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MASTER'S THESIS

Modelling forest fire spread using Cellular Automata

Modellering av skogsbrannspredning ved bruk av cellular automata

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ACKNOWLEDGEMENTS

This thesis is the finishing work of a Master in Fire Safety Engineering at the Western Norway University of Applied Sciences and is part of BUILDER WP 4 Wildland-urban-interface (WUI) (NFR-301569). The objective of this work was to improve my knowledge about forest fires dynamics, the potential arising problem due to climate change, as well as develop programming skills through building a simulation tool and automated utilization of Geographical Information Systems data.

The work has been conducted during the COVID-19 pandemic, while working as a full-time Fire Safety Engineer at COWI AS and later starting my own company, Ignist AS in 2021. This was shown to be challenge with regards to the total work load, but also due to the multiple new skills that had to be taught, including Python programming and writing in LateX. The vision of how a simple to use simulation tool should work and how the results are to be presented proved to be a tough nut to crack, but through hard work and discipline the result is something to be proud of.

I want to thank my supervisors, Nieves Fernandez Anez and Bjarne Christian Hagen, for providing guidance and feedback throughout this project. Thank you for introducing me to the fascinating world of Cellular Automata!

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Joakim Folkesson, May 2022

ABSTRACT

Forest fires are common events that have been a part of the human race since 1.5 millions years BP. Despite forest fires being a natural part of our environment, many consider them problematic due to the perception of a rising occurrence, severity and losses. With higher global temperatures, forest fires are predicted to increase around the globe, negatively affecting the risk of lives, health and infrastructure. In an environment where the forest fire risk increases, mitigating and preventive actions are required and this thesis focus on the mitigating actions of fire fighting operations in Sweden, and the possibility of predicting fire spread using simulation tools.

A simulation tool using Cellular automata was developed using a probabilistic mathematical model by Alexandrisis et al. [21], including an additional parameter for the Fire Weather Index to account for fuel moisture levels. The cellular automata is a 2D grid consisting of a number of cells distributed in a matrix form and the tool simulates fire spread between the cells based on a number of rules and cell states.

The software development has focused on minimizing user input to enable operational use and automatically gathers data (weather, Fire Weather Index, elevation, land-use etc.) through Geographic Information Systems such as Google Maps and the Swedish Meteorological and Hydrological Institute (SMHI). When using the tool the user specifies a geographical location (latitude and longitude) for the fire starting point and the date/time. The results are exported to a .csv datafile that is imported and visualized using Kepler.gl.

As a part of the thesis a software proof-of-concept was developed and tested through three steps. The first step verifies the fundamental functions of the software, testing fire spread without external factors, with wind, and with slope to ensure that all parameters are working as intended. Additionally the Fire Weather Index parameter was tested for each case, which was confirmed to increase or decrease the fire spread rate of the model.

Secondly the land-use identification algorithm was tested using three sub-scenario environments; forest only, forest/water, and forest/water/urban. The results confirms that the software can identify the land-use, with reduced accuracy at the interfaces between two land-types.

Finally a case study was conducted and the simulation tool was tested and compared to the Västmanland fire in Sweden, 2014. The results from the simulation was that the software did manage to detect the land-use and correctly show a similar fire spread direction as the real fire. There were some discrepancies with regards to the temporal development and the total area burnt, but the foundational parts of software are shown to be satisfying and will provide a good basis for future work.

SAMMENDRAG (Norwegian)

Skogbrann er et fenomen som har vært en naturlig del av samfunnets historie siden 1.5 millioner år BP. Til tross for at skogbranner er en naturlig del av vårt miljø anser mange dem som problematiske grunnet økt omfang av antall hendelser, alvorlighet og verditap. Med høyere globale temperaturer antas antallet skogbranner å øke i fremtiden, noe som vil påvirke både menneskeliv og infrastrukturen vår. I et miljø hvor risiko for skogbrann øker, er det viktig at det planlegges for forebyggende- og konsekvensreduserende tiltak. Denne oppgaven tar for seg konsekvensreduserende tiltak gjennom brannvesenets innsats i Sverige, og hvordan simuleringsverktøy kan bistå med økt informasjon om hvordan en pågående skogbrann vil spre seg.

Som en del av oppgaven er det utviklet et cellebasert simuleringsverktøy basert på en probabilistisk matematisk modell av Alexandridis et al. [21]. I tillegg er det foreslått en ny parameter som tar for seg brenselets fuktighetsgrad. For å definere fuktighetsgraden brukes en brannrisikoindeks for skogbrann levert av Sveriges meteorologiske og hydrologiske institutt (SMHI). Simuleringsmodellen er et todimensjonalt rutenett bestående av et antall celler i matriseform. Programvaren simulerer brannspredning mellom cellene basert på forhåndsdefinerte regler og tilstander.

Utviklingen av programvaren har fokusert på å minimere brukerens input for å muliggjøre operativ bruk. Programvaren henter automatisk data (vær, brannrisikoindeks, terreng, typer vegetasjon osv.) fra GIS tjenester som Google Maps og SMHI. Ved bruk av simuleringsverktøyet vil brukeren oppgi den geografiske lokasjonen (latitud og longitud) hvor brannen startet, samt dato og tidspunkt. Resultatene eksporteres til en datafil (.csv) som etterpå kan visualiseres i Kepler.gl.

Som en del av utviklingen har programvaren blitt testet i tre steg. Det første steget tar for seg testing av de fundamentale variablene i den matematiske modellen: brannspredning uten ekstern påvirkning (uten vind og terreng), brannspredning med vind og brannspredning i terreng. Målet med testen er å sikre at alle de individuelle parameterne fungerer som beregnet. I tillegg er parameteren for brannrisikoindeks lagt til hvert enkelt scenario for å se hvordan dette påvirker resultatene.

Det andre steget tar for seg verifisering av en automatisert algoritme for å gjenkjenne arealbruk, herunder tre underscenarioer: Deteksjon av skog, deteksjon av skog og vann samt deteksjon av skog, vann og urbane områder. Resultatet bekrefter at dataprogrammet klarer å identifisere forskjellige typer av bruksområder.

Det siste steget har vurdert simuleringsverktøyets resultat opp mot en brann i Västmanland, Sverige, i 2014. Resultatet viser at verktøyet klarer å identifisere og definere riktig arealbruk, samt kan fremvise riktig retning på skogsbrannspredningen. Ved representasjon av tid så gav simuleringsresultatene en raskere brannspredning sammenlignet med brannen. Tilsvarende gjelder og for påvirket areal, hvor simuleringen viser et større påvirket område. Totalt sett så vurderes resultatet av simuleringen som positivt for en første versjon, og et godt utgangspunkt for videre utvikling.

NOMENCLATURE

CA Cellular Automata

CFD Computer Fluid Dynamics

CFFDRS Canadian Fire Fire Danger Rating System

CFFWIS Canadian Forest Fire Weather Index System

FDS Fire Dynamics Simulator

FWI Fire Weather Index

GIS Geographic Information Systems

HBV Hydrologiska Byråns Vattenbalansavdelning model (Hydrology model)

MSB Myndigheten för Samhällskydd och Beredskap (Swedish Civil Contingencies Agency)

SMHI Swedish Meteorological and Hydrological Institute

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1 Introduction

1.1 Background

Forest fires are common events that are suggested to have been an important component of the natural environment for at least 350 million years [6]. Since the earliest known use of fire 1.5 million years BP [9], ignitions caused by humans have become the most common source of forest fires [16].

Despite forest fires being a natural part of our environment, many consider them increasingly problematic due to the perception of rising occurrence, severity and losses. However, research by Doerr and Santin in 2016 [32] show that the quantitative evidence does not support the perceived trends. They state that the area burned globally appears to have declined over the past decades, and that there is increasing evidence that there are less fires globally today than centuries ago. With regards to the severity of the fires, there is not sufficient data to conclude on the matter. Certain regions, such as the western USA, indicates a small change where the area burned with high-severity has declined compared to the pre-European settlement. Furthermore, fatalities from the fires does not show any clear trends over the past three decades. When comparing human and economic losses derived from wildfire, earthquakes and flood disasters from 1901 to 2014 EM-DAT (International Disaster Database) wildfire is a relatively low-occurring event with few people killed or injured and a less total direct damage cost compared to other disasters. Nevertheless, with higher global temperatures, forest fires are predicted to increase around the globe, negatively affecting the risk of lives, health and infrastructure.

1.2 Problem statement and scope

With the potential problem of increasing consequences of future forest fires, both citizens and authorities must take the risks seriously and act proactively with both preventive and mitigating actions. This thesis focus on mitigating measures and specifically how operational tools may improve the situation for fire fighters using software to predict fire spread.

A study conducted by the Swedish Civil Contingencies Agency (2016) [31] concludes that there is no existing simulation software that is suitable for operational use in the Scandinavian boreal forests, and today hand-calculations along with qualitative judgement are used by trained personnel to plan fire fighting interventions. With the increase in available compute power and GIS data sources, the possibility of having a portable and visually easy-to-use fire spread simulation tool would be valuable to better support decision making.

In this thesis a cellular automata model has been developed to simulate the spread of fire in the Scandinavian boreal forests. A proof-of-concept simulation software will be presented where the focus has been to minimize user input and maximise automatic data gathering from geographical databases. The results are finally visualized on a map using Kepler.gl.

1.3 Limitations

The work covers testing of the software developed as a part of this thesis. It focuses on a single mathematical model using cellular automata, and has the objective of minimizing the user-based input. The solution is that the software automatically gathers various data from external suppliers (Google and SMHI API) as input for the simulation process. The software is not validated for operational use and is only intended as a proof-of-concept, and for the author to better understand the under laying variables and needs when developing a fire spread simulation software.

2 Literature review

This chapter covers previous research on the forest fire phenomena, modelling of forest fire spread and how cellular automata work.

2.1 Fire Behaviour and Fire Environment

Alexander [17] describes fire behaviour as the manner in which fuel ignites, flame develops, fire spreads and exhibits other related phenomena. The fire behaviour is interlinked with the environment, as described by Countryman [18], which is the complexity of fuel, topography, and air-mass factors that influences or modifies the inception, growth, and behaviour of fire. To understand and predict a fire's behaviour, one must understand both phenomenons.

A forest fire is described using specific terminology for the various parts. The fastest moving part is called the "Head", the sides "Flanks" and the slowest moving region is the "Back". Most often the head has the greatest intensity, including rate of spread, flame length and depth [42]. Spotting, or spot fires, is a phenomenon that occurs when fire spreads by burning embers due to wind where they are disposed at a point further ahead from the fire. Since forest fires are heavily affected by the wind direction and speed, the location of the head may rapidly change with weather conditions. The anatomy of a forest fire is illustrated in Figure 2.1-1 .

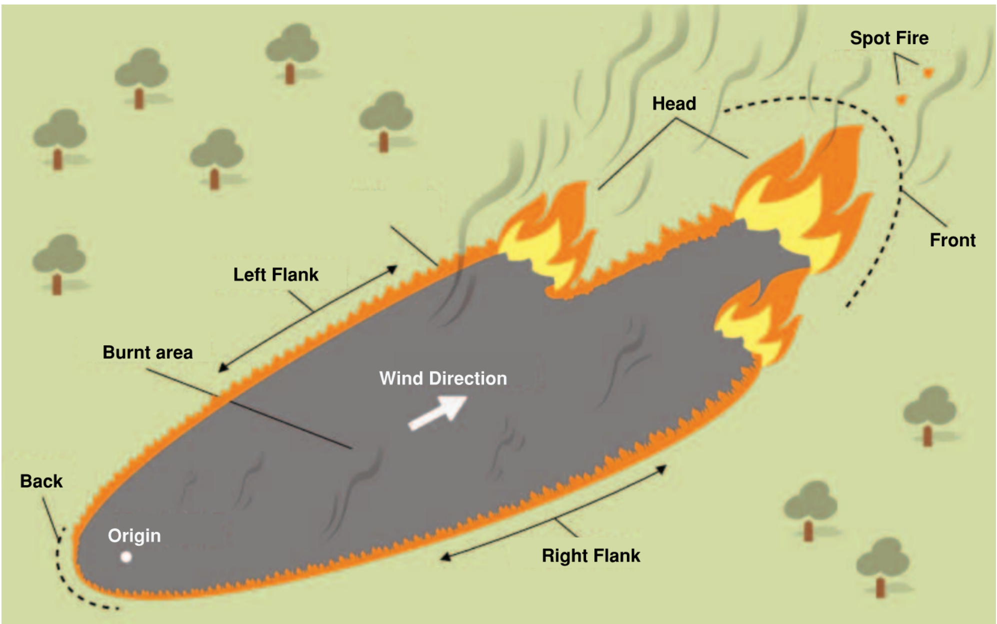


Figure 2.1-1 : Anatomy of a forest fire from Granström [40].

2.1.1 Variables affecting fire spread

Most forest fires start with a single point of ignition and then spreads from this point in all directions where there is available fuel. For a flat surface with homogeneous fuel and no wind the fire front creates a circular shape [42]. In the Canadian Forest Fire Behaviour Prediction System a fire starting from a single point is modelled so that the fire spread rate will continuously increase when excluding external factors, reaching 80 % of its final spread rate after 20 minutes [40]. This realistically varies depending on the type of vegetation, and for grass land the maximum speed can be reached in 10 minutes, while it take 30 minutes or more in forests [17]. More commonly, vegetation fires are affected by external factors influencing the spread rate and four main factors are identified as the contributors to the behaviour of a forest fire [33, 40]:

- Fuel composition
- Moisture content of the fuel
- Wind direction and speed
- Terrain and slope

Fire acceleration and spread rate
Fire acceleration is the rate of which the spread rate increase. The rate of spread is a measure of the speed of progression of a fire perimeter, which is dependent upon flame zone size, shape and environmental conditions [36, 48]. Knowing how fast a forest fire will spread is crucial to understand the possible impacts. Looking at all variables affecting fire spread, the wind is the most used quantity to determine fireline intensity, suppression difficulty and firefighter safety [48].

Depending on the external factors head fire spread rates can range from about 1.5 m/h (lower limit of fire spread in surface fuels) up to 14 km/h for forest fires, and greater than 20 km/h for grass fires [17]. The spread rate is dependent on the fire intensity, which is related to the flame size, illustrated in Figure 2.1.1-1. Flame heights associated with high intensity fires generally average about 15-45 m with occasional flashes up to 185 m or more. For fires spreading against the wind the spread rate is often below 1 m/min and more often around 0.5 m/min [17]. Figure 2.1.1-2 illustrates the relation between fire growth and measurements of head fire distance, spread rate, and acceleration.

Understanding the fire acceleration and spread rate dynamics are important when developing a forest fire simulation tool. The provided data may be used for verifying the foundational functionality of a software and when conducting the initial setup of a simulation scenario.

Fuel composition
Most natural areas are covered by living and dead organic materials, with different types of quality

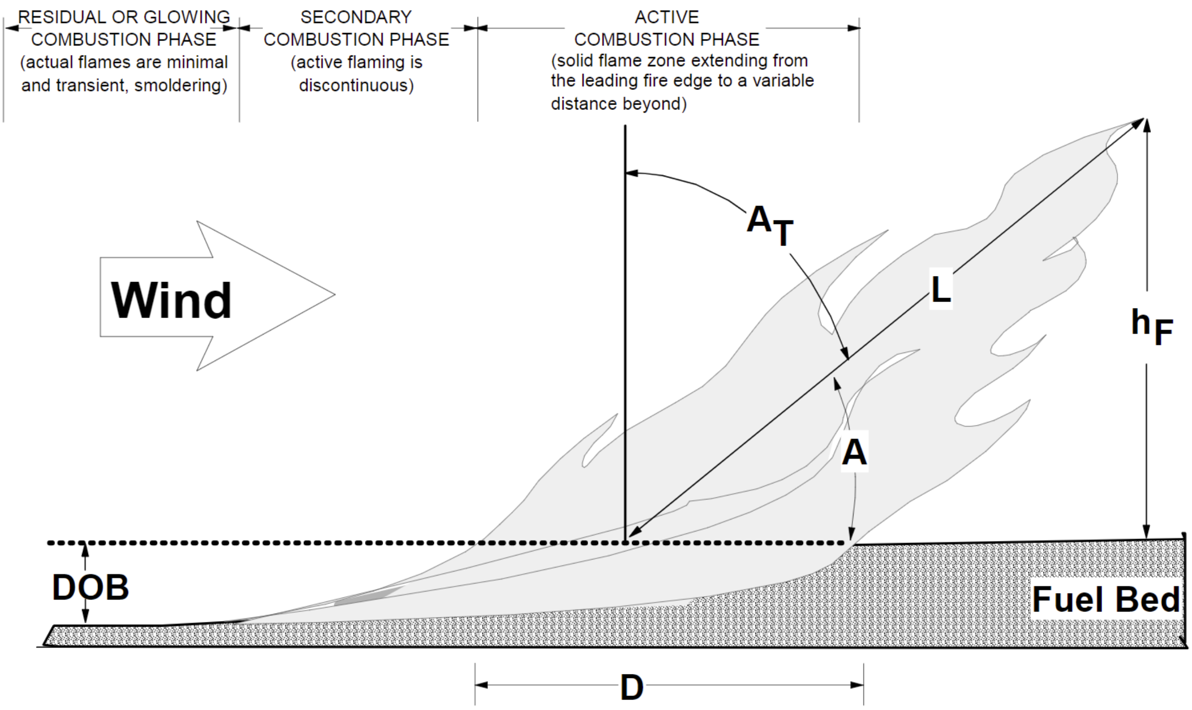


Figure 2.1.1-1: Cross-sectional view of a stylized head fire on level terrain illustrating the energy or heat-release stages during and following passage of the flame front, flame length (L), flame height (h_F), flame angle (A), flame tilt angle (A_T), horizontal flame depth (D), and the resulting depth of burn (DOB) (from Alexander 1982) [17].

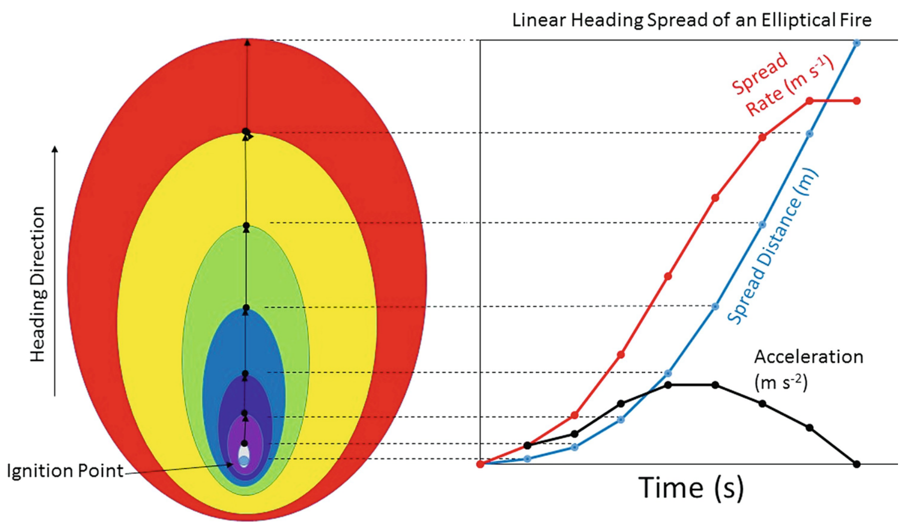


Figure 2.1.1-2: Illustration of hypothetical elliptical fire spread from a point ignition showing time contours of fire growth corresponding to measurements of head fire distance, spread rate, and acceleration [36].

available as fuel for a potential fire. Fuel composition describes the combination of type and density of organic mass available in the fuel bed. The fuel bed consists of different or similar fuel particles in one or more vegetation layers called strata. The strata is typically divided into an over-story, mid-story, under-story and forest floor, and contains vegetation of different life cycle stages (seedlings, saplings, trees, shrubs and detritus) [47]. The variables considered for the various components are their structure, size, arrangement, composition, moisture and flammability, which results in the ease of ignition and heat-release rate of the fuel [47].

Moisture content

Fuel moisture content refers to the moisture present in the fuel, expressed as percentage of the mass of water relative to the mass of dry fuel [43]. The moisture content has a great effect on ignition and combustion of a fuel and is therefore often included in fire behaviour and effects models. A high moisture content requires more energy to sustain combustion, which affects the fuel consumption of a fire. Characterization of fuel moisture is distinguished between live and dead fuels [43].

Granström [19] describes that the ground fuel/moisture relations within the Swedish boreal forests may store large amount of water when raining, which reduces both the risk of ignition and the rate of fire spread. The ground fuel may store up to 4 times its own weight in water (400 % moisture ratio), where almost all must be evaporated before susceptible for ignition. The ignition limit is about 25 % moisture content, and after that the rate of fire spread significantly increases with reduced moisture content [19].

