AKADÉMIAI KIADÓ

One-at-a-Time sensitivity study of a tree burning simulation

Flóra Hajdu[1], László Környei[2] and Rajmund Kuti[3*]

[1] Department of Machine Design, Faculty of Mechanical Engineering, Informatics and Electrical Engineering, Széchenyi István University, Győr, Hungary

[2] Department of Mathematics and Computational Sciences, Faculty of Mechanical Engineering, Informatics and Electrical Engineering, Széchenyi István University, Győr, Hungary

[3] Department of Automation and Mechatronics, Faculty of Mechanical Engineering, Informatics and Electrical Engineering, Széchenyi István University, Győr, Hungary

Pollack Periodica • An International Journal for Engineering and Information Sciences

19 (2024) 1, 53–59

DOI: 10.1556/606.2023.00850

Received: February 28, 2023 • Revised manuscript received: June 2, 2023 • Accepted: June 7, 2023
Published online: October 17, 2023

ORIGINAL RESEARCH PAPER

ABSTRACT

The aim of the research was to carry out the One-at-a-Time sensitivity analysis of a tree burning experiment simulation with a novel fuzzy logic-based method. It was observed that the precent of the remaining tree is sensitive to the moisture content, the crown-base diameter and the tree height. The other variables, which are maximum mass loss rate, maximum heat release rate, and maximum temperature at the top of the tree are moderately sensitive or not sensitive to the selected parameters. The presented results can be used in sensitivity studies and wildfire simulations.

KEYWORDS

sensitivity study, tree burning, numerical simulation, fuzzy logic, fire spread simulation

1. INTRODUCTION

Tree burning simulation is the basis of forest fire simulation. In the literature there are some examples of tree burning simulation.

In [1] a novel, interactive method is presented to model the combustion of botanical trees. Trees are modeled as connected particles with biological and physical properties. The model includes the kinetic behavior of the plant, the combustion with exothermic reaction and dynamic branch motion. Fire is simulated with approximated Navier-Stokes equations, which are solved by a grid-based fluid solver. The combustion model includes the pyrolysis of wood with the accompanying phenomena (evaporation of moisture, formation of a char layer, reduction of wood).

Paper [2] presents the numerical approach Wildland urban interface Fire Dynamics Simulator (WFDS). The model is based on the large-eddy simulation approach. In the model the equations of heat transfer, thermal degradation, combustion, and fluid flow of vegetative are solved numerically. Trees were approximated with simple geometric shapes. The model includes water evaporation and solid fuel pyrolysis. The model was validated with experiments of burning Douglas firs.

In [3] a physics-based model of a multiple burning trees is carried out. Two thermal degradation sub-models (the linear and the simplified Arrhenius) were used in the simulations. The model was compared with statistical analysis to an experimental result of a single Douglas fir. For mesh sensitivity analysis the Mass Loss Rate (MLR) and the Heat Release Rate (HRR) were used. The test simulation consisted of 66 Douglas firs on grassland. The purpose of this simulation was used to test fire spread from the surface fire to the canopy fire. It was shown that physics-based models are suitable for crown fire simulations.

In [4] an inverse analysis was carried out with physics-based simulations using Fire Dynamic Simulation (FDS). A trial-and-error method was used to reproduce the collection of firebrands.

*Corresponding author.
E-mail: kuti.rajmund@sze.hu

AKJournals

A Douglas-fir burning experiment and a forest fire experiment were simulated. It was found that the mass distribution of firebrands around the tree is not uniform.

Sensitivity and uncertainty study is unavoidable in case of engineering design [5]. Sensitivity analysis and uncertainty quantification is spreading in case of Computational Fluid Dynamic (CFD) and fire spread simulations [6]. In case of forest fires one the first attempt to carry out sensitivity analysis was applied to Rothermel's semi-empirical model [7]. Later this analysis was expanded with weather variables [8, 9]. A fully empirical model was also studied with dead fuel moisture content [10] and was extended for crown fire spread [11]. The uncertainty parameters were stand height, canopy base height, canopy bulk density, and load surface fuel depth. Paper [12] presents the characterization of uncertainty of a semi-physical fire spread model. The effect of parameters like flame length and tilt angle, heat convection coefficient on rate of spread, fuel consumption efficiency, and flame temperature and emissivity was examined. In [6] the sensitivity analysis of a physics-based wildfire model is carried out using multi-fidelity Monte Carlo strategy. The Rate Of Spread (ROS) was selected as output variable and the wind speed, fuel bed depth, fuel particle surface area to volume ratio, fuel load, fuel moisture fraction were selected as input parameters. The sensitivity analysis was based on Sobol's variance-based method. It was observed that the moisture content of the fuel, the fuel load, and the wind speed have the highest variance, therefore, they are the most sensitive parameters. In [13] the simulation and sensitivity study of junction fires in case of 2 junction angles was carried out. For the simulation FIRE-STAR3D program was used, which is based on a physics-based fire model. The aim of the research was to observe the effects of the slope and the junction angle and on the fire propagation phases and the ROS. It was observed that the junction angle is more important parameter on the fire spread than the slope. In [14] a global sensitivity study was carried out based on Sobol indices. The main task of the study was to identify the input parameters that contribute most to the ROS variability through a variance-based global sensitivity analysis. It was observed that the near surface wind speed was the most influential parameter. Other influential parameters include the leaf area index, the ignition temperature, the dead fuel moisture content, and the dead fuel particle mass density. In [15] a numerical simulation of a simple model with wind effect and two different fuel types was carried out with randomly distributed trees having different densities. A sensitivity analysis was carried out based on the number of burnt trees. It was shown that the wind and the total tree density have the greatest effect on the forest fire spreading.

