficiency of fighting forest fire and minimal criteria of successful suppression expressed by the elementary information we have regarding the actual fire.

Keywords: *firefighting, economic efficiency, rectangular model, concentric circle model*

Introduction

There is difference between the professional and economical effectiveness. Efficiency is obviously stronger phenomena, in this case not just the professional effectiveness but the criteria of the efficiency must be satisfied. [1] No doubt in the sphere of state protection (e.g. medical service, police, disaster management, and fire service) it is very difficult to speak about efficiency, much easier about the political or social effectiveness. However author is sure there are ways to find the balance between useful actions and costs. Fighting against forest fire is usually a long term intervention meaning that it is very expensive; [2] therefore it is not useless to look through some of its economic aspects.

Economic aspects of forest fire were studied by many authors in different ways. One of the oldest studies focused on the annual rate of area burned in Canada and it calculated how to maximize the return of the investment after forest fire. [3] "The clear message from this analysis is that the correct measure of fire's impact is not the burned timber, but rather the reduction in the annual harvest. And the true business of the fire control agencies is the protection of that annual harvest." [3: 9]

Other researchers studied forest fire threatened countries [4] or regions [5] where economic aspects were also involved mostly with "soft" approaches. There are studies where

1 Ph.D., associate professor, National University of Public Service, Institute of Disaster Management, Department of Fire Prevention and Rescue Control; e-mail: restas.agoston@uni-nke.hu

economic aspects of fighting against forest fire come from technical parts mainly focusing on details of aerial suppression. [6] [7]

New researches count with the economic impact of forest fires in case of wildland urban interface (WUI) [8] or in this special case even with the costs of health problems. [9]

Because of the high expenditures for aerial suppressions there are many studies focusing on economic view of aerial firefighting. Fogarty [10] made a simple comparison of the cost-effectiveness among the aircrafts used for fire suppression; Pekic [11] suggests new high rate spray technique for making higher effectiveness; Marchi (et al.) [12] made geographical analysis of effectiveness using helicopters for first attack. Author evaluates Gould's works as the most relevant literature in this topic; he has many studies focusing on economic aspects of aerial firefighting. [13] [14] [15]

Author uses geometric way to understand the background of the suppression method better making two models, which are rectangular and concentric circle model, to make it easier to understand some features of the economic aspects of firefighting. Naturally, the assumptions in both models are idealistic, meaning that they require more development.

Rectangular Model

First model examine a forested area limited by rectangular without concrete geometric data. Assumptions are idealistic, like homogenous forest, flat area; there is no wind, etc. In this model the fire front spreads linearly. (Figure 1) Author demonstrates this theory by more rectangulars, placing them next to each other, which shows the fire development by geometric. Some part of this model is similar to the model used by Australian experts however not the same. [13]

After starting the intervention *(B)* the controlled line takes α with the frame of this example edge *(C)*. During the suppression this controlled line will continue till the opposite edge of the frame, meaning that the fire front is extinguished *(D)*. Based on Pythagoras theory it is easy to understand that the value of α depends on the speed of fire spread *(v_{fire})* and the speed of suppression *($v_{suppression}$)*. The higher the speed of suppression related to speed of fire spread *(R)*, the higher the angle α is and vice versa.

$$R\left\langle \frac{v_{fire}}{v_{suppression}} \right\rangle \uparrow\downarrow \Rightarrow \alpha\uparrow\downarrow \tag{2.1}$$

Before the fire front forested area can be saved *(M_{forest})*, beyond it can be counted as damages *(K_{forest})*. The main purpose of the suppression is that the value of saved forest must be as high as possible or the damages must be as low as possible. Author means, we search the end values of the positive options.

$$M_{forest} \Rightarrow max;\ and\ K_{forest} \Rightarrow min \tag{2.2}$$

Above statement can be accepted by the view of professional but since it doesn't count with the cost of extinguishing the result can't be the standard for the view of national economy.

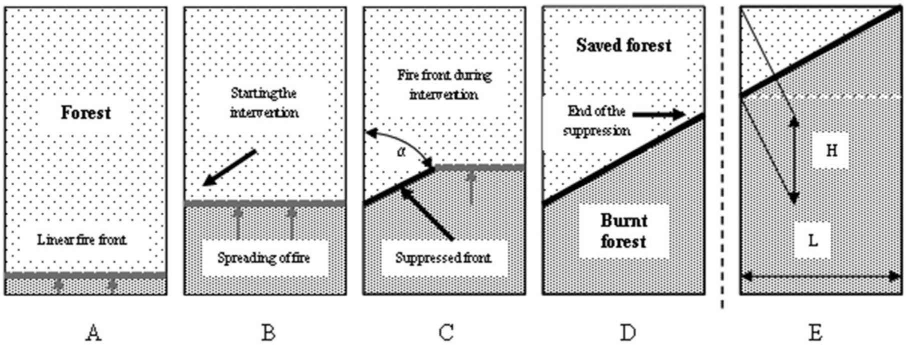

Figure 1. Rectangular model.
(Made by the author.)