Wind

The rate of fire spread increases significantly when affected by wind as the flame is tilted closer to the ground, pre-heating the fuel ahead [19]. Furthermore, Granström [19] states that the wind will increase the rate of combustion due to additional supply of air, which in combination with the pre-heating factor leads to quicker combustion, quicker release of combustible gases and therefore a higher spread rate, intensity and longer flames.

Wind-driven fires originating from a point will typically form an ellipse in the fuel, if the wind direction and velocity remains constant, Figure 2.1.1-3.

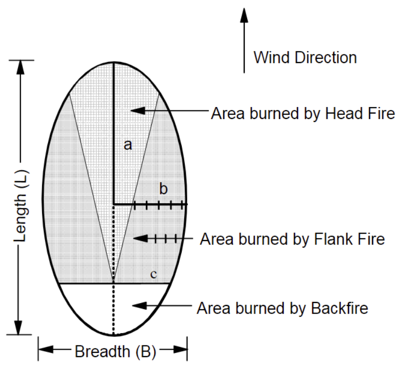


Figure 2.1.1-3: Simple elliptical fire growth model (from Alexander 1985) [17].

Terrain and slope

The terrain is the changes in a landscape surface over a distance, where the vertical component is called elevation. The elevation is measured in height with respect to the sea level, or the mean sea level. A slope is the change in elevation across a distance measured in degrees or as a percentage [45].

The slope is an important parameter when modelling fire behavior. It influences the rate of fire spread where a fire spreads more rapidly up a slope by preheating fuels and increasing their combustibility due to flame length being closer to the ground [19]. On the opposite a fire will spread slower down a slope since the flame is further away from the unburnt fuel. A head fires rate of spread doubles for every 10° of slope and is halved for backing fires [2, 45]. The combination of a sloping terrain along with the wind speed can have an increased effect of the rate of fire spread [12].

Spot fires

Spot fires are a phenomenon occurring from burning embers or sparks that are flying above the flame zone due to thermal updraft created by the convective energy from the fire and then deposited a distance ahead of the fire front. Spotting refers to the fire behavior that produces spot fires [44]. A single spot fire may occur tens of kilometers downwind, or firebrands "shower" unburned fuel a few meters from the fire edge [17]. An example of the impact of spot fires is an incident reported by NRK [51] in Sotra, Norway in 2021, where the fire jumped across a 260 m wide fjord.

2.2 Forest fires in Sweden

The number of forest fires in Sweden threatening properties and infrastructure are relatively low compared to regions in the southern parts of Europe, or areas with boreal forests such as in Canada or Russia [46]. During the latest decades it is mainly the large fires in 2018 that caught a lot of attention, which caused destruction of private properties such as cabins and rural buildings, but no loss of human lives. A study conducted by Sjöström and Granström [46] of fires between 1996-2018, show that 2018 was an exceptional year, with regards to both the number of fire department interventions and the total area burnt. Furthermore, Sjöström and Granström states that the overall trend of annual burnt area between 1900 and today is somewhat constant, but the later years show an increasing trend in the number of uncontrollable fires. In their work they conclude that major fires out of control are more common in rural areas due to:

- Increased time before first intervention by the fire department.
- Dry weather conditions during the days leading up to the event.
- Ignition by lightning strikes or forest machinery. Lack of proper extinguishing when using open flames.

2.2.1 Vegetation type

According to the Swedish National Forest Inventory, the total land area of Sweden is 40.8 million hectares, consisting of 23.1 million hectares of productive forest. The total standing volume of productive forest is about 3.0 billion m^3, of which 39 % is Scots pine, 42 % Norway spruce and 12 % birch [27]. The fuel bed in a Swedish boreal forest typically consist of moss and litter, and is expected to cover more than half of the ground area in the forests. This is a combination of living and dead organic materials with great differences in the fuel quality, depending on the specific types of vegetation. Generally the fuel bed in Scandinavia is favorable for a forest fire, if it is sufficiently dry. The moss layer is about 3-8 cm thick and may store large quantities of water when raining (up to 400 % its own weight). For the moss to pose a fire hazard most of the water content must be evaporated before it becomes sufficiently dry (< 25 %) [40].

2.3 Modelling Fire Behaviour

Mathematical models predicting forest fires have been developed since the late 1960s [2, 5]. The models have increased in complexity and eventually fire simulators were developed along with the improvements in computing power and software engineering. Examples of such simulators are FARSITE (1998) [15], Phoenix (2008) [22], Prometheus (2010) [25] and Spark (2015) [29]. Fire simulators take into account inputs such as fuel type and moisture, wind and the topography over a geographical area to estimate a fire spread that is faster and more detailed than manual calculations.

The aim of a predictive modelling system is to predict the outcome of an initial fire event. The simplest, and earliest models, focused on the likely danger by a fire, or a set of conditions prior a fire outbreak (Fire Index Models). In addition, these systems provided a prediction of the likely spread of a fire, but only at a single dimension, often the rate of spread of the fire front. More modern models have shifted the focus from one-dimensional fire spread to two-dimensional planar models of fire spread [23]. Figure 2.3-1 illustrates the relationship between fire behaviour determinants and their relation to fire modelling.

2.3.1 Physical and quasi-physical models

Physical modelling of fires is based on first principles physics, thermodynamics and processes which controls fire spread. Many of the available models developed since the 1990s are based on the same principles and only differs in the methodology of implementation, or the purpose of use. The models can be separated between a fully physical and quasi-physical model, where the main difference is how combustion chemistry is treated. Fully physical models can then be divided into two types of being intended for operational or experimental use (at least field validation), and those that are pure theoretical meant for research purposes only [23]. From a performance perspective the physical models are very compute intense and requires a high level of detailed data, and

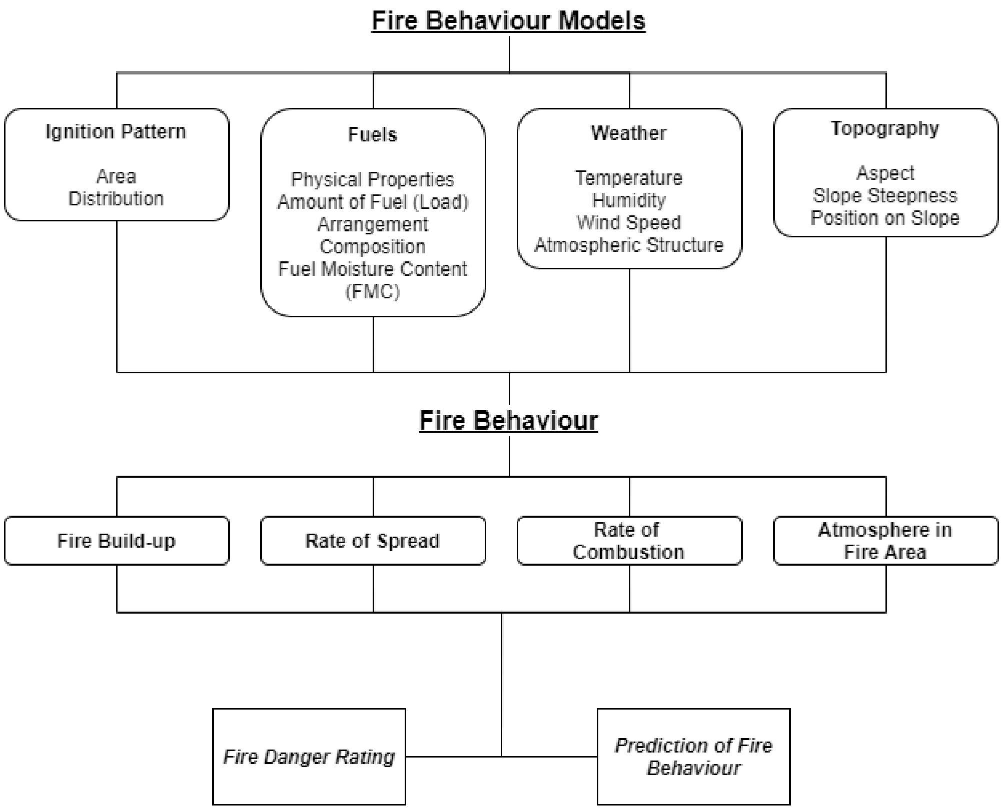


Figure 2.3-1 : The determinants of forest fire behaviour and their relation to fire modelling [16].

therefore the approaches available are not suitable for operational use (fire suppression planning based predicted fire behavior). Sullivan [23] has conducted a review of physical models where a few examples are given in Table 2.3.1-1.

Table 2.3.1-1: Examples of physical or quasi-physical models [23]

Model	Author and year	Description
AIOLOS-F	CINAR S.A., Greece, 1994	A decision support tool for forest fire behaviour prediction. CFD model that uses a 3-dimensional form of the conservation laws to couple the combustion of a fuel layer with the atmosphere to model forest fire spread.
FIRETEC	Los Alamos National Laboratory, USA, 1997	A multi-phase transport forest fire model based on the conservation laws. The model is 3-dimensional working in combination with a hydrodynamics model called HIGRAD.
WFDS	NIST, USA, 2006	An extension of the Fire Dynamics Simulator (FDS). The model is in 3-dimensions for use in predicting the progress of fire through wildland fuel in presence of combustible structures.

2.3.2 Empirical and quasi-empirical models

Empirically based forest fire models are focusing on the characteristic behaviours of a fire. These characteristics are generally the spread rate of the head fire, height of flames, angle of flames and the depth of the flames at the head. The development of empirical models have to some extent been based on observation of forest fires, but a majority of the data comes from experimental fires. Sullivan describes that the experimental method consists of four parts [24]:

1. Characterization and quantification of the fuel and terrain (fuel load, fuel height, moisture, density, combustion characteristics, slope etc.).
2. Observation and measurement of the atmospheric environment (wind speed and direction, air temperature, relative humidity etc.).
3. Observation of the fire itself (speed, spread, flame geometry, combustion rate, combustion residues, smoke etc.).
4. Statistical correlation between the measured quantities to produce a fire behaviour model.

The primary use of these models has been to estimate the spread for suppression planning purposes, traditionally conducted through calculations for plotting on a wall map. Due to this, empirical one-dimension models has most commonly been used where the spread rate in direction with the wind has been assessed since this method is easy to use and wind-speed being widely accepted as the dominant variable for determining the forward speed of a fire front [24]. Examples of existing empirical models are presented in Table 2.3.2-1.

Table 2.3.2-1: Examples of Empirical or quasi-empirical models [23].

Model	Author and year	Description
CFBP	Forestry Canada Fire Danger Group, 1992	Canadian Forest Fire Behaviour Prediction System, a component of the Canadian Forest Fire Danger Rating System (CFFDRS) which incorporates the Canadian Forest Fire Weather Index System (CFWI). Based on observations of ca. 500 experimental, prescribed and forest fires.
USFS	Catchpole et al. for United States Forest Service, 1998	Based on 357 experimental fires on a fuel bed 8 m x 1 m in a 12 m long wind-tunnel and four fuels with different surface-area-to-volume ratios.
Nelson	Nelson, 2002	A quasi-empirical model based on the work of the Nelson and Adkins (1988) model where Nelson extended the dimensional analysis to determine Rate of spread. The results was compared to the data of Weise and Biging (1997), gathered from 65 experiments in a wind tunnel.

2.4 Existing fire behaviour models and systems

There are many forest fire behaviour models throughout the world. Models and systems can be defined as operational if they are actively used for making decisions by fire management, excluding models under development or used by researchers only. The most commonly modeled fire behaviours are the forward flaming spread rate, intensity of the flaming front, transition from surface to crown fire, fire growth, spotting distance and fire acceleration from point source ignitions [39].

In 2016 there were about 20 existing fire spread simulation (or calculation) tools available, where the major part were using the Rothermels model for surface fire spread [31]. Most of these utilize the same underlying principles, but varies in the implementation and through graphical presentation of the results. These models consists of two types of simulation techniques, Cellular automata or vector-based simulation using Huygens principle [11].

Huygens principle is used for the most common models - FARSITE [15] and Prometheus [25], and is considered a great technique when calculating fire spread [31]. One short coming is if the time step becomes too large in situations with heterogeneous fuel, then the fire front has a risk of spreading into a new fuel-type with an estimated spread rate based on the previous fuel-type [31].

Models based on Cellular automata might be the most compute efficient technique, which enables the use of a probabilistic prediction method. Furthermore, these are well adapted for heterogeneous fuel compositions, since each cell contains data for a specific area. An issue with this simulation technique is that the direction of the fire is limited to the closest neighbors and the rules of interaction [31].

The fact that Cellular automata systems are potentially more compute efficient compared to using Huygens principle makes the method a preferable choice when developing a simulation tool intended for fast simulation times and for portable devices.

2.5 Rothermels surface fire spread model

In 1972 Rothermel [4] developed a semi-empirical surface fire spread model that allow users to estimate fire behaviour [41]. The model requires input for both live and dead fuel, where live fuel is grass or shrubs within 1.8 m from the surface. Dead fuel is classified by a time-lag fuel moisture from 1-, 10-, 100, and 1000-h, determined by the time it takes for a particle to lose 60 % of the difference between its moisture constant and the moisture content in a constant environment [41]. Gathering sufficient fuel data to run Rothermel's [4] equation is difficult and therefore predetermined fuel models have been developed. Andrews developed in 2018 [35] a fuel model that is a part of the National Fire Danger Rating System, which is currently including [41]:

- Fuel load (tons/acre, tons/ha) for each dead and live fuel class present in the fuel model.

- Surface area-to-volume ratio (ft^2/ft^3, cm^2/cm^3) for dead, live herbaceous, and live woody fuel.
- Fuel bed depth (feet, cm).
- Dead fuel moisture of extinction (percent)
- Dead and live fuel heat content (BTU/lb, kJ/kg)

The fire spread model was later modified by Albini in 1976 [5] in the FIREMOD program for fire behaviour prediction. These changes have been incorporated in the Rothermel model and included [35]:

- correction for mineral content,
- mineral damping coefficient,
- reaction velocity correlation,
- weighting factors for fuel load,
- moisture of extinction of live fuels, and
- weighting factor on intensity by category.

Rothermel's basic fire spread model, including Albini's modifications, consists of a series of equations including the heat source (Reaction intensity, Propagating flux ratio, Wind factor and slope factor) and heat sink (Bulk density, effective heating number and heat of pre-ignition) [4, 35], presented in Equation 1.

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{ig}} \tag{1}$$

where R is the Rate of spread [ft/min], I_R the Reaction intensity [Btu/ft^2/min], ξ [-] the Propagating flux ratio, ϕ_w the Wind factor, ϕ_s the Slope factor, ρ_b [lb/ft^3] the Bulk density, ϵ the Effective heating number and Q_{ig} [Btu/lb] the Heat of pre-ignition.

2.6 Huygens principle

Huygens principle stems from his discovery about the propagation of light waves [1] where Huygens concluded that "around each particle there is made a wave of which that particle is the centre", illustrated in Figure 2.6-1 and Figure 2.6-2 .

Huygens principle was first used by Sanderlin and Sunderson (1975) in their work for the USDA Forest Service. The model was integrated in an overall real-time decision support system to sim-

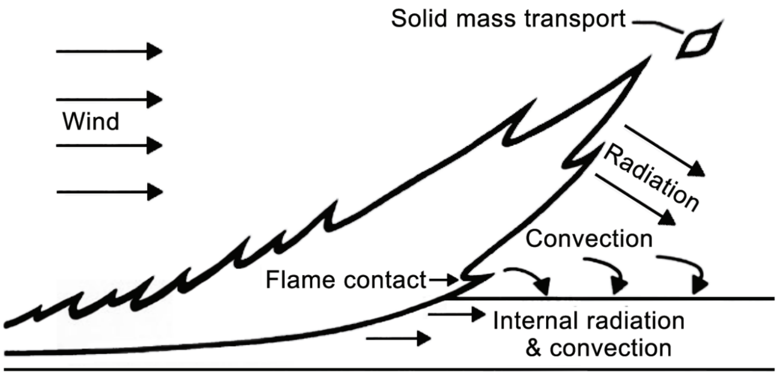


Figure 2.5-1 : Variables affecting fire spread in a fire spread model. Illustration from Andrews [35].

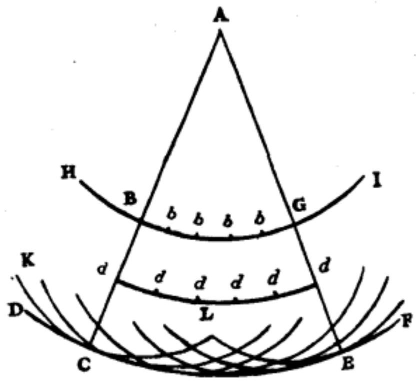


Figure 2.6-1 : Propagation of light waves, as proposed by Huygens [25, 1]

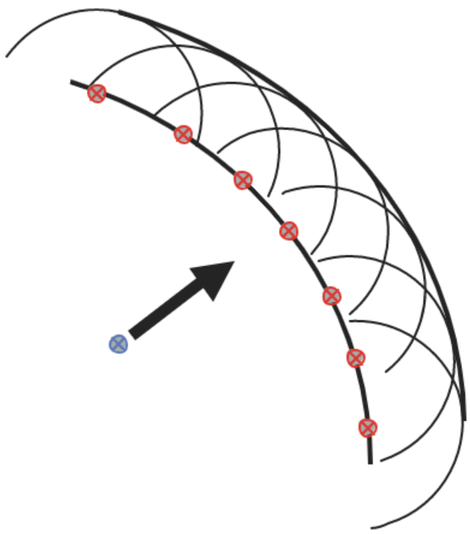


Figure 2.6-2 : Formation of a new wave front using Huygens principle, illustration by Tymstra et al. [25]. Blue circle is the point of origin with the arrow pointing at the spread direction. Red circles are origins of secondary waves.

ulate fire behavior and suppression effectiveness in southern California [25]. Tymstra et al. [25] states the following: "The application of Huygens principle to simulate fire growth assumes that the shape of a fire can be represented by a polygon, a plane figure composed of a sequence of straight-line segments forming a closed path. The points around the perimeter where two line segments meet are the polygons vertices, and each vertex along the perimeter of a fire polygon propagates as an independent elliptical wavelet.", illustrated in Figure 2.6-3 .

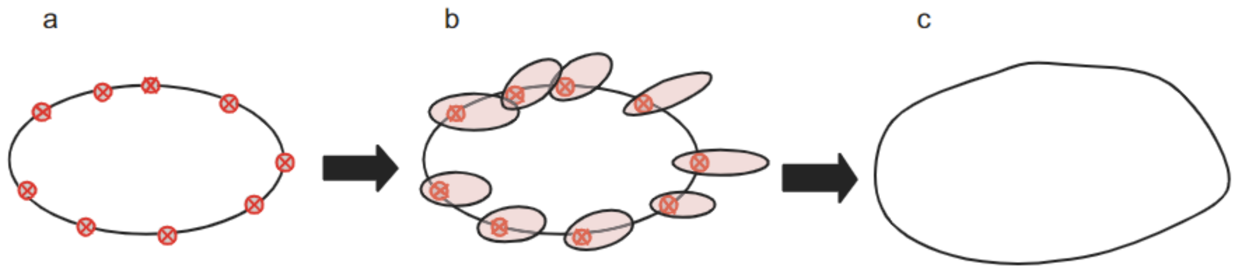


Figure 2.6-3 : Application of Huygens principle to simulate fire growth, illustration from Tymstra et al. [25]. Illustration c is a polygon formed from the outer perimeter of the waves created in illustration b.

2.7 Cellular Automata

A Cellular automata (CA) is a mathematical model consisting of a number of cells normally distributed in a matrix form. This was first introduced by Von Neumann in 1966 [3] and later research by Wolfram [7] showed how complex systems can emerge from simple rules. The method of CA was first used for modelling forest fire spread on hypothetical forests by Karafyllidis et al. [13] and later developed and applied on the Spetses Island fire (1990) by Alexandridis et al. [21] in 2008. More recent fire related applications of CA modelling is multi-layer smoldering combustion by Nieves Fernandez-Anez et al. in 2017 [34], and Velasquez et al. [38] where Alexandridis mathematical model was used along with Geographical Information Systems (GIS).

A Cellular Automata is composed of:

- A grid of cells.
- A set of ingredients called agents, that can occupy the cells.
- A set of local rules governing the behaviors of the agents.
- Specified initial conditions.

2.7.1 State of the art forest fire models

Since 2010 multiple forest fire spread models and tools using cellular automata have been developed, often in teams due to the various skills required to produce a working software. Most of these are pure theoretical models and few are developed into functional products. Three of these models are described below where the tool PROPAGATOR is a web application currently used by

Italian fire management.