According to the literature found it can be stated that sensitivity study was mostly carried out in case of grassland fires and not trees. A novel fuzzy logic-based one-at-a-time sensitivity study of a tree burning simulation is presented in this paper. The method was tested and developed on vibration systems earlier [16–19]. The aim of the research was to test the sensitivity analysis method on new complex task. Another task of the research is to test a simulation model which will be suitable for forest fire simulation later.

2. MATERIALS AND METHODS

2.1. Tree burning simulation

In order to simulate tree burning, the simulation tool FDS was used. This program uses large-eddy approach to solve the low Mach number Navier-Stokes equations with turbulent dissipation, and models foliage and various size branches based on a physics-based model consisting of particles. Several properties are assigned to the particles, including density or moisture content.

To model vegetation fire a pyrolysis model was included in the program simulating multiphase reactions for both vegetation and combustion product. This mimics the behavior of evaporation and dry matter with increasing temperature in an appropriate manner, where combustible gases are produced with the remaining solid turning into charcoal.

There are three reactions in the thermal decomposition of general vegetation with the following governing equations:

$$Wet\ vegetation \rightarrow \nu_{moisture} Moisture + (1-\nu_{moisture}) Dry\ vegetation, \quad (1)$$

$$\nu_{moisture} = \frac{M}{1+M}, \quad (2)$$

$$Dry\ vegetation \rightarrow \nu_{char} Char + (1-\nu_{char}) Fuel\ gas, \quad (3)$$

$$Char + \nu_{O_2,char} O_2 \rightarrow \left(1+\nu_{O_2,char}-\nu_{ash}\right) CO_2 + \nu_{ash} Ash. \quad (4)$$

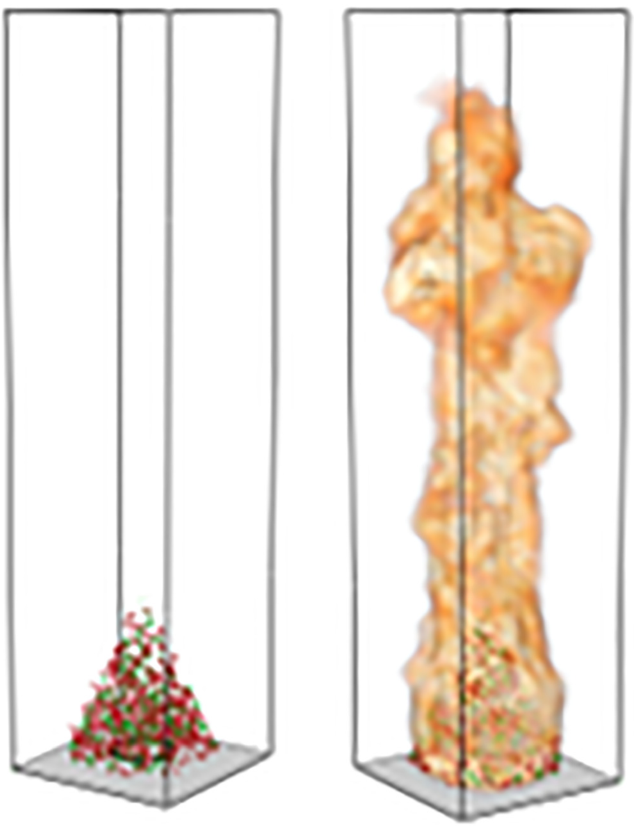

Fig. 1. The initial simulation model

Endothermic moisture evaporation is described by (1) and (2), while endothermic pyrolysis of dry vegetation and exothermic charcoal oxidation are described by (3) and (4), respectively. In the equations, M is the moisture content, $\nu_{moisture}$ is the mass fraction of the moisture, ν_{char} is the mass fraction converted to char during pyrolysis, $\nu_{O_2,char}$ is the mass of oxygen consumed per unit mass of char oxidized and ν_{ash} is the mass fraction of char that is converted to ash during char oxidation [20, 21].

The basis of the tree burning simulation was taken from [2] (Fig. 1). The initial tree has 2 m crown base diameter and 2 m height, 20% moisture content and the ambient temperature is 20 °C. The reaction gas was cellulose.