To maximize the end value of the professional effectiveness' function can't be justify in all cases at the view of national economy. At the latest one all costs of resources must be counted, such as technical and human resources but even the in-material value of the forest and the higher risk of citizens caused by absence of firefighters from urban area.

If the cost of suppression is higher than the saved forest the action is uneconomical in view of national economy. Looking at the rectangular model the efficiency of national economy is valid till the saved forest is higher than the cost of extinguishing.

$$M_{forest} \geq \Sigma\, C_{FF} \Rightarrow \gamma_{NE} \geq 1 \qquad (2.3)$$

M_{forest} – value of the saved forest (€);
C_{FF} – cost of suppression (€);
γ_{NE} – efficiency of the national economy (–).

Using the notation of the rectangular model the first part of formula (2.3) can be expressed also in another way.

$$\frac{1}{2} LHP_{forest} \geq \Sigma\, C_{FF} \qquad (2.4)$$

L – width of the forest area (m);
H – fire spread from the beginning of the suppression till the end of it (m);
P_{forest} – unit value of the forest (€m^{-2}).

This model doesn't count with the burnt area at the beginning of the suppression, not during the action or at the end of it. In this case the efficiency of the extinguishing in view of national economy doesn't depend directly on the burnt area.

Triangles with L width fire front, α angles and H length in this model are same in any time of beginning the intervention and also same the costs belonging to these triangles.

Based on the rectangular model we get the threshold limit in that case, if the cost of firefighting is equal to the value of the saved forest. In cases of later beginning of the suppression, the cost of firefighting remains the same however the value of the saved forest is reducing continuously till that where remains only the *L-α-H* featured triangle *(E)*. It means the threshold limit of the efficiency geometrically.

$$\lim_{M_{forest} \to \Sigma C_{FF}} f(M_{forest}) = \Sigma C_{FF} \tag{2.5}$$

In this case, if both the above threshold limit is realized and the efficiency of the firefighting is valid, in any earlier beginning time of the intervention will satisfy the requirements of the efficiency too. The earlier is the beginning of the suppression, the higher the value of the saved forest is. The limit value gives just the minimum threshold of satisfying the criteria of the efficiency.

The angle α of the suppressed fire front depends on the rate of fire spread and the speed of firefighting. Higher fire spread causes lower angle α and longer time of extinguishing and vice versa. In view of higher efficiency the higher angle α is required.

The rectangular model counts with linear fire front however in the reality almost each fire starts from small ignition points. In case of ideal and positive spread conditions the fire front will spread radially.

Necessary but not yet Sufficient Condition for the Efficient Suppression

Model counts with small ignition point, v_{fire} speed of fire spread, t_{freely} time of freely fire spread, but other conditions are ignored. In this case the burnt area A_{fire} (Figure 2 $A_{t1} – A_{t3}$) can be given with the next formula:

$$A_{fire} = (v_{fire} t_{freely})^2 \pi \tag{3.1}$$

Following time units (sec, min, hour) burnt areas form concentric circles. This model got its name of these circles. Distance between the circles depends on the rate of fire spread. The K_{front} fire front can be given by the formula (3.2) and the changing of it is by the formula (3.3).

$$K_{front} = 2\pi v_{fire} t_{freely} \tag{3.2}$$

$$\Delta K_{front} = 2\Delta t v_{fire} \pi \tag{3.3}$$

In the formula (3.3) the extent of the ΔR radiation change can be given by the formula (3.4).

$$\Delta R = v_{fire} \Delta t \tag{3.4}$$

The effectiveness of the intervention can be demonstrated by the length of the extinguished fire section per the time units, that is, the speed of fire front suppression.

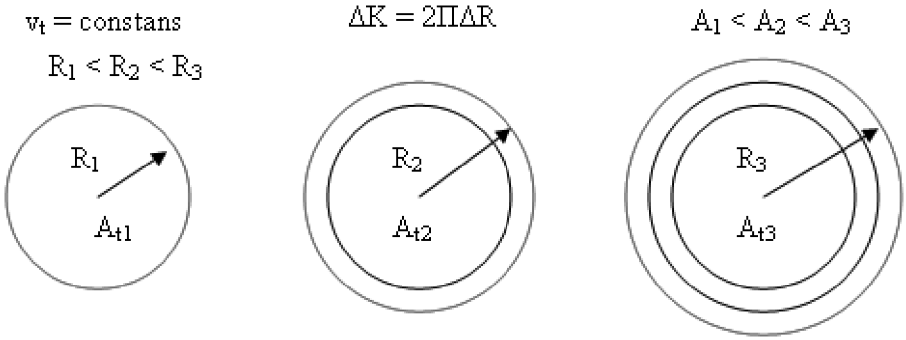

Figure 2. Concentric circles model.
(Made by the author.)