- An improved Cellular Automata for Wildfire Spread - 2015, Ghisu et al. [28]
  A cellular automata approach that is able to mitigate this problem with a redefinition of the spread velocity, where the equations generally used in vector-based approaches are modified by means of a number of correction factors. A numerical optimization approach is used to find the optimal values for the correction factors. The model is based on Rothermels surface fire-spread model, since Rothermels model is applicable to a range of fuels and commonly used in other fire behaviour prediction models.

- Cell2Fire, An open-source cell based forest fire growth model - 2019, Pais et al. [37]
  The software is an open-source cellular automata developed in Python and C++ using the Moore Neighbourhood. One of the objectives was to build a fast tool that scales well in parallel computing environments for use with large forests and large studies that requires many simulation runs. The mathematical model used in the simulation tool is based on the Canadian FBP System proposed by Tymstra et al. [25].

- PROPAGATOR: An Operational Cellular-Automata Based Wildfire Simulator - 2020, Trucchia et al. [49]
  Stochastic cellular automaton model for forest fire spread simulation using the Moore neighbourhood. The development was initiated by the Italian Civil Protection Department in support of the G8 summit 2009. The software was originally based on a Google Web Toolkit interface, with a server written in MATLAB, which made it possible to run fire simulations all over Italy from a simple web interface. In 2017 the program was rewritten using Python with Django REST API and database. In 2020 the fifth release implemented a Rate of Spread model to give a more realistic time parameter as well as fuel moisture and fire fighting actions.

2.7.2 Grid

The grid may contain a larger collection of cells and can be in a one-, two-, or three- dimensional form. The most common type is a two-dimensional grid where there are generally three types, a box, a cylinder or a torus. In the box type the agents will encounter boundaries at all four sides; in the cylinder type they only encounter boundaries at the top and bottoms, and in the torus there are no boundaries. The type of grid selected will have to be based on the system to be simulated [20].

2.7.3 Cells

The cells can be of various geometries (triangle, square, hexagons etc.) and sizes placed on the grid, where squares are the most common type. The chosen shape should be based on the type of study.

The cells will have a defined number of states, where it may be empty or contain a certain type of fuel and properties [20].

2.7.4 Cell Neighborhoods

The neighborhood is the cells located nearby a specific cell. The most common types of neighbourhoods used in a two-dimensional grid are the von Neumann neighborhood and the Moore neighborhood [20]. The neighborhood represents the possible ways properties from a selected cell may spread within a single time-step. Example of Moore and von Neumann neighborhoods are illustrated in Figure 2.7.4-1 and Figure 2.7.4-2.

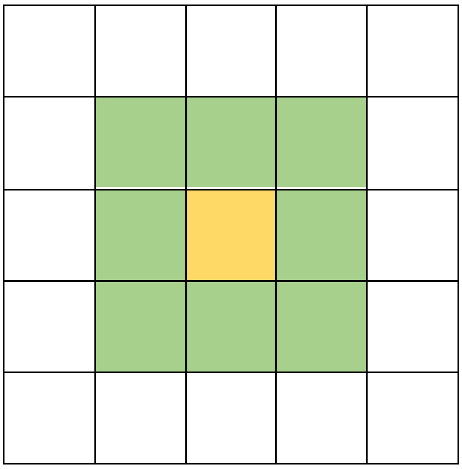


Figure 2.7.4-1: Moore neighborhood for the orange cell.

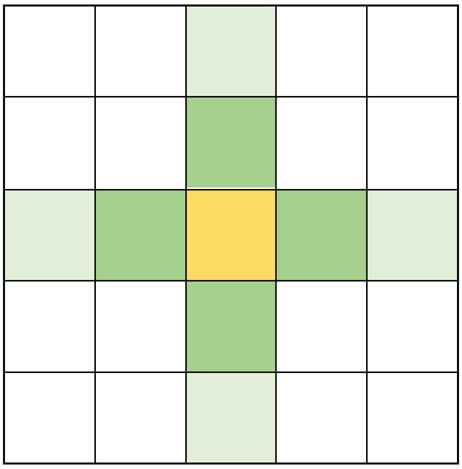


Figure 2.7.4-2: von Neumann neighborhood for the orange cell.

2.7.5 Rules

The movement of an agent on the grid is decided by rules that are governing the evolution of the system. The rules are local and involve a cell itself and the cells in the surrounding neighborhood

[20]. CA rules can be relatively simple, but nevertheless powerful enough to simulate complex behaviours.

2.8 Alexandridis probabilistic fire spread model

In 2008 Alexandridis et al. [21] developed a new mathematical model that could predict forest fire propagation in a 2-dimensional cellular automata, presented in the Applied Mathematics and Computation journal. The model was used to simulate the forest fire on Spetses island in August, 1990.

In the article Alexandridis [21] writes that each cell represents a small patch of land with a square shape, offering eight directions of spread (Moore neighbourhood). The cell state has four options, which evolves in discrete time:

1. Cell contains no fuel.
2. Cell contains fuel and has not ignited.
3. Cell contains fuel that is burning.
4. Cell contained fuel that has burned.

The development of the states are based on a certain set of rules. The rules implies that a cell that catches fire at a current time step can spread to its neighbours at the next time step with a certain probability. The total probability , P_{burn}, is a function of a number of parameters that represents the effect of wind, slope, vegetation type and density, shown in Equation 2.

$$P_{burn} = P_h(1 + P_{veg})(1 + P_{den})P_w P_s \tag{2}$$

P_h is the constant probability, P_{veg} and P_{den} the effects of the type and density of the vegetation, P_w effects of the wind and P_s the effects of the slope.

When comparing the simulation results from the new mathematical model with the Spetses island fire, Alexandridis et al. [21] states that the results were very close to the actual fire, confirming satisfactory prediction of a forest fire spread in heterogeneous terrains.

2.9 Geographical Information System (GIS)

GIS is at a fundamental level a geographical information technology where data is stored and used for digital cartography. The benefit of GIS is the possibility of capturing, editing and analyzing spatial data, which then can be visually presented on a map. Example of GIS databases are Google Maps, Mapbox or Openstreetmap where data is available through an Application Programming

Interface (API). In the case of important forest fire modelling parameters (slope, wind and land-use/vegetation), information that is geography based is required as simulation input to realistically model fire spread in a specific region. Using APIs to automatically access GIS data has a great potential for predicting fire spread, minimizing the manual input to only using longitude, latitude and datetime.

2.10 Fire Weather Index (FWI)

The FWI used in Sweden is based on the Canadian Forest Fire Weather Index System (CFFWIS), which is a part of the Canadian Forest Fire Danger Rating System (CFFDRS; [10]). The system contains multiple indexes which are based on meteorological input data that give a result called the Fire Weather Index. The methodology for calculating the index is described by Van Vagner [8]. This is further described by Granström and Sjöstedt in their report on forest fires trends in Sweden from 2020 [46].

In Sweden the input for the FWI is gathered by the Swedish Meteorological and Hydrological Institute (SMHI) weather data.

2.10.1 Fire dynamics and the relation to the Fire Weather Index

The four main contributors to forest fire dynamics are fuel composition, fuel moisture content, wind velocity and direction, and sloping terrain. With regards to the fuel, the most central part is the type of ground layer and its moisture content. In Sweden the Canadian Fire Weather Index system has been in use since year 2000, which has the intention of being able to model the fuel moisture levels, fires spread rate and intensity, based on weather variables for a standardized type of fuel [40]. The forest fire simulator Prometheus [25] can utilize the Canadian FWI to predict the fire spread, however, the precision of these types of tools are still low in the Nordic countries due to not being calibrated to the Swedish fuel types according to MSB (2016) [31]. The buildup of the FWI system is illustrated in Figure 2.10.1-1.

Fine Fuel Moisture Code (FFMC)

Van Wagner [8] describes that the FFMC represents the moisture content in the upper part of the ground layers, containing litter and other cured fine fuels, such as leaves, branches, etc. The code indicates the ease of ignition and flammability of fine fuel, where the moisture content varies over a daily cycle. The dry-mass of this layer is set to 250 g/m^2 and can, according to the model, contain 0.6 mm water.

Input parameters: Rainfall, relative humidity, wind speed and temperature.

Duff Moisture Code (DMC)

The DMC quantifies the moisture level of the lower part of the ground to represent the moisture

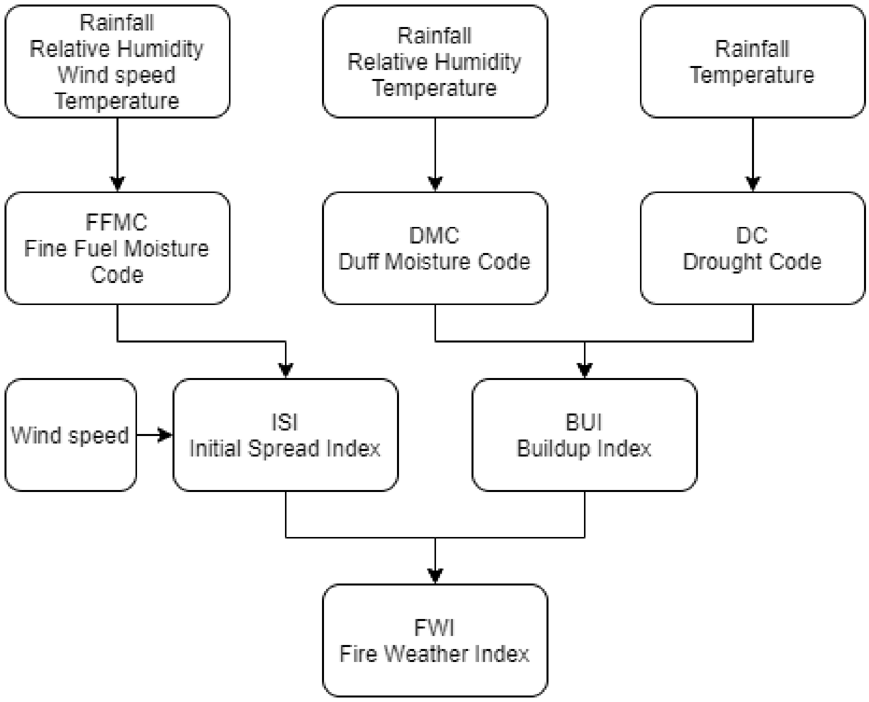


Figure 2.10.1-1: Block diagram of the FWI System [8]

content of some real slow drying forest fuel [8].

Input parameters: Rainfall, relative humidity and temperature.

Drought Code (DC)

While the FFMC only covers the thin surface for fast drying materials and the DMC the moderate depth and dry-weight, Van Wagner describes the real fire danger being affected by the state of the deeper organic layer of large downed wood and availability of water in streams and swamps [8]. The DC describes the very slow-drying moisture index.

Input parameters: Rainfall and temperature.

Initial Spread Index (ISI)

A numerical rating of the expected rate of fire spread. It combines wind, slope and FFMC on rate of spread, but excludes the influence of the variable quantities of fuel [14].

Input parameters: FFMC and wind speed.

Buildup Index (BUI)

A numerical rating of the total amount of fuel available for combustion, based on DMC and DC [14].

Input parameters: DMC and DC.

3 Methodology: Cellular Automata

This chapter covers the methodology of the work, including the mathematical model, explanation of the simulation environment and how the simulation tool was verified.

3.1 Mathematical model

The method used is an approach based on the work by Alexandridis et al. [21], where a two-dimensional Cellular automata is used to predict forest fire spread. In addition a parameter to account for the fuel moisture content is proposed by implementing the Fire Weather Index (FWI). The hypothesis is that FWI can provide value through increasing or decreasing the spread rate probability.

3.1.1 Grid

The mathematical model will use a two-dimensional grid to represent the spatial area where the fire spreads. Each cell is uniform in the sense that it represents a single state within a geographical region. A cell has eight connections and offers a certain probability for the fire to spread in each of the different directions (Moore neighborhood).

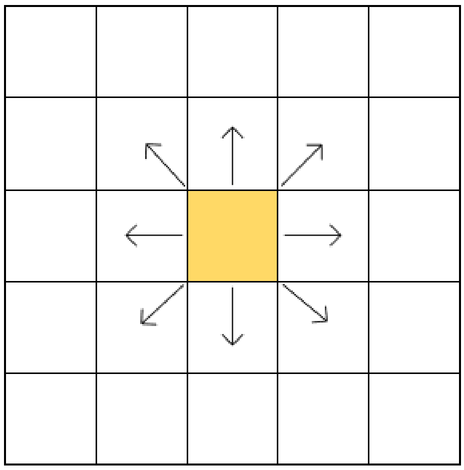


Figure 3.1.1-1: Fire propagation possibilities on a square grid (Moore neighborhood) used in the simulation model.

3.1.2 State of cells

The status of a cell is defined by a number of states that evolve with each time step. Each state is presented as follows:

1. No fuel available and it is assumed that the cells cannot be burned.
2. Cell contains fuel that has not yet been ignited.

3. Cell contains burning fuel.

4. Cell contains fuel that has been burned.

Figure 3.1.2-1 gives an example of the representation of various geographical attributes are translated in cell states along with burning and burnt out cells.

State: Vegetation	State: Vegetation	State: Water	State: Water	State: Water
State: Water	State: Vegetation	State: Burning	State: Burned	State: Burned
State: Water	State: Vegetation	State: Burning	State: Burned	State: Burned
State: Vegetation	State: Burning	State: Burned	State: Burned	State: Burned
State: Burning	State: Burning	State: Burned	State: Burned	State: Burned

2	2	1	1	1
1	2	3	4	4
1	2	3	4	4
2	3	4	4	4
3	3	4	4	4

Figure 3.1.2-1: The cell state coding, from geographical input to values in a matrix.

3.1.3 Rules of evolution

For each simulation step (t) the cells evolve in discrete time as per the following rules:

1. A cell with no fuel cannot catch fire. If state of cell $(x, y, t) = 1$, then state of $(x, y, t+1) = 1$.

2. A burning cell will be burnt out at the next time step. If state of cell $(x, y, t) = 3$, then state of $(x, y, t+1) = 4$.

3. A burnt cell cannot reignite. If state of cell $(x, y, t) = 4$, then state of $(x, y, t+1) = 4$.

4. A cell containing fuel will ignite with a calculated probability based on the neighbouring cells. If state of cell $(x, y, t) = 2$, then state of $(x, y, t+1) = 3$ with a probability of P_{burn}.

3.1.4 Equations

The fire spread is modelled using a modified probabilistic approach developed by Alexandridis et al. [21] with an added parameter to include the effect of moisture content using Fire Weather Index (FWI) data from SMHI [50]. The methodology takes into account wind speed and direction, topography, vegetation density and the fuel moisture content. The individual variables in Equation 3 are further explained in the following sections.

$$P_{burn} = P_0 P_{den} P_w P_t P_{fwi} \tag{3}$$

Basic probability (P_0)

$$P_0 \propto R_0 \cdot 60 \cdot t/L \tag{4}$$

where P_0 is the basic probability of a cell adjacent to a burning cell catches fire at the next time step without wind or topography impacting. R_0 [m/s] is the basic rate of spread, t [min] the discrete time step of the simulation and L [m] is the cell length in meters. The user must be careful when selecting the length of the cell, since P_0 must always be less than one.

By using t [min] in the equation the number of minutes per time step creates a baseline for establishing a simulation time frame. This has to be decided for each individual simulation scenario. For example, if the number of time steps are set to 5 and each time step equals 2 minutes, the total simulated time will be 10 minutes.

The basic probability equation is fundamentally presenting a likelihood of a fire spreading across an entire cell length within one time step.

Topography (P_t)
The rate of fire spread increase with a positive slope due to the flames tilting and preheating the fuel. Cheney et al. [26] describe an equation to account for a correction factor where the slope is positive ($\theta \geq 0$).

$$P_t = e^{c_1 \theta} \tag{5}$$

where c_1 is the experimental correction factor and θ the slope angle. The correction factor, c_1, of 0.063 is used in the work of Alexandridis et al. [21] and will not be adjusted to minimize the uncertainty regarding the number of variables when testing the impact of the Fire Weather Index. The slope angle is calculated based on the height difference between two cells, E, gathered from elevation data in Google Maps Services API [52].

$$\theta = \tan^{-1}[(E_1 - E_2)/L] \tag{6}$$

where L [m] is the cell length. For diagonally placed cells the length between the centres differs and the equation becomes:

$$\theta = \tan^{-1}[(E_1 - E_2)/\sqrt{2}L] \tag{7}$$

Wind velocity and direction (P_w)
In the model an empirical wind-effect relation is applied, where the probability includes the effect of the wind velocity and direction. With the equation the wind direction can come from any point between 0 and 360°, in contrast with many alternative techniques where the direction is from a few discrete values [21].

$$P_w = e^{c_2 V} f_t \tag{8}$$

where V [m/s] is the wind speed, c_2 [-] a correction factor and f_t [-] adjusting for the wind direction. The correction factor, c_2 [-], is set to 0.045 in accordance with the work of Alexandridis et al [21].

$$f_t = e^{c_3 V(cos(\theta)-1)} \tag{9}$$

The wind effect is adjusted based on the relative angle of the wind and flame propagation direction. c_3 is the correction factor and θ the angle between 0 and 360°. The correction factor, c_3, is set to 0.191 in accordance with the work of Alexandridis et al [21].

The flame propagation direction F_{dir} is derived from calculating the angle between the Cartesian coordinates of the burning cell to its neighbour using the $arctan2(dy, dx)$ function. The wind angle is given by either manual input data or from automatic weather data sources.

$$F_{dir} = arctan2(dy, dx) \cdot (180/\pi) \tag{10}$$

Vegetation density and type (P_{den})
The vegetation density and type are variables that cannot be calculated and must be determined based on data. For this thesis the vegetation data source is Google Static Maps, which presents land-use types based on various colors. Due to a limitation in the available data the vegetation density and type is defined as presented in Table 3.1.4-1.

Fire Weather Index (FWI) (P_{fwi})
The software is programmed to automatically gather FWI data from SMHI open data API [50] based

Table 3.1.4-1: Vegetation density probability values, P_{den}

Type	Probability (P_{den})	Description
Open land	0.7	Less dense areas with vegetation, i.e grassland, less dense forests etc. Identified as Beige color in Google Static Maps.
Forest	1.0	Dense vegetation, i.e. forest. Identified as Green color in Google Static Maps.

on Date and Time input. However, this API is new for 2021 and historic data, before march 2021, must be manually configured into the model if it is to be utilized.

The FWI probability factor, P_{fwi}, is subjectively selected and presented in Table 3.1.4-2. The "High Risk" level is set as the point where the other variables are unaffected, i.e. $P_{fwi} = 1.0$, where the FWI does not affect the fire spread probability variables. From the High risk level being considered as normal, the FWI will either increase or decrease the total probability, P_{burn}, by increasing or decreasing the P_{fwi} variable. For example, Very High Risk and Extremely High Risk has a $P_{fwi} > 1.0$ and will increase the total fire spread probability, P_{burn}.

Table 3.1.4-2: The probability factor,P_{fwi}, based on the adjusted FWI classification suggested by Granström [46]

Fire Weather Index	Risk Class	Definition	Probability (P_{fwi})
$FWI < 5$	1	Very Low Risk	0.40
$5 < FWI \leq 11$	2	Low Risk	0.60
$11 < FWI \leq 17$	3	Medium Risk	0.80
$17 < FWI \leq 22$	4	High Risk	1.00
$22 < FWI \leq 28$	5	Very High Risk	1.20
$FWI > 28$	6	Extremely High Risk	1.40

3.2 Simulation Environment

This section details the simulation environment developed using Python as a programming language. The method is inspired by the work of Velasques et al. in 2019 [38] where the mathematical model of Alexandridis et. al. [21] was used for building a Forest Fire Propagation Simulation Tool using Cellular automata and GIS in a Google Maps environment.

A similar approach is used, with the difference that the software is specifically developed for this thesis, possibly using other methods and algorithms, since the code base of previous models is unknown. In addition, modifications has been done to the mathematical model, including the Fire Weather Index as a factor and reducing the number of input variables for vegetation type and density, presented in Table 3.1.4-1. Figure 3.2-1 presents a flow-chart of the process of creating, simulating and presenting the fire simulation data.