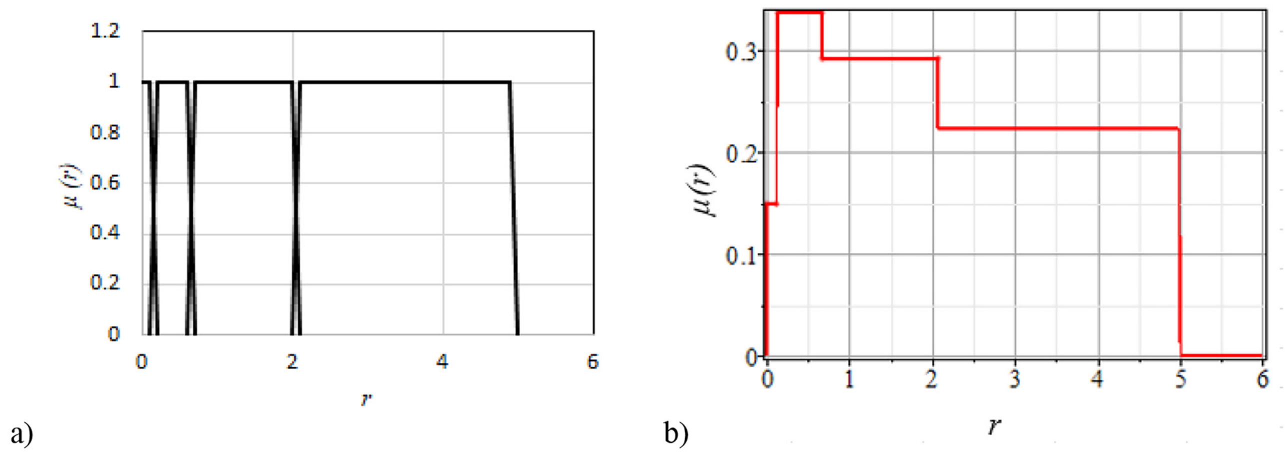

Fig. 2. a) Fuzzy rules for sensitivity sets and defuzzification, b) and example of centroid for defuzzification