Based on the above for demonstrating the capability of the efforts suppressing fire front author introduce the term of *speed of firefighting* (v_{FF}). It means the length of the fire front suppressed by different resources (human resources, special fire engines, aerial means).

$$v_{FF} = \frac{L_{suppression}}{t_{suppression}} \tag{3.5}$$

v_{FF} – speed of firefighting (ms^{-1}; practically it can be $mmin^{-1}$ or $mhour^{-1}$);
$L_{suppression}$ – length of the suppressed fire front (m);
$t_{suppression}$ – time for suppression (s; practically min, or hour).

To extinguish the fire successfully, the condition must be met that the interveners suppress fire spread. The firefighters have to extinguish the fire front, whose growth per unit of time is equal to the change in perimeter based on the concentric circles model. Thus, the success and effectiveness of the firefighters' work should not be related directly to the speed of fire spread but rather to the change in perimeter! At the beginning of extinguishment, the speed of the extinguishment of fire front, in this case the speed of firefighting with different resources must reach and later exceed the speed of the change of the fire front, that is, the change of the fire front within a given unit of time.

$$L_{suppression} > \Delta K_{front} \tag{3.6}$$

Using the formula (3.6) to extinguish successfully, the next criteria must be satisfied:

$$v_{FF} = \frac{\Delta K_{front}}{t_{suppression}} \text{ , or in other form: } v_{FF} t_{suppression} > \Delta K_{front} \tag{3.7}$$

By ordering the above, it becomes clear that in practice the initial condition can be calculated in a simplified way, where we need to take the speed of fire spread multiplied by *2Π*.

$$v_{FF} > 2\pi v_{fire} \tag{3.8}$$

Above in-equality is necessary but not yet sufficient condition for the efficiency of the national economy. Based on mathematical formulas and the logical deductions regarding the concentric circles model author made the following statements:

1. If the speed of extinguishing the fire front – in this case the speed of the firefighting – is below the speed of changing the fire front, the resources are unable to extinguish the fire (initial attack).

2. If the speeds above are identical, the length of fire front will remain but the burnt area will extend (beginning situation; later the balance follow 2πrad).
3. If the speed of extinguishing made by different resources is higher than the increase of the fire front, fire can be suppressed.

Based on the above logical flow we can define both the economic efficiency of firefighting and minimal criteria of successful suppression expressed by the elementary information we have regarding the actual fire. Naturally, the above statements are valid only at the time of beginning the intervention. Later, it modifies as changing the angle of suppressed fire front by the rules of *2***π***rad*.

Results and Discussion: Sufficient Condition for the Efficient Suppression

In the examination of the rectangular model, the conditions of efficient extinguishment in terms of the national economy have already been recorded. Based on them, the extinguishment can be regarded efficient if the amount of the saved value reaches the total costs of the extinguishment. Then, the condition of efficiency is met satisfactorily (2.3). It applies to both the rectangular and the concentric circles model.

One feature of extinguishing forest fires is that regardless of the size of the forest burning, we tend to concentrate on the extinguishment of the fire front, which can be regarded as straight fire line suppression. It can be done or it can be accepted because in case of long-lasting uncontrolled fire spread, the curve of the fire front is hardly perceptible, in practice it can be ignored, so it's linear. If we concentrate on a very small section of fire front, the conclusions of the rectangular model can be applied here, too!

Provided we accept the above statements – the adaptation of the limit values of efficiency set in the rectangular model (2.4) to the very small section of the concentric circles model (3.7) – the formula can be created in the following way:

$$\frac{1}{2}LHp_{forest} \geq \sum C_{FF} \Rightarrow \frac{1}{2}\Delta K v_{fire} t_{suppression}\, p_{forest} \geq \sum C_{FF} \tag{4.1}$$

Moreover, the limit value of the efficiency criterion of firefighting out of formula (3.8):

$$2\pi v_{fire} = v_{FF} \tag{3.9}$$

By reversing the equation and substituting the form pertaining to the actual time of formula (3.3):

$$C_{FF} t_{suppression} \leq \frac{1}{2} 2\pi v_{fire} t_{suppression} v_{fire} t_{suppression}\, p_{forest} \tag{4.10}$$