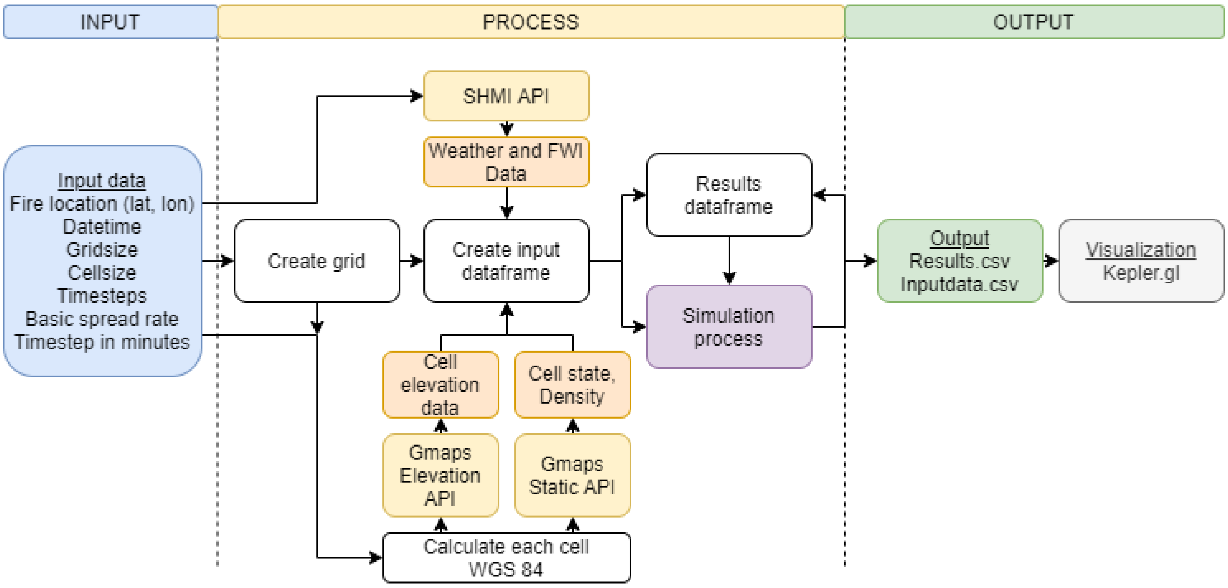


Figure 3.2-1 : Simulation process flow-chart.

3.2.1 Grid and cells

The grid and cells are created based on user input for grid-length (meters) and cell size (meters). The number of cells on each side of the grid is equal to grid size divided by the cell size, i.e. 100 m grid-length / 20 m cells gives a grid with 5 x 5 number of cells.

The geographical location of the grid, WGS 84, is based on user input for the fire start location as a latitude and longitude position. To support fire spread in any direction this is assumed to be in the centre of the grid. The geographical position of the cell in a Cartesian coordinate system (0,0) is then calculated using the Geopy package in Python to find the WGS 84 coordinates for the southern most part of the grid (1/2 * gridlength [m]) and from that point half a grid-length west. The WGS84 coordinates for cell (0,0) is stored and used as a basis for calculating the WGS 84 geographical coordinates for the remaining cells within the grid.

3.2.2 Edges

Cells that are placed on the edges must be handled separately since these does not contain all 8 neighbours in the Moore neighbourhood. There are theoretically three alternatives:

1. Edges remain constant - This is considered to be the simplest solution, where the value of the cells are left with their state as constant.
2. Edges wrap around - The grid can be visualized as a strip of paper that is wrapped into a ring. A cell of the left side is connected to a cell on the right side, which creates an infinite

grid. This solution is not practical for spatial analysis since it is unrealistic that the status of two cells geographically far away would impact each other.

3. Edges have different neighbourhoods and rules - Separate rules can be created for cells with a reduced number of neighbours.

For the simulation model used in this thesis, option 1 is selected due to it being practical to implement and that the borders are far from the studied area, and will not influence the results.

3.2.3 Geographical Information System (GIS)

The simulation relies on geographical data that is automatically gathered from Google Elevation API [52], Google Static Maps API [52] and SMHI API [50] based on the input for latitude, longitude, date and time. Elevation data and land-use data is gathered for each cell, while the weather data is gathered once and is static throughout the simulation. In principle the weather data could have been varying with time, but has been deemed out of scope for this proof-of-concept software.

The returned GIS data is cell elevation, land-use input as RGB colors (initial cell state), weather data (wind direction, wind speed, temperature, FWI index). The data is then stored in a dataframe for each individual cell, illustrated in Figure 3.2.3-1.

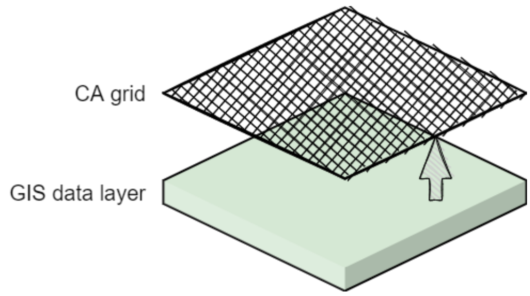


Figure 3.2.3-1: Data transfer from GIS datasource to the Cellular automata layer

3.2.4 Cell state and Vegetation density

The initial cell state is based on GIS data for each cell and the type of land use. The process fetches a single pixel from Google Static Maps API [52] for each cell WGS 84 location and an RGB sorter interprets the type of land-use and defines a cell state and vegetation density as defined in Table 3.2.4-1.

The list in Table 3.2.4-1 provides a general understanding of the available map colors, but practically Google use several nuances of the same color and therefore a single color type for land-use cannot be utilized to determine a particular state and vegetation density. To solve this the algorithm were run multiple times in various geographical locations to detect and manually sort the RGB colors that could arise. Through this a dictionary of colors were created which improved the results

Table 3.2.4-1: Land-use sorting rules

RGB Colors	Type	Cell State	Vegetation density
Blue	Water	State 1	0
Green	Forest	State 2	High
Beige	Land	State 2	Low
Grey	Urban	State 1	0
Unknown	-	State 2	Low

of the sorter. In case the fetched color is not in the pre-defined lists, the software will assume and apply a State 2 with low density vegetation.

3.2.5 Simulation process

The simulation runs as a loop limited by the selected number of time steps. For each time step the software checks the current state (t) of each cell in the grid, from (0,0) to (X,X) and updates the cell state in the next time step ($t+1$) based on the rules.

3.2.6 Output and Visualization

The software exports two datafiles, input.csv and results.csv. The input datafile contains all the input variables required to run the simulation, i.e. Cartesian plane location (X,Y), geographical cell location (latitude, longitude), initial cell state, initial time step, datetime, P_{den}, cell elevation, wind direction, wind velocity and FWI index value.

The results.csv file contains the following data: Cartesian plane location (X,Y), geographical cell location (latitude, longitude), cell state, time step, datetime and elevation. The software adds one row for each cell and time step, which means that the number of rows is equal the number of cells * number of time steps.

For visual presentation the tool Kepler.gl is used, where the results.csv data can be imported and the presentation modified through selection of colors, data and filtering functions. Kepler.gl is developed by Uber as an open source project. On the projects Github site the application is described as follows: *"Kepler.gl is a data-agnostic, high-performance web-based application for visual exploration of large-scale geolocation data sets. Built on top of Mapbox GL and deck.gl, kepler.gl can render millions of points representing thousands of trips and perform spatial aggregations on the fly."*

3.3 Model Verification

The model is tested on 12 scenarios with various conditions to verify the fundamental variables of the software, as well as the impact of the probabilistic values for the Fire Weather Index parameter. The verification process is separated into three parts, where the first one tests the fundamental equations of the model, based on selected input variables. The second part tests the land-use determination function, to verify how well it performs in various environments. Three locations has been selected - A forest, forest and water interface, and a forest with water and urban interface. The forest, water and urban scenario also looks at elevation data to verify that this is correctly implemented from the GIS data.

The last verification test takes a historic forest fire event to understand if the results are comparable to a real use case.

3.3.1 Part 1 - Verifying the fundamental variables and FWI

The simulation settings and description of the 12 simulation scenarios are presented in Table 3.3.1-1 and Table 3.3.1-2. The purpose is to validate that the fundamental parameters (wind, slope, FWI) of the simulation software are working as intended.

Table 3.3.1-1: Simulation settings

Variable	Setting
Gridsize	400 m
Cellsize	10 m
Basic Spread Rate	0.1 m/s
Time per time step	1 min
Time steps	25

Table 3.3.1-2: Simulation scenarios

Scenario	Slope	Wind dir.	Wind speed	FWI	Veg. density
1-4	No	0	0	None/Low/Med/High	Forest
5-8	No	90 deg	5 m/s	None/Low/Med/High	Forest
9-12	20%	0	0	None/Low/Med/High	Forest

3.3.2 Part 2 - Verifying the automated land-use determination process

Three randomly selected locations in Sweden are chosen to test how the land-use determination process is working, presented in Table 3.3.2-1 and Table 3.3.2-2. The system populates each cell with vegetation data using the Google Maps static APIs/RGB sorter, and elevation data using

Google Elevation API. The scenarios are covering a pure forest, a water forest interface and finally a water, forest and urban interface.

Table 3.3.2-1: Land-use simulation settings

Variable	Setting
Gridsize	400 m
Cellsize	10 m
Basic Spread Rate	0.1 m/s
Time per time step	1 min
Time steps	25

Table 3.3.2-2: Land-use simulation scenarios where the information is automatically gathered from GIS data.

Scenario	Lat/lon	Slope	Wind Dir.	Wind Sp.	FWI	Veg. den.
Forest	60.686094, 14.994751	GIS	0	0	None	GIS
Forest and Water	60.667519, 14.744299	GIS	0	0	None	GIS
Forest, Water and Urban	59.349421, 18.195604	GIS	0	0	None	GIS

3.3.3 Part 3 - Case study mixing GIS input and historic data

The purpose of the case study is to test if the developed simulation tool provides a reliable result when compared to a real world fire. The scenario chosen is a forest fire in Sweden 2014 that is well documented by the Swedish Civil Contingencies Angency (MSB) in their report "Skogsbranden i Västmanland 2014 - Observatörsrapport" [30]. At the time this was the largest forest fire in Sweden and in the report MSB states that the event is unique both with regards to size and its impact on the Swedish contingency management planning system.

The fire started on the 31st July with the first emergency call at 13:29, close to the municipality of Sala, with an approximated size about 20 x 30 meters. At 16:20 there was a flight mapping of the area and the reported size had then increased to 2000 meters in length and about 500 m width, at the widest point. The fire started at a time when the ground was severely dried out and the FWI was classified as very high, but not at extreme levels. On 2nd august there was about 5 kilometers of uncontrolled fire front with open flames or glowing embers along the then west-flank. When the wind changed from South-West to South-East on the 3rd August, the previous west-flank became the fire front and the fire continued to spread. On the 4th August between 12-16:40 the fire had an average spread rate of about 43 m/min, but it has been estimated that it may have been up to 80 m/min between 15:00 and 16:40. During that afternoon about 2/3 of the total area was burnt.

As of 5th August over one thousand people were forced to evacuate their homes. On the 11th August it was reported that the fire was under control. The final affected region is illustrated in Figure 3.3.3-1.

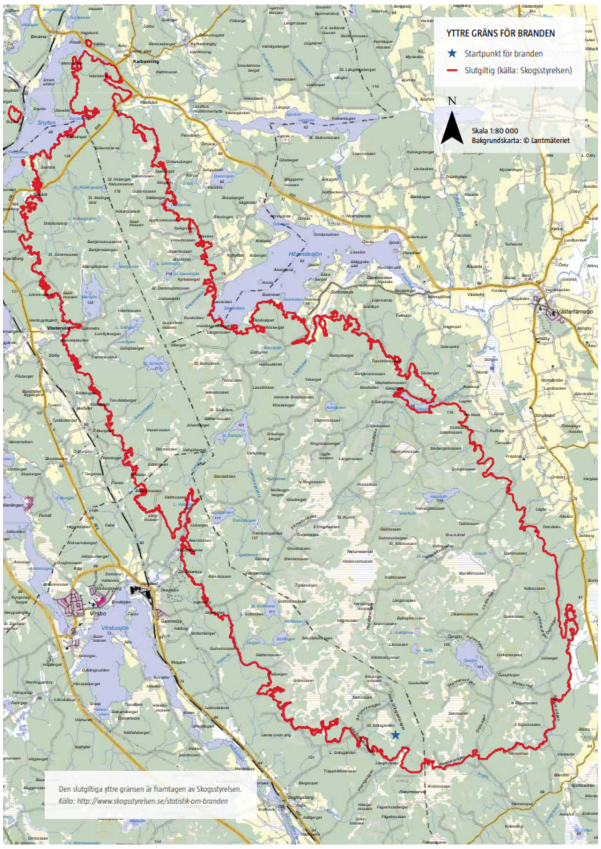


Figure 3.3.3-1: Total area burnt [30].

Simulation scenario

The large affected area and the long time horizon of the fire event makes it difficult to conduct a full scenario simulation. Therefore only the first couple of hours on the 31st July 2014, from fire start at 13:30 to 17:00, are to be further assessed. The burnt area illustrated in Figure 3.3.3-2 is the region that will be simulated. It was reported that the fire reached the lake "Öjesjön", North-East from the starting point, at around 19:00, which is a distance of about 3000 meters.

The fire was reported to have spread 2000 m between 13:30 - 16:20, which gives an average spread rate of ca. 12 meters/minute during 170 minutes. Additionally the report states that an average spread rate of 10 meters/minutes was identified by observers at 15:50. This was the speed including wind effect, and to calculate the basic probability P_0 for the simulation, the equation is relying on the basic spread rate without external impacting factors such as wind or slope. The basic spread rate input has therefore been decided to be 6.0 meters/minute (0.1 meters/second).

When the basic spread rate is decided the cell size and minutes per time step is selected. Having a cell length of 50 m gives a reasonable amount of cells when using a grid size of 6000 m·6000

Figure 3.3.3-2: Area burnt at evening, 31st July [30].

m, resulting in a total 120·120 cells. To ensure a balanced P_0, 4 minutes per time step is selected, which results in a basic probability of $P_0 = 0.48$.

For wind direction and velocity the report states 5.1-7.7 m/s with occasional tops up to 9 m/s coming from South-West. Wind velocity and direction has been selected to be constant, 6.5 m/s coming from 225 degrees due to current software limitations of not being able to handle variable wind velocities. The Fire Weather Index data for the region and date is identified in the report as Risk Class 5, Very High Risk (FWI between 22-28) and will provide a P_{fwi} value of 1.20.

Fire fighters managed to extinguish parts of the North-west flank and south of the fire in an early phase. The simulation tool does not include the possibility of handling the effects of firefighting and will therefore have to be considered when evaluating the results.

All input variables are presented in Table 3.3.3-1 and the fire development illustrated in Figure 3.3.3-3.

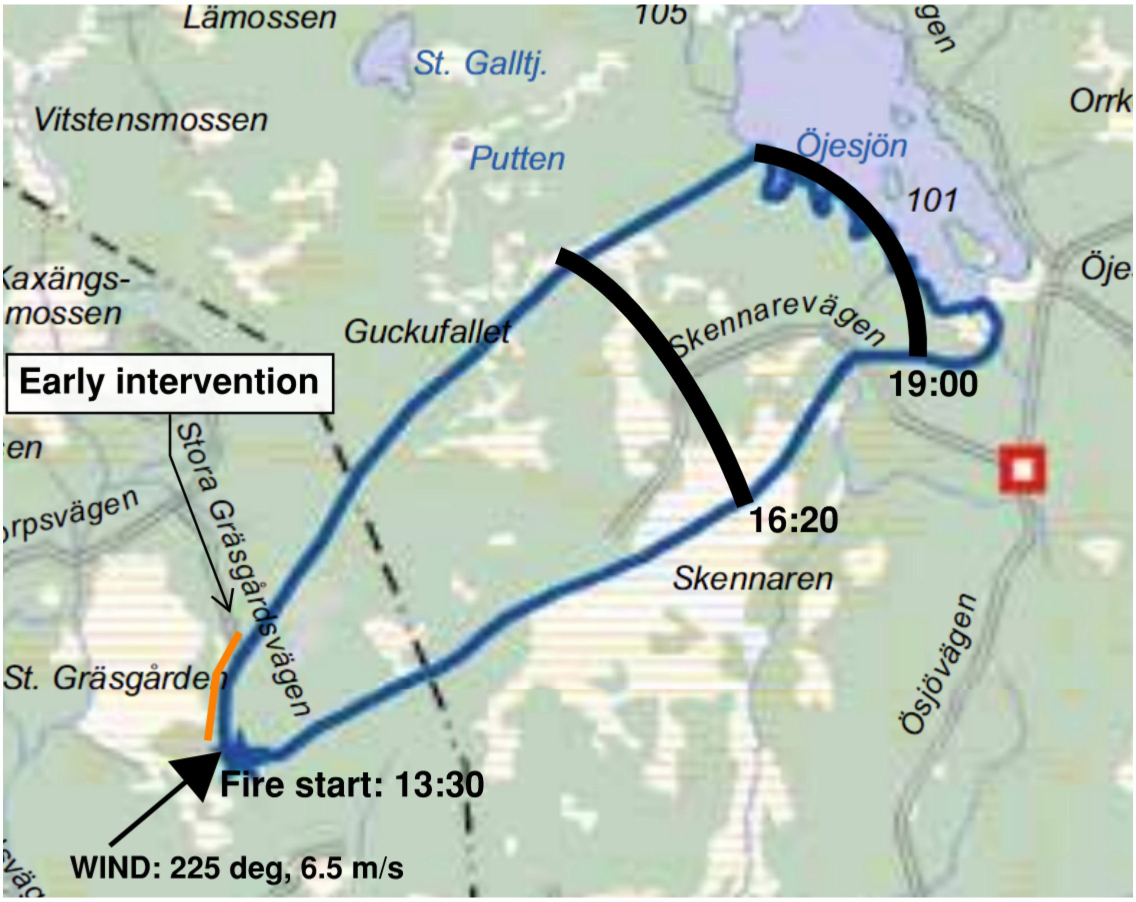


Figure 3.3.3-3: Illustration of the fire development timeline on the 31st July 2014.

Table 3.3.3-1: Case study input data

Variable	Setting
Fire starting point	59.840066, 16.202062
Gridsize	6000m · 6000 m
Cellsize	50 m
Basic Spread Rate	0.1 m/s
Minutes per time step	4 min
Time steps	60
Wind speed	6.5 m/s
Wind direction	225 degrees
FWI	25 (Very High Risk)
Cell type and Vegetation density	Google Static Maps API
Elevation	Google Elevation API

4 Model Verification Results and Discussion

This section presents the results from the simulation scenarios described in section 3.3. The purpose of the verification process is to verify that the software can produce results that are similar to what would be expected for a forest fire spread scenario. The testing has been divided into three parts where first the fundamental functions are tested, second the land-use determination process and last a comparison with a forest fire that occurred in 2014.

4.1 Verifying the fundamental variables and FWI

The investigated scenarios are 40 x 40 grids simulated in 25 time steps where all input variables are controlled. Three main scenarios are defined - Flat surface with no wind, flat surface with wind and a sloped 20 % surface without wind. All three cases are tested with varying FWI parameters, from no impact, to low, medium and high risk levels. Since the FWI probabilities are qualitatively selected the purpose is to identify how the propagation pattern changes with a varying probability. The basic simulation settings are presented in Table 4.1-1 and the specific settings for each scenario is detailed in the sections below.

Table 4.1-1 : Simulation settings

Variable	Setting
Gridsize	400 m
Cellsize	10 m
Basic Spread Rate	0.1 m/s
Time per time step	1 min
Time steps	25

4.1.1 Flat Surface and FWI

The scenarios, presented in Table 4.1.1-1, and Figure 4.1.1-1 to Figure 4.1.1-4 includes a flat surface with no wind and the FWI parameter from no impact to low, medium and high risk levels.