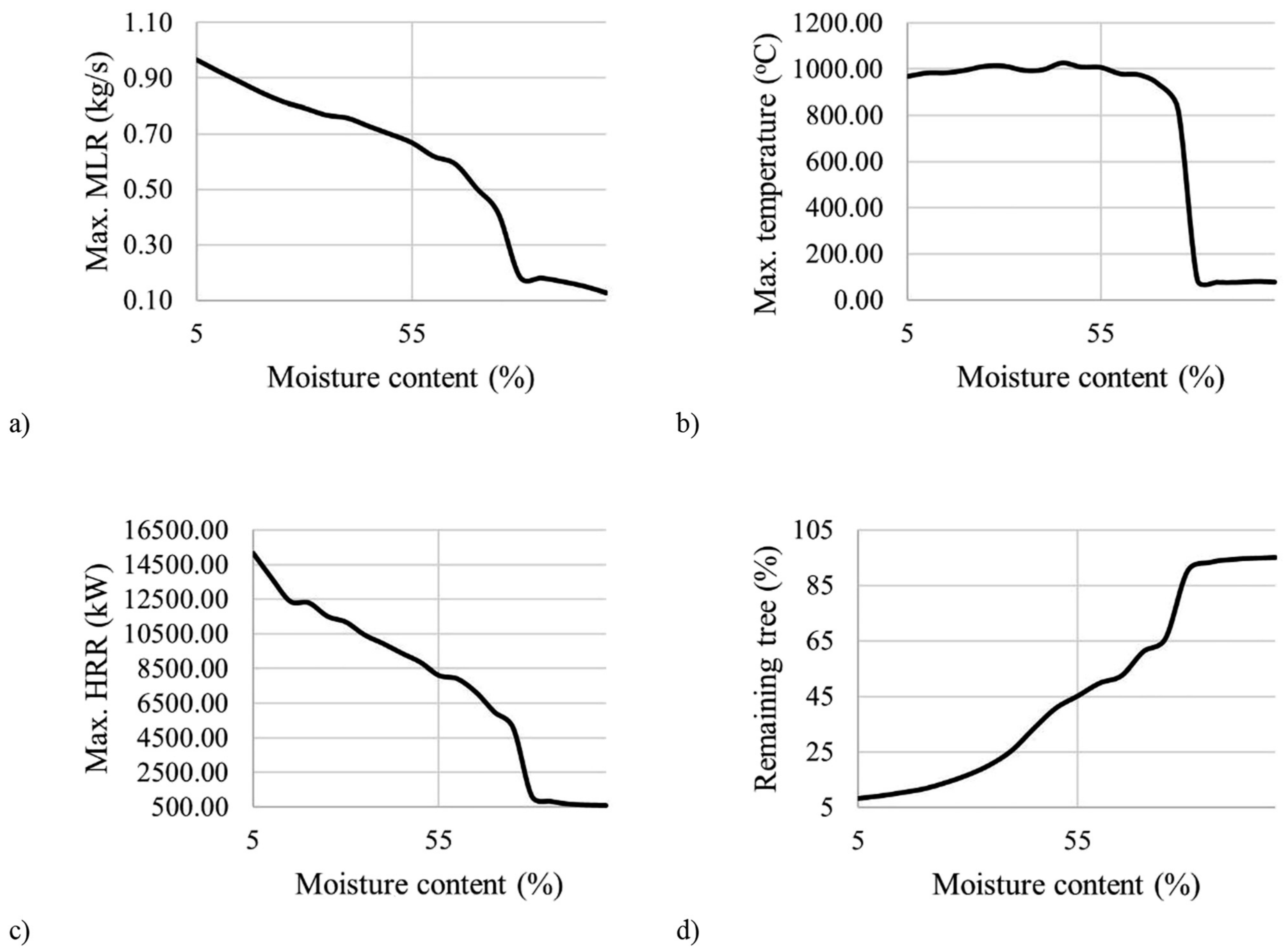

Fig. 3. Sensitivity diagrams in case of the moisture content are the variable parameter, a) max. MLR, b) max. temperature, c) max. HRR, d) percentage of the remaining tree

The output variables are maximum MLR, the maximum temperature at the top of the tree, the maximum HRR and the percent of remaining tree (see Fig. 2). To calculate the percent of remaining tree the mass loss was calculated, and was compared to the original mass. The mesh size was 0.1 × 0.1 × 0.1 m. The simulation was run on a Message Parsing Interface (MPI) cluster using 4 nodes.

The trees were ignited with particles in a circular ignitor source with a diameter of 0.8 m, temperature of 1,500 °C and heat release rate per unit area of 60 kW m^{-2}. The ignition lasted for 10 s.

2.2. Sensitivity study

First, the sensitivity of a selected output variable was calculated using sensitivity functions versus parameter diagrams. The resulting Sensitivity Idex (*SI*) is the ratio of the relative changes in the output variable and the parameter,

$$SI = \frac{\Delta V}{\Delta p}, \tag{5}$$

where ΔV and Δp are the relative changes in the output variable and the parameter, respectively.

Next, sensitivity sets were created using fuzzy sets (Fig. 3a). Based on the sensitivity index the sensitivity function was divided into segments, which is used to determine the membership μ_y using the following formula:

$$\mu_y = \sum \frac{R_i}{R}, \tag{6}$$

where R_i is the length of the examined segment, and R is the length of the entire examination range. Then, using the same rules (Fig. 3a) and utilizing Maple's function *defuzzify*, the centroids for defuzzification can be determined. See an example in Fig. 3b. Finally, the Sensitivity Number (SN) can be obtained for determining the degree of sensitivity [16].

The border of the sensitivity numbers can be calculated with defuzzification taking 0.5–0.5 at the selected set, therefore:

- not sensitive if $SI < 0.34$;
- moderately sensitive if $0.34 \leq SI < 1.1$;
- sensitive if $1.1 \leq SI < 2.8$;
- extremely sensitive if $2.8 \leq SI$.