C_{FF} – unit costs of firefighting (average; €h^{-1}; €min^{-1});

$$C_{FF} t_{suppression} \leq \frac{1}{2} 2\pi \left(\frac{v_{FF}}{2\pi}\right)^2 t^2_{suppression}\, p_{forest} \tag{4.11}$$

Ordering the above formulas and interpret it to a unit time, that is $t_{suppression} = 1$ min, we can get for the speed of the firefighting the distance of suppression per a minute, that is $v_{FF} = \mathbf{l_{FF}}\, 1min^{-1}$.

$$l_{FF} \geq \sqrt{\frac{4\pi C_{FF}}{p_{forest}}} \tag{4.12}$$

Based on the above formula we can see that some data are enough for the statement of efficient suppression in view of national economy: as the length of suppressed fire front per unit *(l_{FF})*, the unit cost of average firefighting *(C_{FF})* and the unit costs of forest *(p_{forest})*. Remake the formula and apply it to speed of fire spread:

$$C_{FF} \leq \pi p_{forest} v_{fire}^2 \tag{4.13}$$

It has to take into account that the above values are limit values; by satisfying them aerial firefighting will satisfy the criteria of efficiency in view of national economy too.

References

[1] RESTÁS, Á.: Az erdőtűzoltás hatékonyságának közgazdasági megközelítése. (An approach to measure the economic efficiency of fighting forest fires.) *Védelem – Katasztrófa- Tűz- és Polgári Védelmi Szemle,* 18 5 (2011), 47–50.

[2] THEO, M. T.: Initial Attack Air Tanker – Marsh S-2AT Turbo Tracker. *Aerial Fire Fighting Conference,* Rome, 3–4 November, 2009. (Presentation)

[3] WAGNER, C. E. van: The Economic Impact of Forest Fire. *Annual Meeting of Intermountain Fire Council,* Alberta: Banff, October 1983. (This paper is a part of a Proceedings to be published by the Northern Forest Research Centre, Canadian Forestry Service)

[4] SCIPIONI, A., GABELLINI, B., CALDARI, F., CAVALENSI, A.: Forest Fires in Italy 1998. *IFFN,* 21 (1999), 60–70.

[5] DIMITRIOU, A., MANTAKAS, G., KOUVELIS, S.: *An analysis of key issues that underlie forest fires and shape subsequent fire management strategies in 12 countries in the Mediterranean basin.* Final report prepared by Alcyon for WWF Mediterranean Programme Office and IUCN. May 2001.

[6] FOGARTY, L., SLIJEPCEVIC, A: The influence of wind speed on the effectiveness of aerial fire suppression. In. *Fire Technology Transfer Note,* No 17. Rotorua: New Zealand Forest Fire Research Institute, 1998.

[7] ROBERTSON, K.: Aerial Fire Suppression Workshop. In. *Fire Technology Transfer Note,* No 18. Rotorua: New Zealand Forest Fire Research Institute, 1998.

[8] RASKER, R: *Solutions to the Rising Costs of Fighting Fires in the Wildland-Urban Interface.* Bozeman: Headwaters Economics, 2009.

[9] RITTMASTER, R., ADAMOWICZ W. L., AMIRO, B., PELLETIER, R. T.: Economic analysis of health effects from forest fires. *Canadian Journal of Forest Research,* 36 4 (2006), 868–877. DOI: https://doi.org/10.1139/x05-293

[10] FOGARTY, L.: Comparison of the cost-effectiveness of some aircraft used for fire suppression. In. *Fire Technology Transfer Note,* No 15. Rotorua: New Zealand Forest Fire Research Institute, 1998.

[11] PEKIĆ, Z.: High rate spray technique – a new way for effective aerial wildfire suppression. *International Wildland Fire Conference,* Seville, 13–17 May, 2007.

[12] MARCHI, E., NERI, F., TESI, E., FABIANO, F.: Analysis of Helicopter Activities in Forest Fire-Fighting. *Croatian Journal of Forest Engineering,* 35 2 (2014), 233–243.

[13] GOULD, J., PLUCINSKI, M., McCARTHY, G., HOLLIS, J., HANDMER, J., GANEWATTA, G.: Effectiveness and efficiency of aerial firefighting in Australia. *Fire Note,* 50 11 (2009); 1–4.

[14] GOULD, J. S., PLUCINSKI, M. P., McCARTHY, G. J.: *Aerial suppression – need for evaluation: Bushfire Behaviour and Management.* Canberra: CSIRO Forestry and Forest Products, 2004.

[15] LOANE, I. T., GOULD, J. S.: *Aerial suppression of bushfires: cost-benefit study for Victoria.* Canberra: CSIRO Forestry and Forest Products, 1986. DOI: https://doi.org/10.25919/5c002929cc095