Table 4.1.1-1: Input data for Scenario 1-4

Scenario	Slope	Wind direction	Wind speed	FWI (P_{fwi})	Vegetation density
1	None	0	0	None	Forest
2	None	0	0	Low (0.6)	Forest
3	None	0	0	Med (0.8)	Forest
4	None	0	0	High (1.0)	Forest

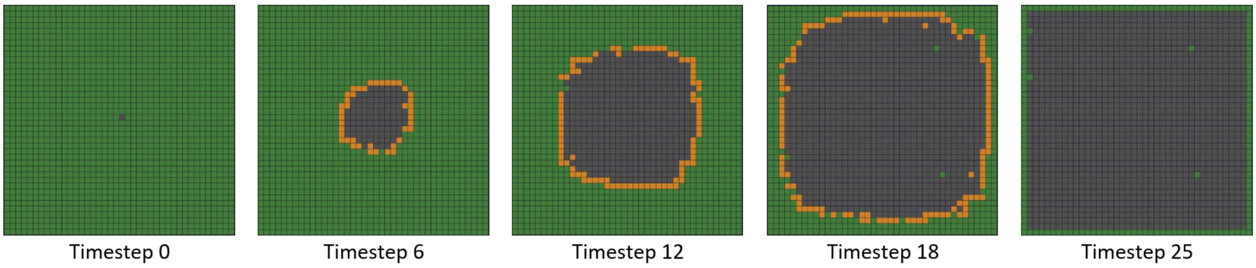


Figure 4.1.1-1: Scenario 1 - Flat surface, no wind or FWI probability

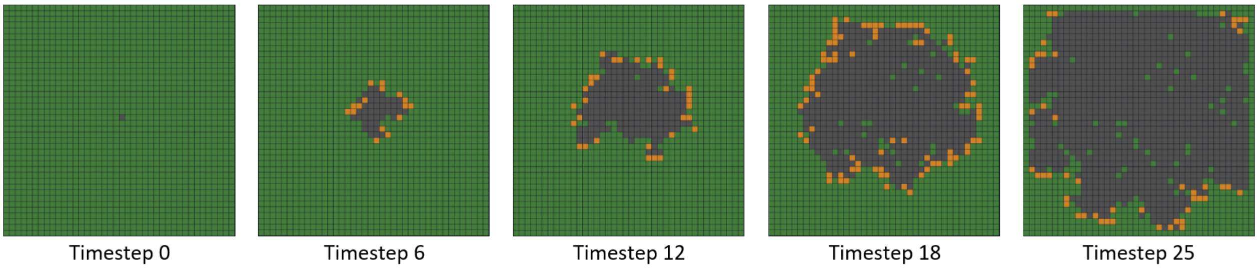


Figure 4.1.1-2: Scenario 2 - Flat surface, no wind and low FWI ($P_{fwi} = 0.6$)

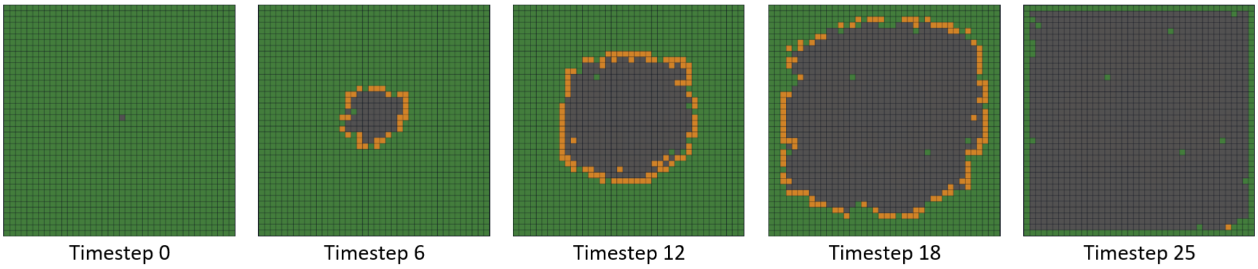


Figure 4.1.1-3: Scenario 3 - Flat surface, no wind and medium FWI ($P_{fwi} = 0.8$)

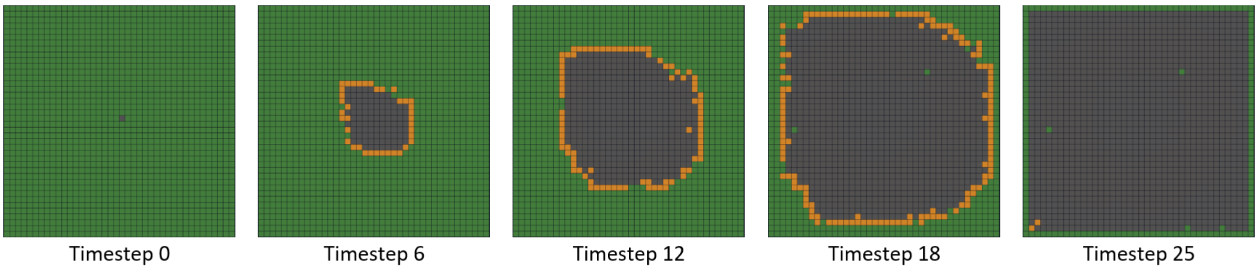


Figure 4.1.1-4: Scenario 4 - Flat surface, no wind and high FWI ($P_{fwi} = 1.0$)

In all four study scenarios, the ignition starts in the center of the grid and gradually develops outwards towards the edges with every time step. Reviewing scenario 1 the spread created is a solid circular pattern, which indicates an spread that evenly grows throughout the simulation. The results are as expected for a fire spread without any external factors affecting, in line with the literature for a point fire creating a circular shape [42].

When introducing the FWI probability this show a direct impact on the total probability, P_{burn}. Scenario 2 was simulated with $P_{fwi} = 0.6$ and the simulation result in a more scattered behaviour, still spreading from the centre towards the edges, but with uneven line of spread. This fits well with an expected reduction in the overall probability, P_{burn}, resulting in a more random propagation behaviour and a reduced spread rate. For scenario 3 and 4, the the P_{fwi} variable is set to 0.8 and 1.0, and the results gradually moves towards a less randomized behaviour as can be seen in scenario 1. This is to be expected since the P_{fwi} variable was omitted in scenario 1, and in scenario 4 $P_{fwi} = 1.0$, leading to the variable not affecting the overall P_{burn} equation in both scenarios.

The conclusion of the test is that the overall setup is working as intended and the software is able to simulate a point fire, resulting in the fire developing in a circular pattern in a homogeneous vegetative setup without any external factors. When introducing the FWI parameter, P_{fwi}, the overall probability and fire spread rate can be reduced or increased, illustrated in the changes from Figure 4.1.1-1 to Figure 4.1.1-4.

4.1.2 Wind impact and FWI

The scenarios, presented in Table 4.1.2-1, and Figure 4.1.2-1 to Figure 4.1.2-4 includes a flat surface with wind velocity of 5 m/s coming from East (90 degrees). The FWI parameter varies from no impact to low, medium and high risk levels.

Table 4.1.2-1: Input data for Scenario 5-8

Scenario	Slope	Wind direction	Wind speed	FWI (P_{fwi})	Vegetation density
5	None	90°	5 m/s	None	Forest
6	None	90°	5 m/s	Low (0.6)	Forest
7	None	90°	5 m/s	Med (0.8)	Forest
8	None	90°	5 m/s	High (1.0)	Forest

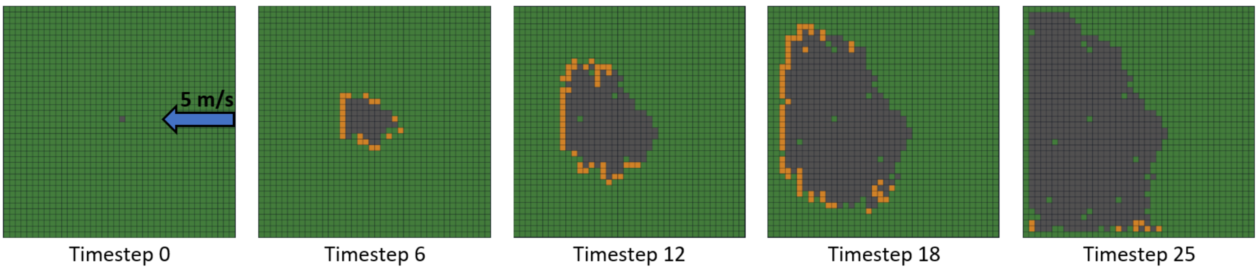


Figure 4.1.2-1: Scenario 5 - Flat surface, Wind 5 m/s from East (90 degrees) and no FWI.

The results show fire spread with a 5 m/s wind coming from the East (90 degrees). The fire is again starting at the centre, with the wind increasing the fire spread probability, P_{burn}, in the wind direction and reducing the probability against the wind. Scenario 5 with no FWI impact show satisfying results with regards to wind impact, but at time step 18 and 25 a slight diversion South is occurring, and it is not clear if this is a result from the equations or if it is random behaviour. When introducing the FWI parameter, P_{fwi}, in scenario 6-8 the impact of the overall reduced probability is

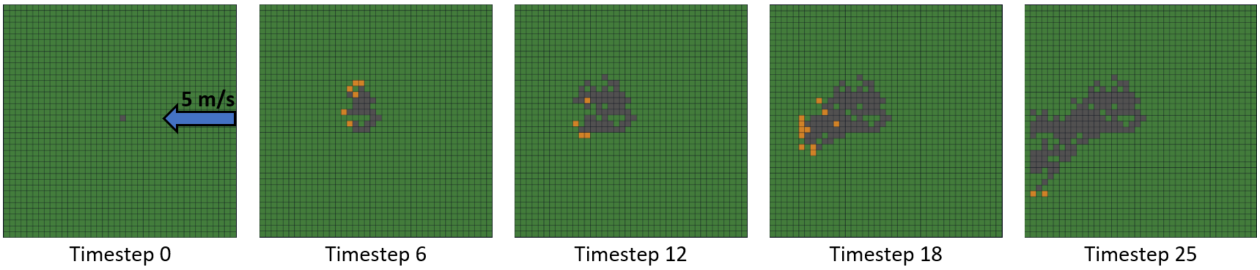


Figure 4.1.2-2: Scenario 6 - Flat surface, Wind 5 m/s from East (90 degrees) and low FWI ($P_{fwi} = 0.6$).

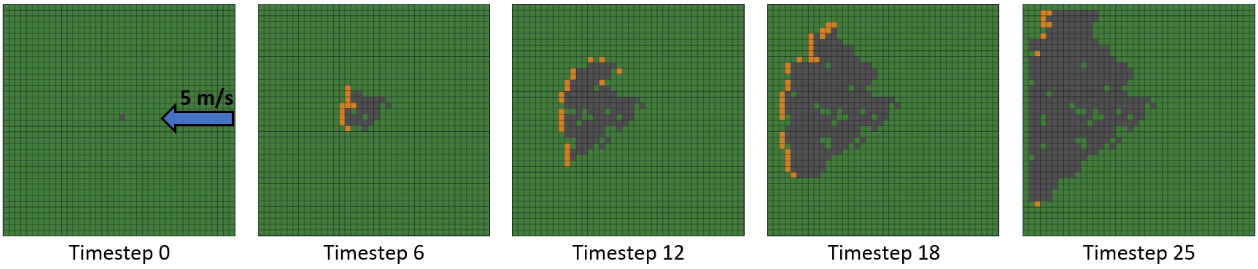


Figure 4.1.2-3: Scenario 7 - Flat surface, Wind 5 m/s from East (90 degrees) and medium FWI ($P_{fwi} = 0.8$).

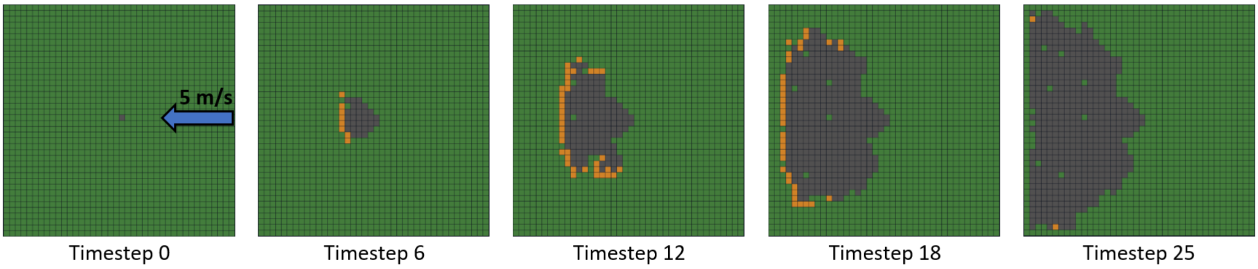


Figure 4.1.2-4: Scenario 8 - Flat surface, Wind 5 m/s from East (90 degrees) and high FWI ($P_{fwi} = 1.0$).

identified through an increased random behaviour and reduced spread rate, especially in scenario 6 where $P_{fwi} = 0.6$. For scenario 7-8 the value of the FWI parameter gradually increases, resulting in a less random behaviour, similar to scenario 2-4. For all FWI scenarios the wind impact is successful and the fire front moves in the direction of the wind, as intended in the mathematical model.

The overall results are considered successful and the wind equation increase the probability of fire spread in the wind direction and reduce the probability of spreading against the wind. There are some uncertainties related to the fire spread diversion towards the sides (North or South), and if this is an effect of random behaviour or not. For future work additional tests should be conducted using various wind direction and velocities.

4.1.3 Sloped surface and FWI

The four scenarios, presented in Table 4.1.3-1, and Figure 4.1.3-1 to Figure 4.1.3-4 introduce a 20 % sloping surface with no wind. The FWI parameter varies from no impact to low, medium and high risk levels.

Table 4.1.3-1: Input data for Scenario 9-12

Scenario	Slope	Wind direction	Wind speed	FWI (P_{fwi})	Vegetation density
9	20 %	0	0	None	Forest
10	20 %	0	0	Low (0.6)	Forest
11	20 %	0	0	Med (0.8)	Forest
12	20 %	0	0	High (1.0)	Forest

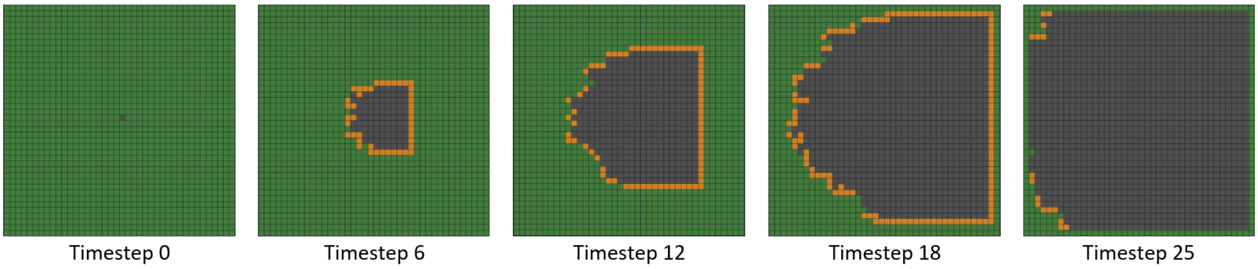


Figure 4.1.3-1: Scenario 9 - Sloped 20 % surface to the East, no wind and no FWI.

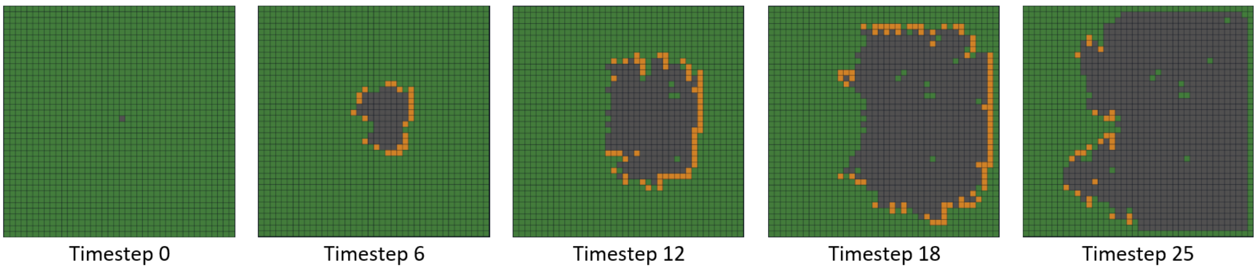


Figure 4.1.3-2: Scenario 10 - Sloped 20 % surface to the East, no wind and low FWI ($P_{fwi} = 0.6$).

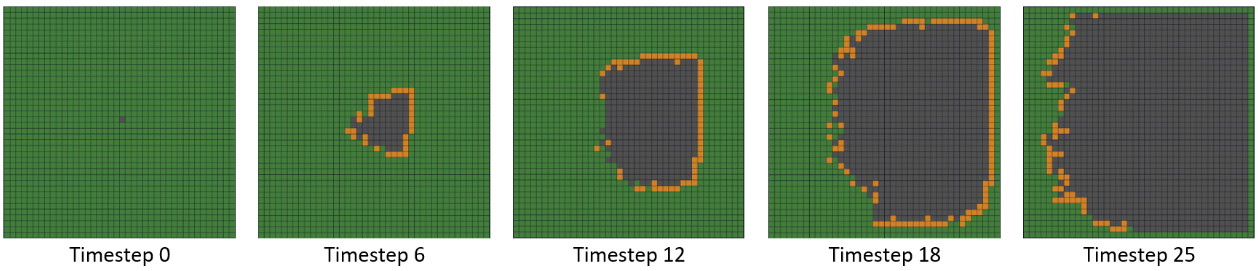


Figure 4.1.3-3: Scenario 11 - Sloped 20 % surface to the East, no wind and medium FWI ($P_{fwi} = 0.8$).

Scenario 9-12 cover a sloped surface of 20 % increase (2 m over a 10 m cell length) from West to East. Scenario 9 illustrates a clear result that the elevation equation increases the probability

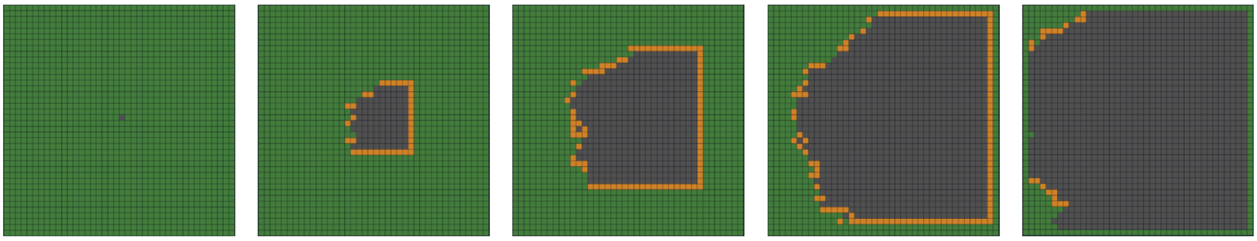


Figure 4.1.3-4: Scenario 12 - Sloped 20 % surface to the East, no wind and high FWI ($P_{fwi} = 1.0$).

of spread towards the East, possibly too much considering a square-shape is established, which indicates that the total probability is close to 1 (100 %) for each time step. Even though slopes have a large impact on fire spread rates, it is unrealistic that spread occurs with a 100 % certainty. This is also an indication of the limitation of the mathematical model where a fire cannot spread faster than the length of the cell. In scenarios where the spread rate vastly exceeds the expected basic spread rate, the software cannot handle this issue due to Moores neighborhood being used. A solution to this can be to extend the neighborhood and allow spread one or two rows ahead, with a reduced probability.

Looking at Figure 4.1.3-2 to Figure 4.1.3-4, the introduction of the FWI parameter can affect the overall fire spread probability. Scenario 10 show that with a reduced probability the fire spread result goes from a distinct square shape to more realistic circular shape. When increasing P_{fwi} from 0.6 to 1.0 in scenario 11 and 12 the shape becomes more similar to the square shape in scenario 9.

The overall results are positive and the slope equation manage to impact the spread direction. The results does show that the fire spreads upwards a positive slope in all directions for every time step. This is probably due to the maximized spread rate through P_{burn} reaching close to 1.0. This would mean that even if wind is added in the same direction, the fire cannot spread faster, which is a limitation of the model.

There are two possible solutions to this issue. It may be solved by allowing spread to cells further away than the closest neighbour, i.e. modifying the neighbourhood. Using this method a greater variance in spread distance may be achieved, enabling the use of a small cell size along with steep slope or wind speeds. An alternative approach may be to modify the simulation setup through an increased cell size along with the basic spread rate to allow for a cell covering a greater geographical area. It is however considered that the first approach may be preferable since it allows for a greater variation in spread rates. Further work should be conducted to various slopes to better understand the sensitivity of the equation and its impact to the overall results.

4.2 Verifying the automated land-use determination process

This section presents the verification results from testing the automatic land-use determination process of the software. The purpose of the simulation conducted is to confirm that the spread does not involve cells that are determined to not contain any fuel (water or urban areas). Three scenarios with different land-use are tested: 1. Forest, 2. Forest and water, 3. Forest, water and urban. Additionally the location of scenario 3 was chosen to verify that the elevation gathering module gave correct results. The input variables are presented in Table 4.2-1 and Table 4.2-2 and the locations illustrated in Figure 4.2-1 .

Table 4.2-1 : Simulation settings for GIS data verification

Variable	**Setting**
Gridsize	400 m
Cellsize	10 m
Basic Spread Rate	0.1 m/s
Time per time step	1 min
Time steps	25

Table 4.2-2 : Simulation scenarios for GIS data verification

Scenario	**Lat/lon**	**Slope**	**Wind Dir.**	**Wind Sp.**	**FWI**	**Veg. den.**
Forest	60.686094, 14.994751	GIS	0	0	None	GIS
Forest and Water	60.667519, 14.744299	GIS	0	0	None	GIS
Forest, Water and Urban	59.349421, 18.195604	GIS	0	0	None	GIS

4.2.1 Forest land-use

The location selected is a forest in a central location of Sweden, illustrated in Figure 4.2.1-1. The software was able to identify all cells as forest through the use of the RGB color sorter. The fire simulation did include elevation data varying between 220-250 meters above sea level, but not any wind or FWI input. The results in Figure 4.2.1-2 show a relatively uniform fire spread that is somewhat impacted by the elevation since it spreads more rapidly towards the South-West corner, which is a high point of the terrain. The software is considered to behave as expected.