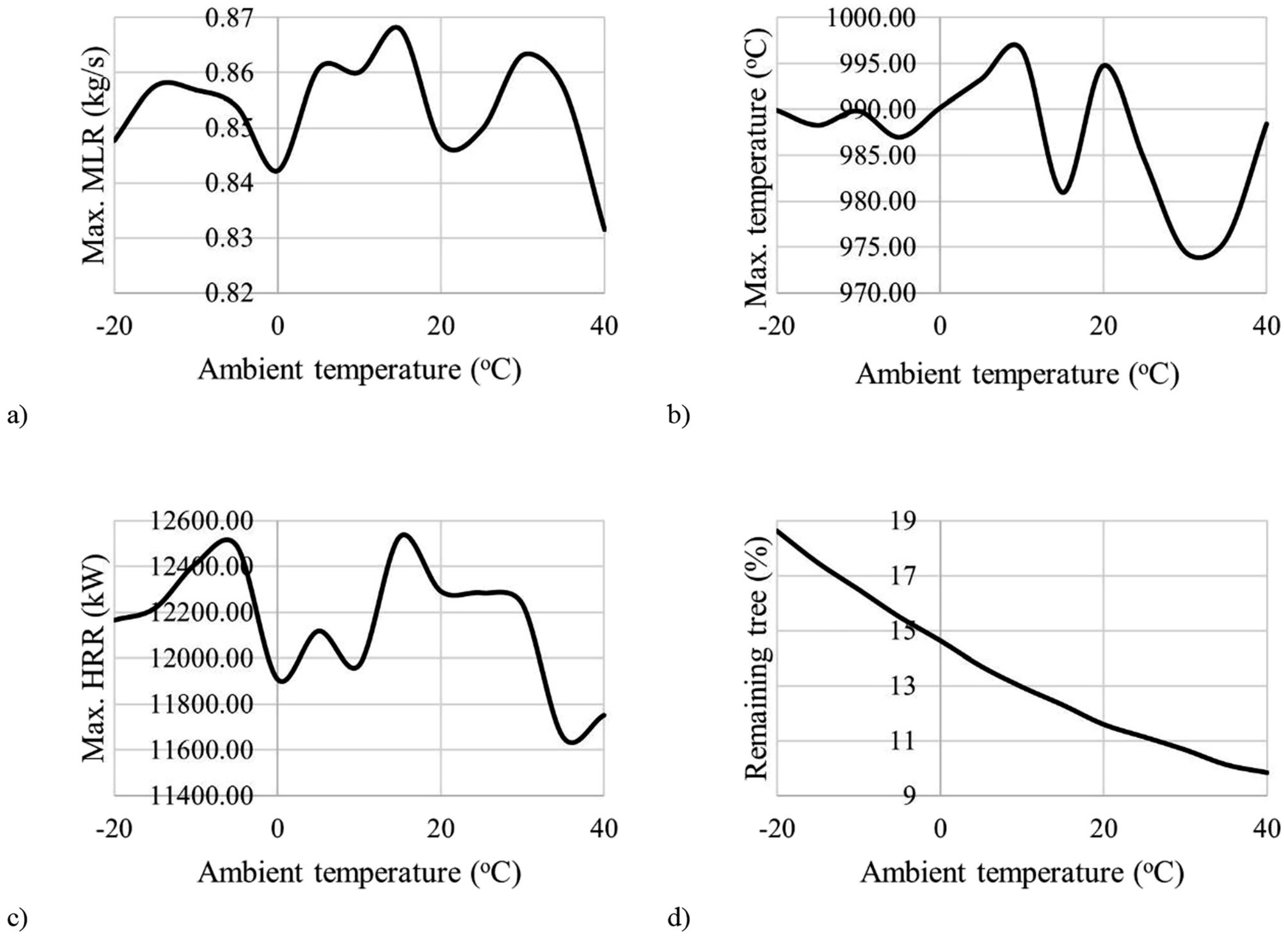

Fig. 4. Sensitivity diagrams in case of the ambient temperature are the variable parameter, a) max. MLR, b) max. temperature, c) max. HRR, d) percentage of the remaining tree

More details about the sensitivity study method can be found in [15–18].

3. RESULTS AND DISCUSSION

3.1. Moisture content as variable parameter

The moisture content was changed between 5% and 100%. The initial parameter was 20%. The sensitivity functions are shown in Fig. 3.

It can be seen that the maximum MLR decreases more or less linearly as the moisture content increases till 65%. After that there is a large decrease in the maximum MLR till 80%, which is followed by a constant value. The parameter is more sensitive between 65 and 80%. The explanation is that in case of large moisture content the tree did not ignite. The maximum temperature remains similar in every moisture contents till 75% moisture content. After that there is a large decrease and the temperature will remain the same. The parameter is more sensitive between 75 and 80%. The maximum HRR decreases as the moisture content increases. The decrease is faster, when the moisture content is 5–15% and 75–80% therefore the parameter is more sensitive to the maximum HRR in that ranges. After 80% the HRR remains constant. More percent of the tree remains as the moisture content increases. This variable changes exponentially as the moisture content increases. It changes faster when the moisture content is larger; therefore the parameter is more sensitive to the percent of the remaining tree at that range. The parameter becomes constant after 80%, therefore the parameter is not sensitive in that range. The sensitivity numbers are 0.53, 0.10, 0.30 and 2.2, respectively. Therefore, the maximum MLR is moderately sensitive, the HRR, and the ambient temperature are not sensitive and the percent of remaining tree is sensitive to the moisture content.

3.2. Ambient temperature as variable parameter

The ambient temperature was changed between −20–40 °C. The initial ambient temperature was 20 °C. The sensitivity functions are shown in Fig. 4.

It can be seen that the maximum MLR, the maximum temperature and the maximum HRR remains more or less the same as the ambient temperature changes. The percent of the tree remaining decreases linearly as the ambient temperature increases. The sensitivity numbers are 0.10, 0.08, 0.08 and 0.38, respectively. Therefore the maximum

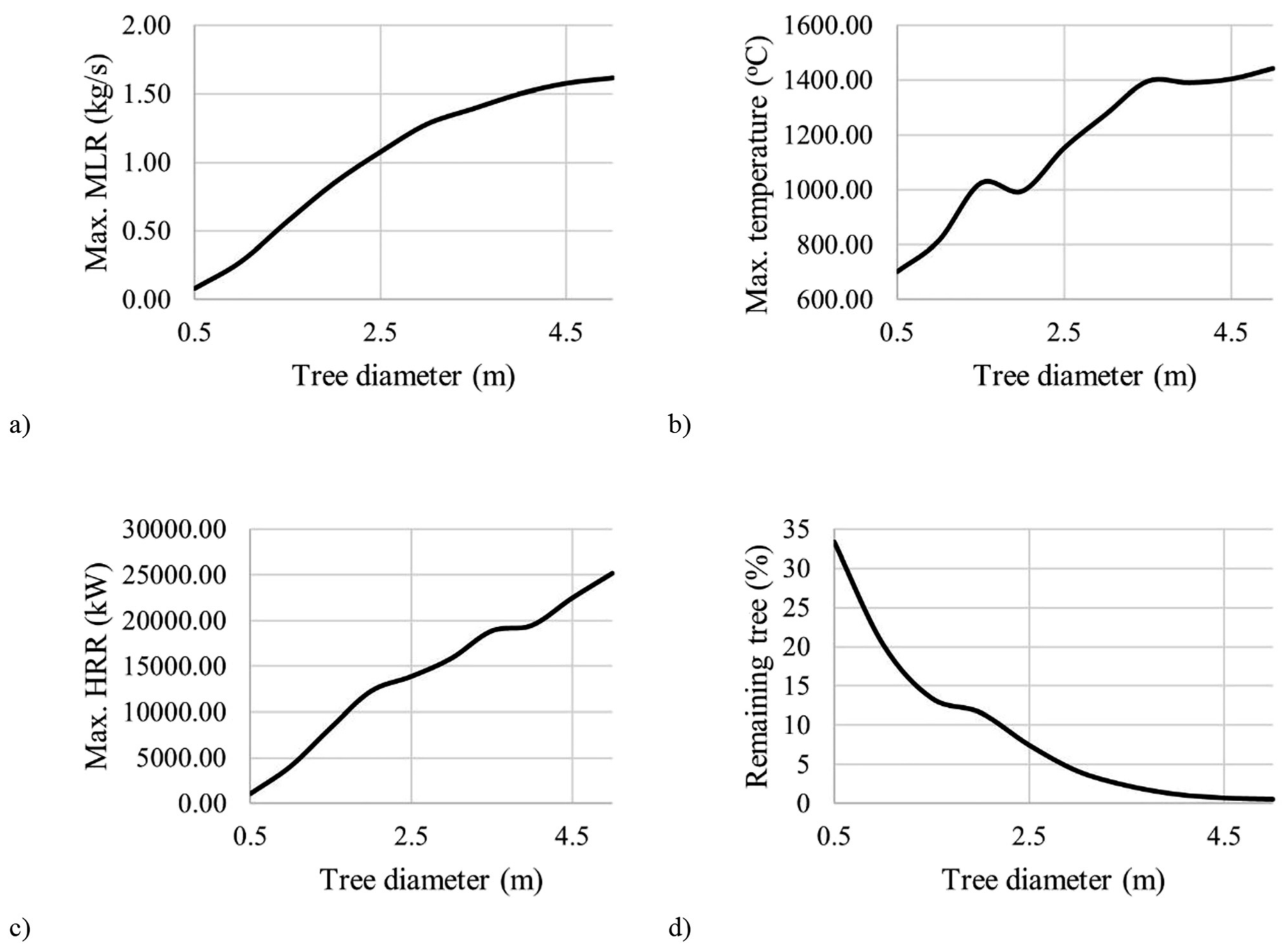

Fig. 5. Sensitivity diagrams in case of the tree diameter is the variable parameter, a) max. MLR, b) max. temperature, c) max. HRR, d) percentage of the remaining tree

MLR, the HRR, and the ambient temperature are not sensitive and the percent of the remaining tree is moderately sensitive to the ambient temperature.

3.3. Crown base diameter as variable parameter

The crown base diameter was changed between 0.5 and 5 m. The initial diameter was 2 m. The sensitivity functions are shown in Fig. 5.

The maximum MLR increases as the crown base diameter increases. The increase is faster, when the tree diameter is smaller; therefore the parameter is more sensitive to the maximum MLR at that range. The maximum temperature first increases as the crown base diameter increases, then at around 3.5 m it remains the same. Therefore, the parameter is more sensitive to the maximum temperature when it is smaller. The maximum HRR changes more or less linearly as the crown base diameter increases. The percent of the remaining tree decreases exponentially as the crown base diameter increases. The decrease is faster, when the tree diameter is small; therefore the parameter is more sensitive to the percent of the remaining tree at that range. The sensitivity numbers are 1.14, 0.77, 1.28 and 2.32, respectively. Therefore the temperature is moderately sensitive and the MLR, HRR, and the percent of the remaining tree are sensitive to the crown base diameter.

3.4. Tree height as variable parameter

The tree height was changed between 0.5 and 5 m. The initial height was 2 m. The sensitivity functions are shown in Fig. 6.

The maximum MLR increases as the tree height increases. The increase is faster when the tree height is smaller; therefore the parameter is more sensitive to the maximum MLR at that range. The maximum temperature first increases then decreases. The tree height is more sensitive to the maximum temperature when it is smaller. The maximum HRR increases when the tree height increases. The increase is faster when the tree height is smaller. Therefore, the parameter is more sensitive to the maximum HRR at that range. The percent of the remaining tree decreases exponentially as the tree height increases. It changes faster; when the tree height is smaller therefore the parameter is more sensitive to the percent of the remaining tree at that range. The sensitivity numbers are 0.95, 0.68, 0.98 and 1.85, respectively. Therefore, the maximum MLR, the maximum temperature, and the maximum HRR are moderately sensitive and the percentage of the remaining tree is sensitive to the tree height.