4.2.2 Forest and water land-use

The location selected is a forest and water interface in a central part of Sweden, illustrated in Figure 4.2.2-1. The software was able distinguish between water and vegetative areas, but had

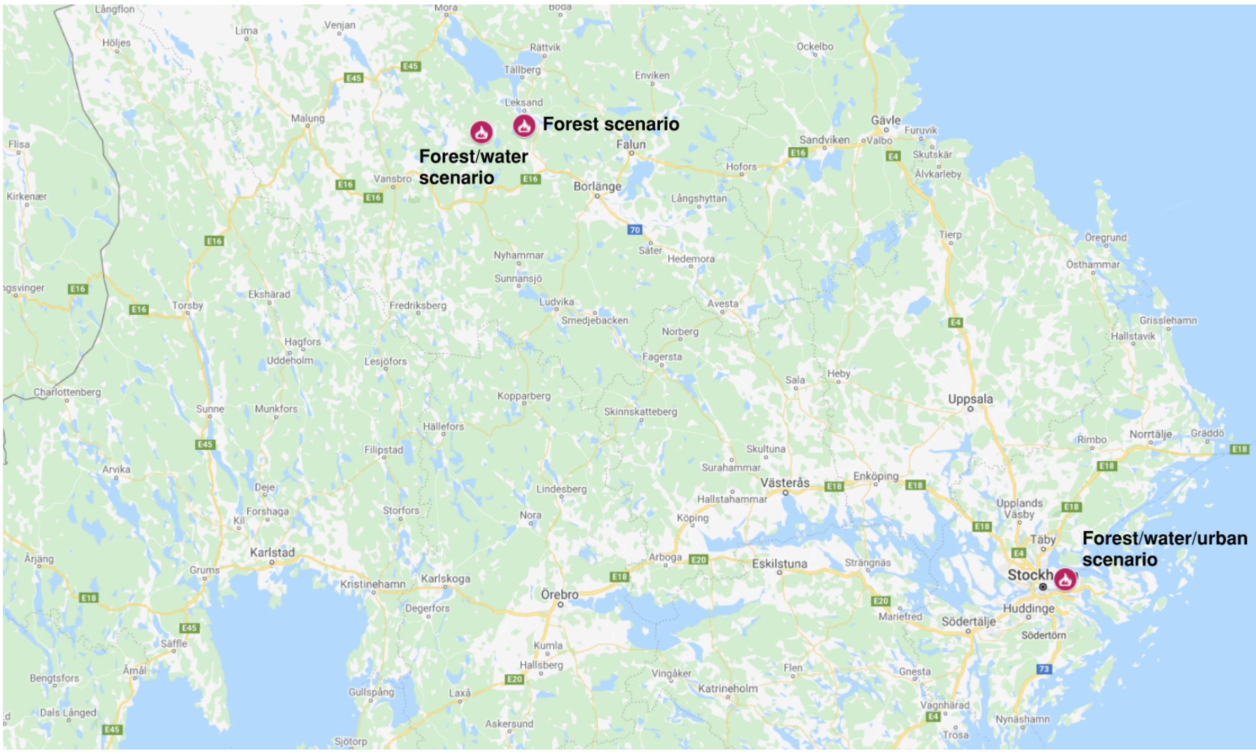
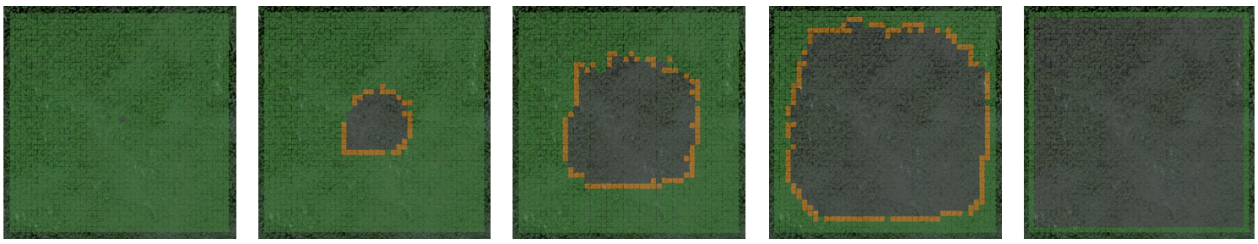


Figure 4.2-1 : Scenario locations in Sweden.

Google Satellite | Google Static Map | Simulation results in Kepler.gl

Figure 4.2.1-1: Scenario Forest GIS land-use and elevation identification.



Timestep 0 | Timestep 6 | Timestep 12 | Timestep 18 | Timestep 25

Figure 4.2.1-2: Scenario Forest GIS land-use and elevation identification - Simulation with no wind or FWI input. Green cells contains fuel (forest, grass-land), orange is the fire-front and grey are burnt-out cells.

some trouble at the interfaces. Assessing the interfaces in Figure 4.2.2-2 the cells on the West side are defined as water, while placed over a forest in the satellite map. This can be a result of the RGB sorter not being able to properly sort some of the colors, but could also be a mismatch between Google Static maps placement of the water edge compared to the satellite images. Additionally there is a limitation with regards to the cell size, since a single pixel of an image decides the properties of an entire 10 m·10 m cell. The result is still considered acceptable since the software is able to follow the interface even though not perfect.

The fire scenario ran without wind and FWI variables, but with elevation data varying between 251 - 261 m above sea level. With regards to the slope there was no large impact identified, indicated in the results in Figure 4.2.2-2. This is most likely due to the modest slope of 2.5 % (10 m / 400 m). The fire spreads fairly uniformly across the vegetative areas and can be seen to somewhat reduce in speed towards the North. This can be explained by the vegetation density being less, which is successfully identified by the software based on the Google Static Map in Figure 4.2.2-1.

The conclusion is that the software is able to gather acceptable data from the GIS sources and implement them in the fire simulation. There is possible improvement to be made with regards to the RGB sorter and the identification of land use.

Figure 4.2.2-1: Scenario Forest/Water GIS land-use and elevation identification. Figure illustrates location selection and grid placement.

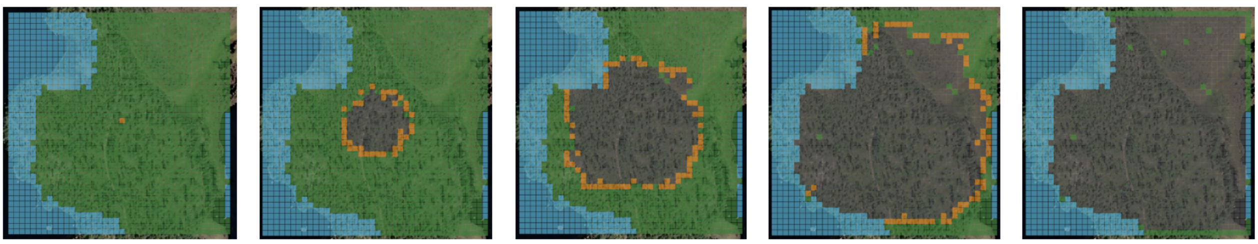


Figure 4.2.2-2: Scenario Forest/Water GIS land-use and elevation identification - Simulation with no wind or FWI input. Blue cells contains no fuel (water), green are cells containing fuel (forest, grass-land), orange is the fire-front and grey are burnt-out cells.

4.2.3 Forest, water and urban land-use

The location is in Stockholm, Sweden, where the grid is placed covering a forest, water and urban area, illustrated in Figure 4.2.3-1. Assessing the results in Figure 4.2.3-3, the software is able to identify the water and urban areas, automatically defining them as cells not containing fuel. The results from the land-use identification is more accurate at the interfaces compared to the previous Forest-Water scenario. Figure 4.2.3-3 is also illustrating the elevation of the cells ranging between 10-50 m above sea level. The fire start location is at an elevation of 30 m. From that point there is a gradual negative slope towards the water at 10 m, and a positive slope towards the north in the figure at 50 m. The urban area is about the same height as the fire start location, 30 m.

Figure 4.2.3-2 illustrates the fire spread development, where it spreads more rapidly towards the highest point, South-West in the image. The fire spreads slower to the North due to the negative slope and finally stops at the water interface. To the South-East the fire reaches the urban area at time step 18, but since this is defined as a region not containing any fuel (same as the water) the fire propagation stops. Further development is required to properly handle the forest-urban interface and how fire spreads between the two land-types.

The results from the test are satisfactory due the software managing to identify water and urban areas, and properly defining the correct initial cell state. The fire propagates as expected with the impact of positive and negative slopes, and stops at the water and urban interfaces (not containing any fuel).

Google Satellite | Google Static Map | Simulation results in Kepler.gl

Figure 4.2.3-1: Scenario Forest/Water/Urban GIS land-use and elevation identification. Figure illustrates location selection and grid placement.

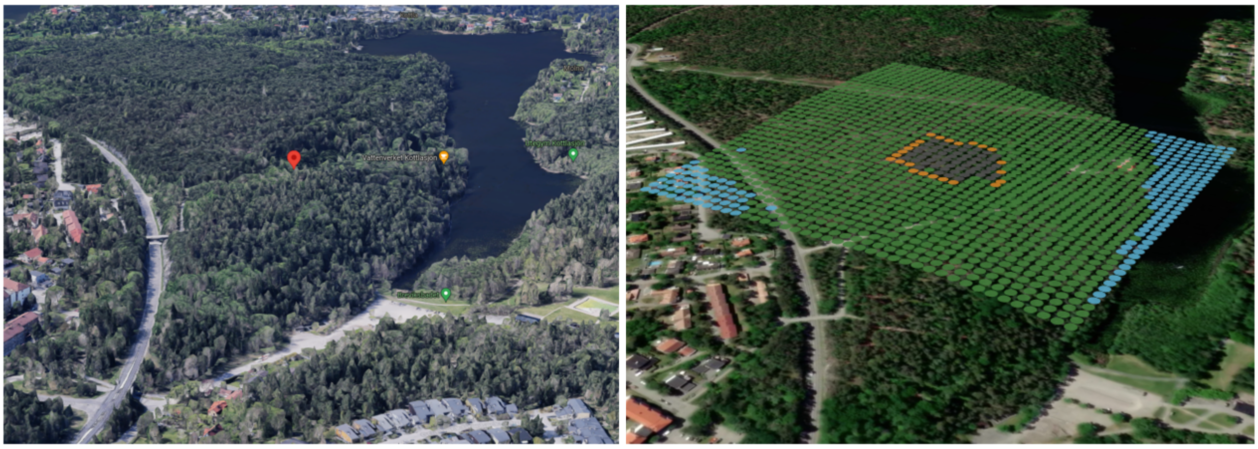


Figure 4.2.3-2: Scenario Forest/Water/Urban GIS land-use and elevation identification - Illustration of the elevation data for each cell, automatically gathered from Google Elevation API.

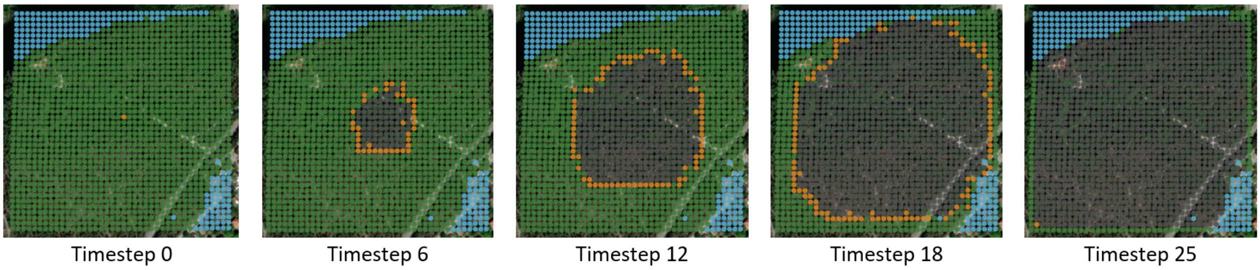


Figure 4.2.3-3: Scenario Forest/Water/Urban GIS land-use and elevation identification - Simulation with no wind or FWI input. Blue cells contains no fuel (water or urban areas), green are cells containing fuel (forest, grass-land), orange is the fire-front and grey are burnt-out cells.

4.3 Case study

This section presents the results from the case study where the Västmanland fire in 2014 is simulated. Table 4.3-1 details the input data. Figure 4.3.1-1 shows images of the region and the 6000 m · 6000 m grid placement, with Figure 4.3.1-2 illustrating the elevation data gathered for the area. The terrain varies with the lowest point at the South-West corner at 72 meters above sea level (red in Figure 4.3.1-2), and the highest point in the North, ca. 130 meters above sea level (dark blue in Figure 4.3.1-2). The fire simulation results are presented in Figure 4.3.1-4 to Figure 4.3.1-7 using screenshots of the status at approximately every 30 minutes of simulated time, covering the timeline between 13:30 to 17:00 on the 31st July 2014. Figure 4.3.2-1 show a comparison between the reported and the simulated fire spread timeline.

4.3.1 Simulation performance and export files

The case study was the longest running simulation and took about 18 hours to complete using an average business laptop with an Intel Core i5 processor. This time can be separated into two parts: Gathering the input GIS data and running the simulation.

Table 4.3-1 : Case study input data

Variable	**Setting**
Fire starting point	59.840066, 16.202062
Gridsize	6000 m · 6000 m
Cellsize	50 m
Basic Spread Rate	0.1 m/s
Minutes per time step	4 min
Time steps	60
Wind speed	6.5 m/s
Wind direction	225 degrees
FWI	25
Cell type and Vegetation density	Google Static Maps API
Elevation	Google Elevation API

The input data was gathered for each cell, hence, 2 API requests (Google Static Maps API and Google Elevation API) per cell. This took about 0.1 seconds per cell, times 14400 cells, resulting in ca. 1500 seconds. The remaining time was used running the simulation calculation for 60 time steps.

During the simulation the laptop processor consistently ran at about 20 % capacity and the RAM never came close running out of the 16 GB memory. The final results was exported to a results.csv file of 55 MB in size, containing about 860,000 rows (14400 cells * 60 time steps). The input data for the simulation was saved to a inputdata.csv file of 1.15 MB, containing the simulation input for each individual cell. Once the input data is gathered this would not be required to be repeated if additional tests would be necessary, since the software can use the inputdata.csv as an import file. When the simulation was finalized the results.csv file was imported to Kepler.gl for visualizing the results. Kepler.gl worked as intended, but due to the large amounts of data in the case study the performance of the visualization was reduced compared to the previous verification tests and the Kepler.gl required more time to filter the data when scrolling between the time steps.

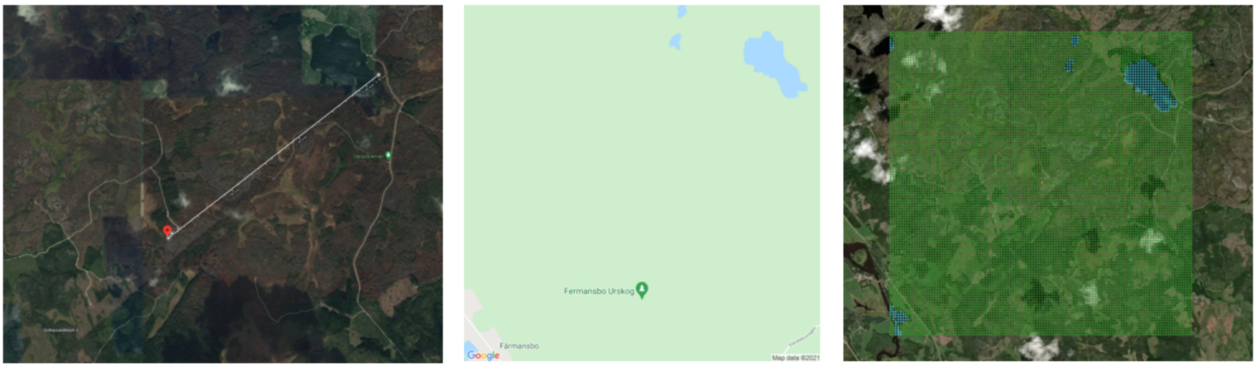


Figure 4.3.1-1: Case study location in Google satellite view showing a 3.2 km measuring line, Google Static map and the final simulated grid placement in Kepler.gl. The grid coordinates are automatically placed by the software and cover an area of 6000 m x 6000 m with a total of 14440 cells.

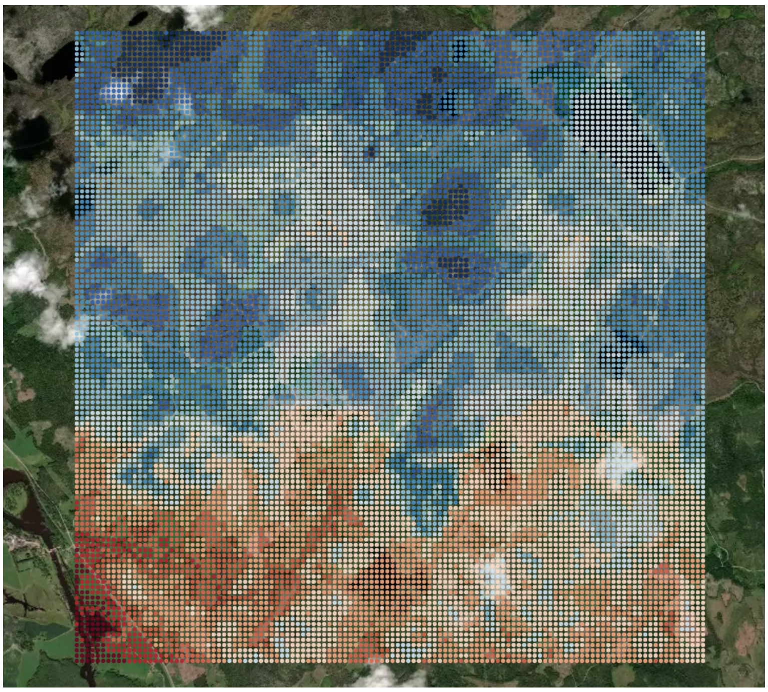


Figure 4.3.1-2: Elevation data where dark red colors represents the lowest points at 72 meters above sea level. Dark blue represents the highest points, ca. 130 meters above sea level.

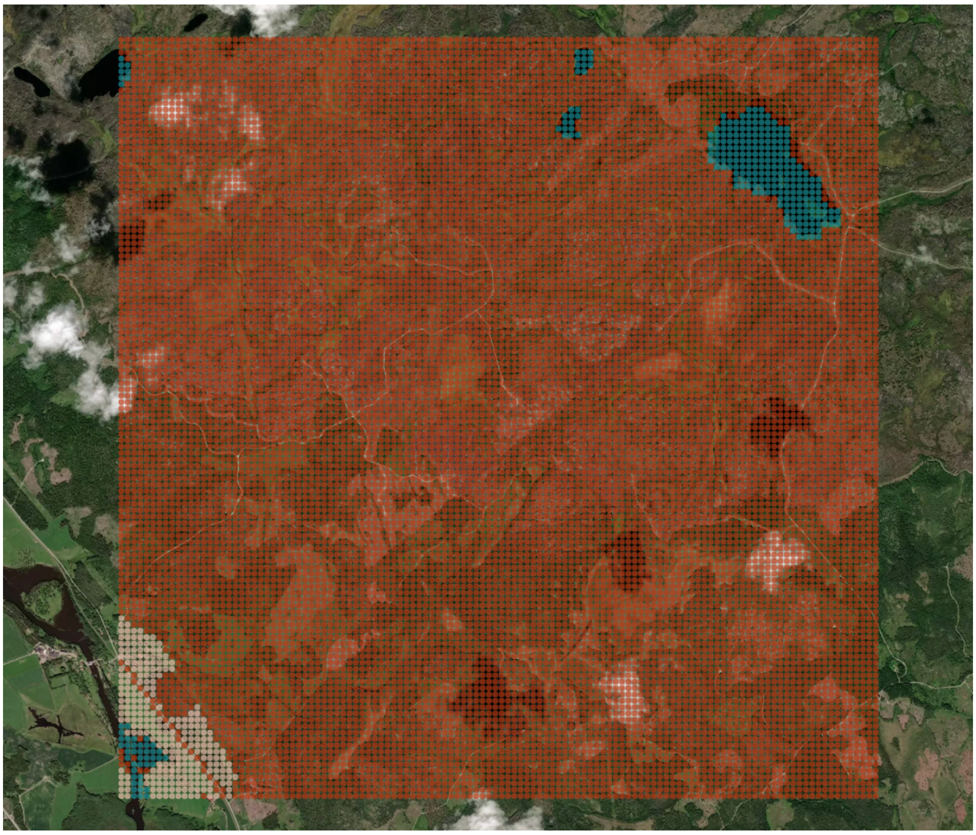


Figure 4.3.1-3: Vegetation density data, where dark red colors represents forest, $P_{den} = 1.0$, light colors grass-land, $P_{den} = 0.7$, and blue colors non-combustible cells, $P_{den} = 0$.