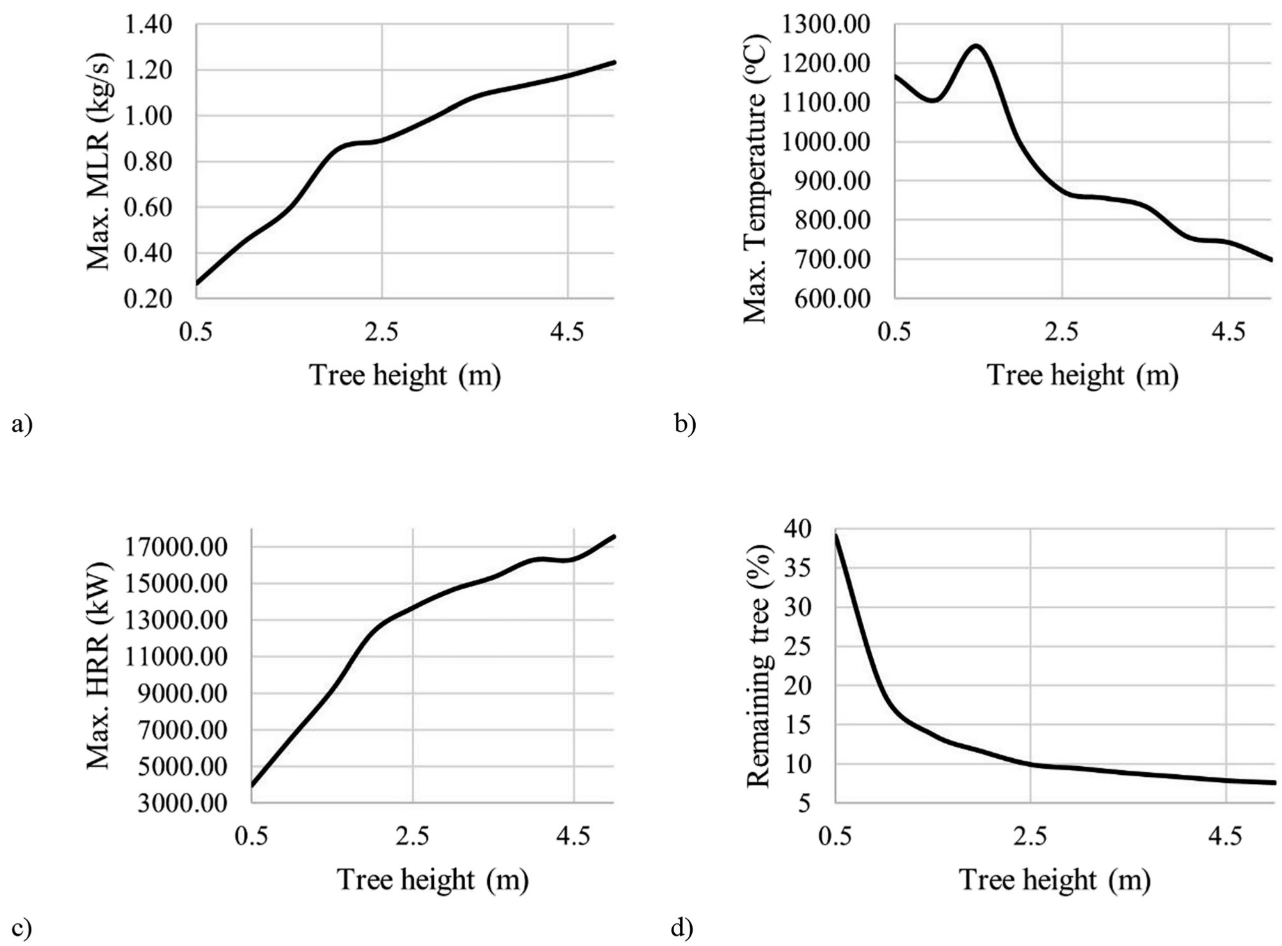

Fig. 6. Sensitivity diagrams in case of the tree height is the variable parameter a) max. MLR, b) max. temperature, c) max. HRR, d) percentage of the remaining tree

4. CONCLUSION

In this paper the One-at-a-Time sensitivity study of a numerical simulation of a tree burning experiment was carried out with a novel fuzzy-based method. It was studied how different variables like maximum MLR, maximum temperature at the top of the tree, maximum HRR and percent of the remaining tree are sensitive to parameters like the fuel moisture content, the ambient temperature, the crown base diameter and the tree height. It was observed that the maximum MLR is moderately sensitive, the HRR, and the ambient temperature are not sensitive, and the remaining tree is sensitive to the moisture content. The maximum MLR, the HRR, and the ambient temperature are not sensitive, and the percent of the remaining tree is moderately sensitive to the ambient temperature. The temperature is moderately sensitive and the MLR, HRR, and the percent of the remaining tree are sensitive to the tree diameter. The maximum MLR, the maximum temperature, and the maximum HRR are moderately sensitive, and the percentage of the remaining tree is sensitive to the tree height. Further research tasks are to carry out a global sensitivity analysis with more parameters and to develop a forest fire simulation using the results presented in this paper.

ACKNOWLEDGEMENTS

The Author's would like to thank to Dr. William Mell for sharing FDS example files and relevant scientific literature.

REFERENCES

[1] S. Pirk, M. Jarząbek, T. Hädrich, D. L. Michels, and W. Palubicki, "Interactive wood combustion for botanical tree models," *ACM Trans. Graphics*, vol. 36, no. 6, 2017, Art no. 197.

[2] W. Mell, A. Maranghides, R. McDermott, and S. L. Manzello, "Numerical simulation and experiments of burning Douglas fir trees," *Combustion and Flame* vol. 156, no. 10, pp. 2023–2041, 2009.

[3] K. A. M. Moinuddin and D. Sutherland, "Modeling of tree fires and fires transitioning from the forest floor to the canopy with a physics-based model," *Mathematics Comput. Simulation*, vol. 175, pp. 81–95, 2020.

[4] A. Wickramasinghe, N. Khan, and K. Moinuddin, "Determining firebrand generation rate using physics-based modeling from experimental studies through inverse analysis," *Fire,* vol. 5, no. 1, 2022, Art no. 6.

[5] Á. Kenéz and A. L. Joó, "The impact of parameter estimation uncertainty in extreme wind speed models," *Pollack Period.*, vol. 18, no. 1, pp. 78–83, 2023.

[6] M. M. Valero, L. Jofre, and R. Torres, "Multifidelity prediction in wildfire spread simulation: Modeling, uncertainty quantification and sensitivity analysis," *Environ. Model. & Softw.*, vol. 141, 2021, Art no. 105050.

[7] R. Salvador, J. Piol, S. Tarantola, and E. Pla, "Global sensitivity analysis and scale effects of a fire propagation model used over Mediterranean shrublands," *Ecol. Model.*, vol. 136, nos 2-3, pp. 175–189, 2001.

[8] K. Anderson, G. Reuter, and M. D. Flannigan, "Fire-growth modeling using meteorological data with random and systematic perturbations," *Int. J. Wildland Fire*, vol. 16, no. 2, pp. 174–182, 2007.

[9] M. A. Finney, I. C. Grenfell, C. W. McHugh, R. C. Seli, D. Trethewey, R. D. Stratton, and S. Brittain, "A method for ensemble wildland fire simulation," *Environ. Model. & Assess.*, vol. 16, pp. 153–167, 2011.

[10] M. G. Cruz, "Monte Carlo-based ensemble method for prediction of grassland fire spread," *Int. J. Wildland Fire*, vol. 19, no. 4, pp. 521–530, 2010.

[11] M. G. Cruz and M. E. Alexander, "Modeling the rate of fire spread and uncertainty associated with the onset and propagation of crown fires in conifer forest stands," *Int. J. Wildland Fire*, vol. 26, No. 5, pp. 413–426., 2017.

[12] X. Yuan, N. Liu, X. Xie, and D. X. Viegas, "Physical model of wildland fire spread: parametric uncertainty analysis," *Combust. Flame*, vol. 217, pp. 285–293, 2020.

[13] A. Hassan, G. Accary, D. Sutherland, S. Meradji, and K. Moinuddin, "Physics-based modeling of junction fires: Sensitivity and validation studies," in *Advances in Forest Fire Research*, D. X. Viegas and L. M. Ribeiro, Eds, House-Refuge, 2022, pp. 315–322.

[14] F. C. Roubelat, A. Costes, W. P. Antolin, and M. C. Rochoux, "Identifying the most influential parameters in experimental grass fire spread modeling using global sensitivity analysis," in *Advances in Forest Fire Research*, D. X. Viegas and L. M. Ribeiro, Eds, House-Refuge, 2022, pp. 240–245.

[15] H. S. Song and S. H. Lee, "Sensitivity analysis on ecological factors affecting forest fire spreading: Simulation study," *Korean J. Agric. For. Meteorol.*, vol. 15, no. 3, pp. 178–185, 2013.

[16] F. Hajdu, Gy. Molnárka, and R. Kuti, "Modeling and sensitivity analysis of nonlinear firefighting systems using Maple," in *Maple in Mathematics Education and Research*, R. M. Corless, J. Gerhard, and I. S. Kotsireas, Eds, Springer, 2021 pp. 234–251.

[17] F. Hajdu and Gy. Molnárka, "Testing output variables for sensitivity study of nonlinear vibration systems," *Pollack Period.*, vol. 15, no. 2, pp. 70–81, 2020.

[18] F. Hajdu, Gy. Molnárka, and R. Kuti, "One-at-a-Time sensitivity study of a nonlinear fire truck suspension model," *FME Trans.*, vol. 48, no. 1, pp. 90–95, 2020.

[19] F. Hajdu, "Sensitivity study of a nonlinear semi-active suspension system," *Acta Technica Jaurinensis*, vol. 12, no. 3, pp. 205–217, 2019.

[20] K. McGrattan, S. Hostikka, J. Floyd, R. McDermott, and M. Vanella, *Fire Dynamics Simulator User's Guide*. NIST Special Publication, 1019.

[21] F. Hajdu, L. Környei, D. Beke, and R. Kuti, "Examination of vegetation fire spread with numerical modeling and simulation using fire dynamic simulator," *Acad. Appl. Res. Mil. Public Manage. Sci.,* vol. 21, no. 3, pp. 85–100, 2022.