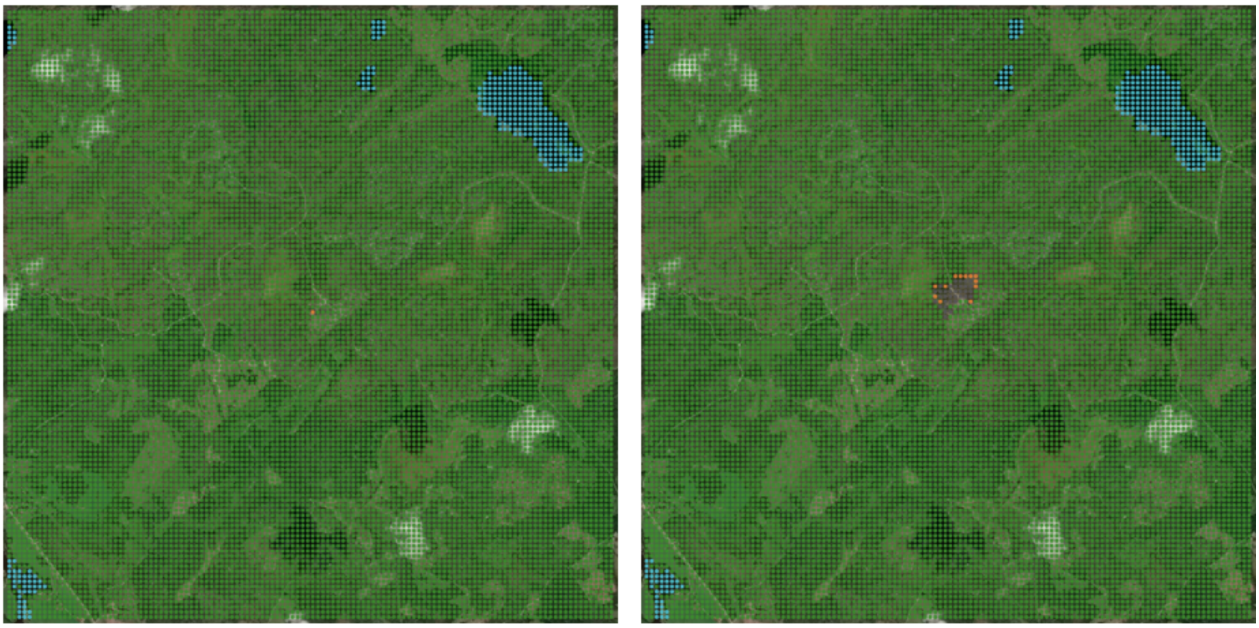


Figure 4.3.1-4: Simulation results at time step 0 (13:30) and time step 7 (14:00) with the point of ignition at the centre of the grid. Orange cells are burning, grey cells burnt out, blue cells contains no fuel (water) and green cells represents an area containing vegetation.

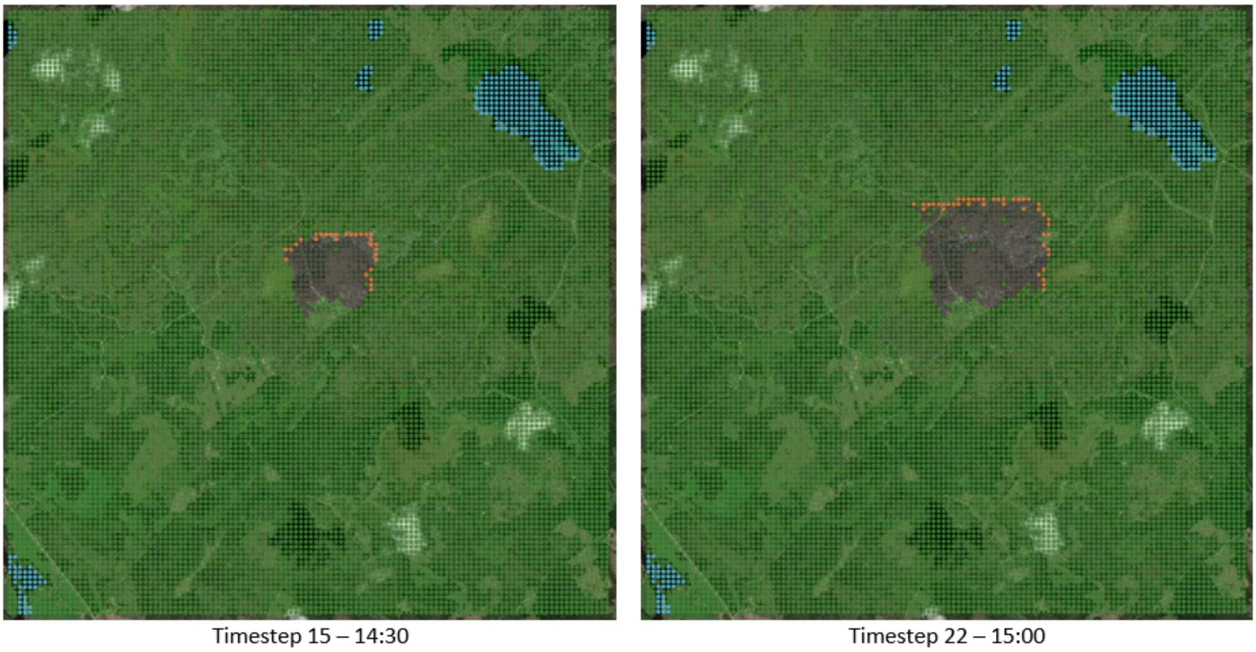


Figure 4.3.1-5: Simulation results at time step 15 (14:30) and time step 22 (15:00). Orange cells are burning, grey cells burnt out, blue cells contains no fuel (water) and green cells represents an area containing vegetation.

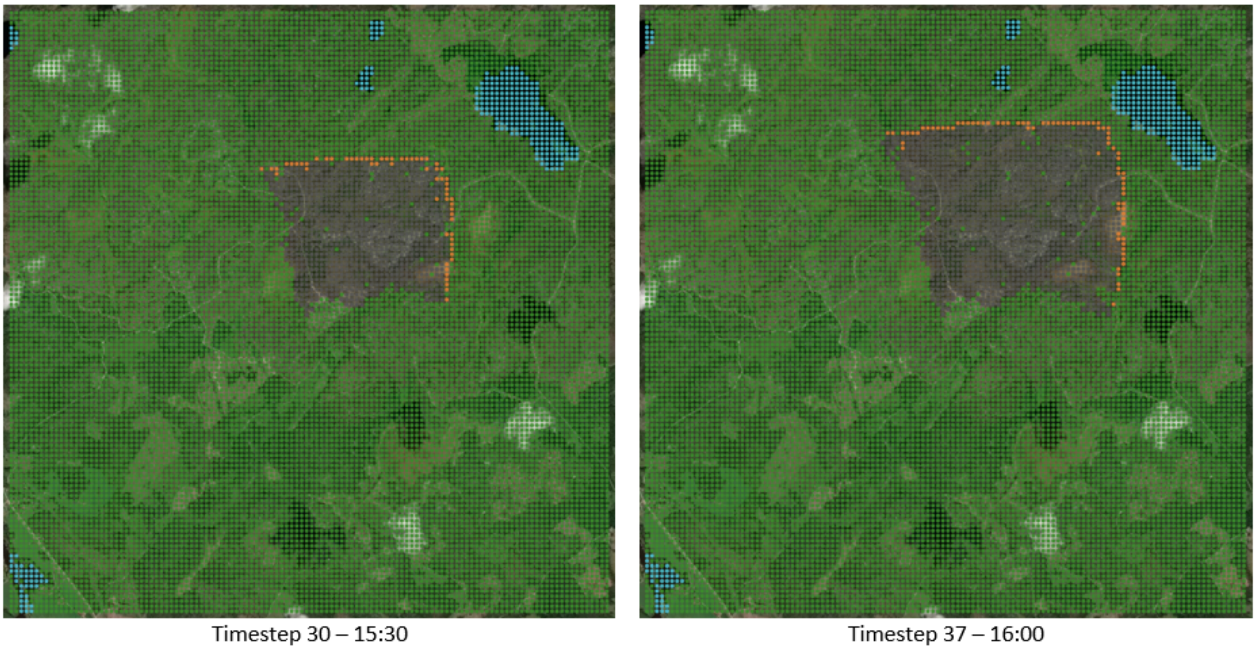
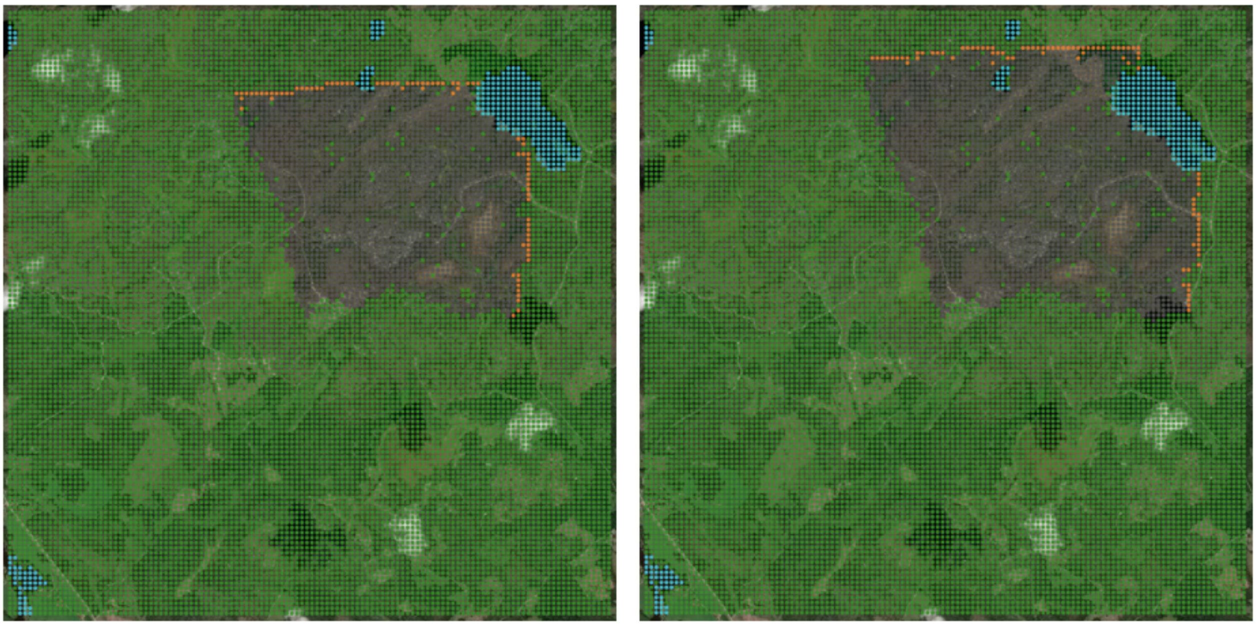


Figure 4.3.1-6: Simulation results at time step 30 (15:30) and time step 37 (16:00). Orange cells are burning, grey cells burnt out, blue cells contains no fuel (water) and green cells represents an area containing vegetation.



Timestep 45 – 16:30 Timestep 52 – 17:00

Figure 4.3.1-7: Simulation results at time step 45 (16:30) and time step 52 (17:00). Orange cells are burning, grey cells burnt out, blue cells contains no fuel (water) and green cells represents an area containing vegetation.

4.3.2 Conclusion

Figure 4.3.2-1 illustrates a comparison between the reported timeline and area affected, and the simulated fire spread. The results are successful with regards to the automatic gathering of the required land-use and elevation input data, and implementing these into the simulation. Furthermore, the use of the visualization tool provides a powerful presentation of the large amount of data points that are calculated. The simulated spread direction is similar to the actual fire, which indicates that the wind direction and speed is properly implemented. There are some discrepancies with regards to the total affected area and the increased spread rate of the simulation. These are details that should be further investigated in future work. Some uncertainties does exist due to the simulation software not accounting for dynamic wind changes, which did occur during the actual fire, and the basic spread rate which was qualitatively estimated from an average rate of spread stated in the report.

Overall the results are satisfactory and the software does prove that the method used is able to simplify the simulation process and present the results in a comprehensive way. It can be concluded that the proof-of-concept is a baseline for further development of an operational simulation tool.

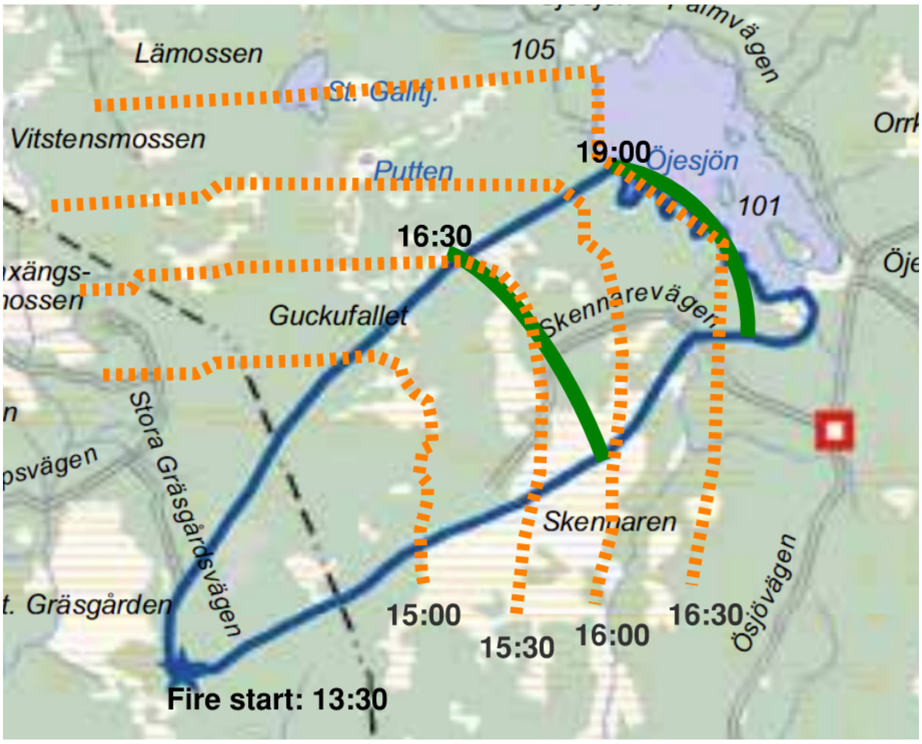


Figure 4.3.2-1: Comparison between the simulated fire and the reported timeline. Green lines illustrates the reported fire spread and orange lines the simulated fire spread.

4.4 Model evaluation

4.4.1 Mathematical model

The mathematical model developed by Alexandridis et al. [21] was chosen due to its simplicity and previous testing. The model is probabilistic in the way that it calculates a final probability for the fire to spread from one cell to the next (P_{burn}). The probability increase or decrease depending on the input of various factors, but in the end produces a binary result by giving the cell a state of burning or not burning. The method cannot handle partial spread within a cell and this can be problematic when having large cells that may contain variations of fuel types. In such a scenario more accurate results may be achieved if the cell size is reduced.

4.4.2 Basic probability

The model relies heavily on the Basic Probability (P_0) where the user has to provide input for the basic spread rate without external factors (wind, slope), cell length and the time in minutes for each time step. P_0 must be a value between 0-1, but if the probability is too low the other variables cannot compensate for this and the pattern of spread becomes unrealistically low. On the other hand the value cannot be too high, where it is stated that the probability of a fire spreading is close to 1 and simulation becomes unrealistically high. This behaviour can be seen in the testing scenarios (scenario 9 and 12) where the fire front has a square shape and spreading for each time step with a 100 % probability to all neighboring cells. Due to this the user has an important role of balancing P_0. Further developing the model the sensitivity of this variable should be studied, and its impact compared to the probability of slope, wind etc. The mathematical model should also be further assessed alongside implementing alternative mathematical models, and see how they perform side by side.

Due to the basic probability being a relation between the basic spread rate, cell size and time step in minutes an understanding of the expected spread rate must be known before running the simulation. For an operational, predictive simulation tool, it is not feasible to expect this input from the user for every fire event due to spread rates varying between 1.5 - 14 km/h depending on the circumstances. The way the model is working, it is limited to simulate fire spread within a certain region from the basic spread rate, i.e. it is unable properly simulate spread if it becomes to slow or to fast due to external factors. A possible solution to this issue is to introduce new rules for spread, or a different neighborhood, that allows spread to cells further away from the burning cell. This may be achieved by a introducing a reduced probability the further away from the burning cell that is calculated.

4.4.3 Wind and Slope equations

The software utilizes the wind and slope equations directly as written by Alexandridis et al. [21], including the correction factors. The correction factors are variables derived from calibrating their method to the fire scenario tested at that time, hence, these might not be suitable for use in the Scandinavian boreal forests. Further development of the fire model should include a study into how these factors affects fire spread and a suggest an improved value that might give better results.

4.4.4 Vegetation type and density

Assessing the impact of vegetation type and density requires detailed data for the area to be simulated. One of the objectives for the software was to automate as much of the process as possible and it was difficult to find a data-set that contained the required information that could easily be implemented, no matter which coordinate was given. The software use Google Static Maps colors to determine if a cell contains vegetation, water, urban or similar. For vegetative areas this came down to two types, open-land (grass etc.) or dense forests. Based on this the vegetation density received two alternatives, where a less dense vegetation reduces the probability of fire spread.

The method is performing well identifying non-combustible cells (water or urban), with a reduced accuracy at interfaces different land-use. This may be due to the cell size of 10·10 m or 50·50 m, and the identifier picking a single pixel in this area and comparing it to a pre-defined library of colors. This library is limited, hence cannot correctly identify all areas. Any area identified as unknown will be defined as a forest. Furthermore, this solution relies on Google correctly drawing their static maps with the right color, and also having updated maps based on the latest satellite images. It is not known how often Google updates their land-use map data and there is a risk of not providing the correct input data to the simulation tool.

For a forest fire simulation tool the vegetation type and density is of high importance and to develop this software further improved data-sets must be identified.

4.4.5 Using the Fire Weather Index

The Fire Weather Index probability variable was added with the intention of varying the spread based on the moisture level of the fuel. High moisture levels gives a reduces spread rate and lower moisture levels increases the ignitability and spread rate. The Fire Index levels was then given a probability based on the authors subjective assessment, with a high risk level being the neutral in the equations where P_{fwi} was equal to 1.0, i.e. the FWI variable does not impact the other variables with regards to fire spread probability. The other FWI risk levels either increases or decreases the probability of fire spread.

4.5 Summary

A fire spread simulation tool has been developed and through verification has been proved to account for the fundamental variables of fire spread. The software has an algorithm that is successful in determining various land-use cases, including forests, grass-land, water and urban areas and automatically implement these in the simulation. Furthermore, weather data is automatically collected from the SMHI API based on date and time, and utilized in the simulation without any need for user input.

The objective of developing a simple to use and understand tool for operational use is achieved by minimizing user input, automatic gathering of input data from various sources, and presenting the results in a visual map-environment. This proof-of-concept can be a first version of a possible operational tool that is calibrated towards the use within the Scandinavian boreal forests.

5 Model Improvements

This chapter cover a discussion of the results, model performance and limitations, and suggested software improvements.

5.1 Results

This thesis has been focused on developing a forest fire simulation software tool that automates the process of gathering data, processing it and presenting a comprehensive visual solution to the end user on a satellite map. The methodology used has verified the fundamental variables of a forest fire (topography, wind, vegetation type and density) to be correctly represented through selected simulation scenarios. Additionally, the Fire Weather Index was introduced and tested as a parameter to represent the potential fuel moisture content using a linear probability spectrum. The FWI parameter was successfully verified to increase or decrease the overall probability of a fire spreading from one cell to the other.

Today there is no existing simulation software that is suitable for use in the Scandinavian boreal forests, and hand-calculations along with qualitative judgement is used by fire fighting personnel during fire fighting interventions. The development of a suitable software and easy to use tool could therefore improve the handling of forest fires, both through enabling improved preventive and mitigating measures. This is becoming increasingly important since global warming may change the overall Scandinavian climate, leading to longer dry periods during the summer months, and an increased risk of forest fires.

5.1.1 Model performance and limitations

The results from the simulation indicate that the model can predict the flame front propagation taking into account the fundamental forest fire parameters. However, there are limitations to the cellular automata methodology and Alexandridis [21] mathematical approach.

First, large grids require a lot of compute resources. The limitation can be mitigated using a high performance computer and by developing software that fully utilize a multi-core processor. If a forest fire prediction software is to be used on portable devices the grid- and cell size may need to be controlled in relation to the available performance. With time the performance of such devices is expected to increase, enabling improved possibilities using larger and more detailed grids.

Second, using a cell-based approach the properties of a single cell is homogeneous. If the cell size becomes too large the content may not accurately represent the actual conditions. There is a balance between selecting a sufficiently fine grid that more accurately represent the content of a cell, and a larger cell that improves the performance, but is less accurate over the selected area. The right balance must be decided by the user, depending on the simulation scenario.

Third, large forest fires can interact with the atmosphere. Heat from the combustion can cause natural updraft that affects the air movement in a region causing atmospheric instability. There are an increasing amount of forest fire behaviour simulators that are coupled with atmospheric simulation models, this is however computationally more expensive and gathering of input data can be difficult.

Last, the model has a limitation of representing high spread rate when it greatly varies from the basic spread rate input. For each time step the model can calculate the probability of fire spread to the eight neighbouring cells, but it can never propagate the flame front further than a single cell length. This limits the propagation representation, but can be solved by introducing a different neighbourhood, using 16 or 32 points instead of the 8 points used in the Moore neighbourhood.

5.1.2 Visual presentation

The software automatically use the .csv results file, exporting it to Kepler.gl for visual presentation of the data. The Kepler.gl software is specifically developed by Uber for presenting large data sets, with the original purpose of understanding vehicular travelling patterns. Using Kepler.gl did prove to be an excellent tool for presenting the scenarios where the fundamental variables were tested, but did have a reduced performance when handling the case study data. This is assessed to be due to the large amounts of data, in this case sorting 14 400 data points (cells) per timestep, among a total of 864 000 data points. To improve the performance issue, two options may be considered; Improving the data storage methodology and developing a dynamic grid that evolves with the fire front.

5.2 Software functionality and future improvements

5.2.1 Data storage methodology

The current software stores the values of each cell for each timestep, resulting in large amounts of data points. The number of data points may be reduced if the data file only stores the initial state of each cell and when a change occurs. For non-combustible cells, the cell state will never change since it can not burn, hence a single data point for each cell is sufficient. For combustible cells there are three states; Cell containing fuel, cell burning or a cell that has burnt out. Imagining a simulation grid consisting of 14 400 cells, the maximum number of data points will be three cell states times the number of cells, i.e. 43 200 data points. Using this methodology only the change in cell state and at which time step it occurred is saved in the database. This enables a simulation to be run for an unlimited number of time steps, without increasing the data storage. Comparing this with the current case study simulation setup, where 864 000 data points were gathered running the simulation of 14 400 cells for 60 time steps.

Improving the data storage methodology using the above approach will reduce the utilized memory and improve the efficiency of the simulation process due to fewer operations.

5.2.2 Continuous memory offloading

The current software continuously saves the state of each cell for each time step, but does not export the data until the entire simulation is finalized. The consequence of this solution is that a failure would result in a need to restart the entire process. To avoid this, the data for each completed time step can be exported to a .csv file and removed from the software memory. This would ensure that a file containing readable results up to the point of failure is always available. The data can then be used to either present a visualization up to the point of failure, or be used as an import to the software to continue the simulation. Additionally, continuous offloading of data from the short-term memory should improve the software performance due to less data points available when conducting look ups.

Being able to restart a simulation from any point in time would also give the user an opportunity of defining an ongoing forest fire and starting the simulation where the fire front already has spread over a certain time. This function can be imagined using a touch-based device where the operator view a satellite map, marking the fire front with a finger. From that point the operator can push a button to start the simulation.

5.2.3 Dynamic grid

The common practice when using cellular automata is to have a pre-defined grid before starting the simulation process. This gives the benefit of knowing the relations between the individual cells and the start/end points. However, the method also limits the spatial simulation coverage and any changes in the grid size would require a restart of the simulation.

The concept of a dynamic grid would mean that the number of cells and locations are directly related to the burning cells and the flame propagation. One can imagine a single burning cell at location X,Y and a setup where 3 cells are defined in each direction of that cell. After the first time step the burning cell would have propagated in a direction and new cells are created 3 steps away from the new burning cell. The GIS data for the new cells are automatically fetched when created, meaning that only the data required to continue the simulation after each time step are saved into the model.

The method removes the need for the initial data gathering phase for all cells, and only gathers data for the cells that are likely to participate in the fire propagation. Additionally, the solution does not have a spatial limitation, considering that the grid is continuously developing with the fire front. Coupling the dynamic grid concept with the suggested improved data storage method, one would be able to design a software that is more compute efficient and minimize storage. This would again improve the visualization process post simulation due to less data required to present the same results.

5.3 Forest fire simulation contributions

The thesis has presented a new method of simulating forest fire spread that automates a large part of the input data gathering and visual presentation. The software has an algorithm that is successful in determining various land-use cases, including forests, grass-land, water and urban areas and automatically implement these in the simulation. Additionally weather and Fire Weather Index data is automatically gathered from the SMHI API based on date and time, and utilized in the simulation without any need for user input. The result is a proof of concept for an operational tool with the vision of being used on a internet connected mobile device, improving decisions made by fire service personnel.

6 Conclusion

In this thesis a forest fire spread simulation tool has been developed and verified. The tool is developed in Python, using cellular automata and the mathematical model of Alexandridis et al. [21] for predicting fire spread. An additional parameter introducing the fuel moisture content has been proposed using the Fire Weather Index, which is a forest fire risk index used in Sweden since the year 2000.

The objective when developing the software was to enable operational use through minimized input, visual presentation of the results and automated gathering of input data using Geographical Information Systems. Ultimately this is a first step towards an operational fire spread tool that is suitable for use in the Scandinavian boreal forests.

Through verification the software has proved to be able to model the most important variables affecting forest fire spread: Fuel composition, fuel moisture content, wind direction and speed, and slope. This is achieved by the user only providing the geographical location of the fire starting point through latitude and longitude, date/time for the fire event, and the area to be simulated. The remaining data such as land-use, wind, elevation, Fire Weather Index etc. is automatically gathered from external services, in this case Google Maps API and the Swedish Metrological and Hydrological Institute API, and seamlessly implemented in the simulation.

For determining the land-use a separate algorithm had to be developed that relies on the Google Static Maps coloring and an RGB sorter. The RGB sorter determines the initial cell states such as water, forest, grass-land or urban areas. The software is prepared for additional types of land such as roads, but requires mapping of the available colors. The solution is however dependent on how Googles algorithm choose to present various regions. Testing the land-use algorithm presents positive results with regards to finding forest, water, or urban areas. In certain areas the algorithm does not properly follow the interface between land and water, but it is not determined why this occurs. Possible explanations can be an error due to the color mapping or a mismatch between the cell WGS 84 coordinates and under laying satellite images.

When testing the fundamental variables of the model the results were positive and the software is able to simulate fire spread. On a flat surface the fire spreads uniformly in a circular shape and when introducing either wind of slope the spread direction is affected. For the wind parameter the introduction of wind results in increased probability of spread in the direction of the wind, and a reduced probability when against the wind. Similar results are reached when testing the slope equation, where a positive slope increases the probability of spread and a negative slope reducing the probability of spread. The FWI variable was tested to verify if it may represent the impact of fuel moisture content, and the results show that the method used can increase or decrease the overall probability in all scenarios.

The case study compared a simulated fire to a fire in Sweden in 2014 and the results show that the software is able to automatically gather the required input data using external sources and implement these in a simulation. The simulated fire propagates in the same direction as the fire and reviewing the temporal development, the simulation has a higher spread rate, but still manage to present a result similar to the fire in 2014. The overall results are positive for a proof-of-concept, and the software is a successful first version that can be used as a baseline for further development.

7 Further work

Forest fires are complex and when developing a simulation tool to predict fire spread, time and knowledge is of essence. The work conducted is a proof-of-concept and additional work is needed on multiple fronts, both with regards to developing the model used in this thesis, but also investigating alternative mathematical approaches and data sources. If a true operational tool is to be developed it must not only be able to provide reliable results, but also ensure a simple to use interface, minimal user input and quick simulation times.

For the particular work of this thesis the fundamental variables are suggested tested with various wind directions and velocities. When verifying the wind variable, it resulted in some instances of unnatural fire spread behaviour, where the fire front was slightly diverted towards one of the sides. Additionally there is a correction factor in both the wind and slope equations that were utilized as presented by Alexandridis et al. [21] in their initial work. These correction factors were calibrated towards that particular case study, and may not be applicable in the Scandinavian boreal forests.

Further potential work is to study the sensitivity of the basic probability, (P_0), and its impact compared to the probability of slope, wind etc. This was not a part of this thesis, but should be further assessed along with studying the implementation of alternative mathematical models and see how they perform side by side.

The the land-use identification algorithm generally demonstrated positive results when identifying forest, water or urban areas. It did however show that improvement may be possible with regards to the precision at the interface points between different types of land-use. The methodology used is able to define various land-uses, but cannot identify specific vegetation types and densities. This comes down to the type of data source, where it is not currently within the Google maps domain to provide this type of detailed data. If an alternative data source containing detailed vegetation data was available, this could be implemented and probably improve the results of a future simulation model.

The current mathematical model used with cellular automata has a limitation when the calculated fire spread rate greatly varies from the basic spread rate input. Future work may be focused on reviewing alternative neighbourhoods that could solve for a greater variation in spread rates.

References

[1] Christiaan Huygens. “Treatise on Light”. In: *Science* 37.955 (1913). ISSN: 0036-8075. DOI: 10.1126/science.37.955.610.

[2] A. G. McArthur. “Fire behaviour in eucalypt forests”. In: *Forestry and Timber Bureau* (1967).

[3] Jacob T. Schwartz, John von Neumann, and Arthur W. Burks. “Theory of Self-Reproducing Automata”. In: *Mathematics of Computation* (1967). ISSN: 00255718. DOI: 10.2307/2005041.

[4] R C Rothermel. *A mathematical model for predicting fire spread in wildland fuels*. Vol. 115. 1972, p. 40. URL: https://www.fs.usda.gov/treesearch/pubs/32533%20https://books.google.pt/books?id=AfyMv5NBSjoC.

[5] Frank A. Albini. *Estimating wildfire behavior and effects*. 1976. ISBN: GTR-INT-30.

[6] E. M. Kemp. “Pre-Quaternary fire in Australia.” In: *Fire and the Australian biota* (1981).

[7] Stephen Wolfram. “Computation theory of cellular automata”. In: *Communications in Mathematical Physics* (1984). ISSN: 00103616. DOI: 10.1007/BF01217347.

[8] C. E. Van Wagner. *Development and structure of the Canadian forest fire weather index system*. 1987. ISBN: 0662151984.

[9] C. K. Brain and A. Sillent. “Evidence from the Swartkrans cave for the earliest use of fire”. In: *Nature* (1988). ISSN: 00280836. DOI: 10.1038/336464a0.

[10] B. J. Stocks et al. “The Canadian Forest Fire Danger Rating System: An Overview”. In: *The Forestry Chronicle* (1989). ISSN: 0015-7546. DOI: 10.5558/tfc65450-6.

[11] I.A French, D.H Anderson, and E.A Catchpole. “Graphical simulation of bushfire spread”. In: *Mathematical and Computer Modelling* 13 (1990), pp. 67–71.

[12] D. R. Weise and G. S. Biging. “Effects of wind velocity and slope on flame properties”. In: *Canadian Journal of Forest Research* (1996). ISSN: 00455067. DOI: 10.1139/x26-210.

[13] Ioannis Karafyllidis and Adonios Thanailakis. “A model for predicting forest fire spreading using cellular automata”. In: *Ecological Modelling* (1997). ISSN: 03043800. DOI: 10.1016/S0304-3800(96)01942-4.

[14] S.W. Taylor, R.G. Pike, and M.E. Alexander. “Field guide to the Canadian Forest Fire Behavior Prediction (FBP) system. Special Report 11”. In: *Fire Management Network, Northern Forestry Centre, Canadian Forest Service* January (1997), Viii+60 p.

[15] Mark A. Finney. “FARSITE: Fire Area Simulator - Model Development and Evaluation”. In: *USDA Forest Service - Research Papers RMRS* (1998). ISSN: 05025001. DOI: 10.2737/RMRS-RP-4.

[16] G.L.W. Perry. "Current approaches to modelling the spread of wildland fire: a review". In: *Progress in Physical Geography* 22.2 (June 1998), pp. 222–245. ISSN: 14770296. DOI: 10.1191/030913398675585936. URL: http://openurl.ingenta.com/content/xref?genre=article&issn=0309-1333&volume=22&issue=2&spage=222.

[17] M E Alexander. *Fire behaviour as a factor in forest and rural fire suppression*. Tech. rep. 2000.

[18] C M Countryman. "The concept of fire environment". In: *Fire Management today* (2004).

[19] Anders Granström. "Brandbeteende och tolkning av brandriskindex Anders Granström". In: (2005), pp. 1–62.

[20] Lemont B. Kier, Paul G. Seybold, and Chao Kun Cheng. *Modeling chemical systems using cellular automata: A textbook and laboratory manual*. 2005. ISBN: 1402036574. DOI: 10.1007/1-4020-3690-6.

[21] A. Alexandridis et al. "A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990". In: *Applied Mathematics and Computation* 204.1 (2008), pp. 191–201. ISSN: 00963003. DOI: 10.1016/j.amc.2008.06.046.

[22] Kevin G Tolhurst, Brett Shields, and Derek M Chong. "Phoenix: Development and Application of a Bushfire Risk Management Tool". In: *Australian Journal of Emergency Management, The* (2008).

[23] Andrew L Sullivan. "Wildland surface fire spread modelling, 1990 - 2007. 1: Physical and quasi-physical models". In: *International Journal of Wildland Fire* 18.4 (2009), p. 349. ISSN: 1049-8001. DOI: 10.1071/wf06143.

[24] Andrew L. Sullivan. "Wildland surface fire spread modelling, 1990 - 2007. 2: Empirical and quasi-empirical models". In: *International Journal of Wildland Fire* 18.4 (2009), p. 369. ISSN: 1049-8001. DOI: 10.1071/WF06142. URL: http://www.publish.csiro.au/?paper=WF06142.

[25] Cordy Tymstra et al. *Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Information Report NOR-X-417. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB, Canada. https://cfs.nrcan.gc.ca/publicati.* Vol. 417. 2010, pp. 1–83. ISBN: 1100146741.

[26] N. Phillip Cheney et al. "Predicting fire behaviour in dry eucalypt forest in southern Australia". In: *Forest Ecology and Management* (2012). ISSN: 03781127. DOI: 10.1016/j.foreco.2012.06.012.

[27] Skogsstyrelsen. *Skogsstatistisk årsbok 2013*. 2013. ISBN: 9789187535017.

[28] Tiziano Ghisu et al. "An Improved Cellular Automata for Wildfire Spread". In: *Procedia Computer Science* 51 (2015), pp. 2287–2296. ISSN: 18770509. DOI: 10.1016/j.procs.2015.05.388.

[29] Claire Miller et al. “SPARK A bushfire spread prediction tool”. In: *IFIP Advances in Information and Communication Technology*. 2015. ISBN: 9783319159935. DOI: 10.1007/978-3-319-15994-2{_}26.

[30] MSB, Marianne Stålheim, and Katarina Hildingsdotter. *Skogsbranden i Västmanland 2014*. Tech. rep. MSB, 2015. URL: https://www.msb.se/sv/publikationer/skogsbranden-i-vastmanland-2014--observatorsrapport/.

[31] Jan Burman et al. *Kartläggning av spridningsmodeller för brand i vegetation : Test av modeller lämpliga för svenska förhållanden*. Tech. rep. 2016. URL: https://www.msb.se/sv/publikationer/kartlaggning-av-spridningsmodeller-for-brand-i-vegetation--test-av-modeller-lampliga-for-svenska-forhallanden-studie/.

[32] Stefan H. Doerr and Cristina Santín. “Global trends in wildfire and its impacts: Perceptions versus realities in a changing world”. In: *Philosophical Transactions of the Royal Society B: Biological Sciences* (2016). ISSN: 14712970. DOI: 10.1098/rstb.2015.0345.

[33] Morgan J. Hurley et al., eds. *SFPE Handbook of Fire Protection Engineering*. New York, NY: Springer New York, 2016. ISBN: 978-1-4939-2564-3. DOI: 10.1007/978-1-4939-2565-0.

[34] Nieves Fernandez-Anez, Kim Christensen, and Guillermo Rein. “Two-dimensional model of smouldering combustion using multi-layer cellular automaton: The role of ignition location and direction of airflow”. In: *Fire Safety Journal* (2017). ISSN: 03797112. DOI: 10.1016/j.firesaf.2017.03.009.

[35] Patricia L. Andrews. *The Rothermel surface fire spread model and associated developments: A comprehensive explanation*. Tech. rep. 2018. DOI: 10.2737/RMRS-GTR-371.

[36] Mark A. Finney. “Fire Acceleration”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2019. DOI: 10.1007/978-3-319-51727-8{_}11-1.

[37] David L. Martell et al. *Cell2Fire: A Cell Based Forest Fire Growth Model*. 2019. URL: https://arxiv.org/abs/1905.09317.

[38] Washington Velasquez et al. “Wildfire propagation simulation tool using cellular automata and GIS”. In: *2019 International Symposium on Networks, Computers and Communications, ISNCC 2019*. 2019. ISBN: 9781728112435. DOI: 10.1109/ISNCC.2019.8909129.

[39] Mark A. Finney. “Operational Wildland Fire Behavior Models and Systems”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}246.

[40] Anders Granström. *Brandsommaren 2018*. Tech. rep. Umeå, 2020.

[41] Faith Ann Heinsch. “Fuel Model”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020, pp. 520–538. DOI: 10.1007/978-3-319-52090-2{_}178.

[42] LaWen T. Hollingsworth. “Heading Fire”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}184.

[43] Jeffrey M. Kane and Nuria Prat-Guitart. “Fuel Moisture”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}115.

[44] Sara McAllister. “Spotting/Spot Fire”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}190.

[45] Kimberley Opie. “Slope and Terrain”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}240.

[46] Johan Sjöström and Anders Granström. *Skogsbränder och gräsbränder i Sverige - Trender och mönster under senare decennier (Abstract in English)*. 2020. ISBN: 9789179270322.

[47] Nicholas S. Skowronski and Michael R. Gallagher. “Fuel Characterization Techniques”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}84.

[48] Andrew L. Sullivan and James S. Gould. “Wildland Fire Rate of Spread”. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Cham: Springer International Publishing, 2020. DOI: 10.1007/978-3-319-52090-2{_}55.

[49] Andrea Trucchia et al. “PROPAGATOR: An Operational Cellular-Automata Based Wildfire Simulator”. In: *Fire* 3.3 (July 2020), p. 26. ISSN: 2571-6255. DOI: 10.3390/fire3030026.

[50] SMHI. *SMHI FWI API*. 2021.

[51] Roy Hilmar Svendsen and Cato Heldal Kristensen. *NRK - Sotra brannen*. June 2021.

[52] Google. *Google Maps Services API*.

Appendices

A Software source code

```
from IPython.display import display
from datetime import datetime
from datetime import timedelta
import googlemaps
import requests
import json
import time
import random
import math
import numpy as np
import pandas as pd
import geopy.distance
import geopy.point
from keplergl_cli import Visualize
from requests.api import get
from PIL import Image
from io import BytesIO

# INPUT
Name = 'Simulation name'
LocationInput = [59.41987502957706, 5.304179423902133] #Fire start location
zoom = 10
area_radius = 200 #Grid radius from Location input [m]
CellSize = 10 #Cellsize [m]
NUM_ITERATIONS = 25
Date_string = '2014-07-31'
Time_string = '13:30:00'
Basic_Spread_Rate = 0.1 #meters per second
Timestep_min = 1 #The timestep in minutes

#API
Google_API = '[Google API key]'
Google_secret_key = '[Google secret key]'
MapBox_API = '[MapBox API key]'
gmaps = googlemaps.Client(key=Google_API)

#Initial calculations
latitude = round(LocationInput[0],6)
longitude = round(LocationInput[1],6)
NoCells_X = int(area_radius * 2 / CellSize)
NoCells_Y = int(area_radius * 2 / CellSize)
```

```
Total_cells = NoCells_X*NoCells_Y

DateTime = Date_string + ' ' + Time_string

#Check Basic probability
Basic_probability = (Basic_Spread_Rate*60*Timestep_min)/CellSize
print('Basic probability: ' + str(Basic_probability))
print('Number of cells: X ' + str(NoCells_X) + ', Y ' + str(NoCells_Y) + ' Total: ' +
    str(NoCells_X*NoCells_Y) + ' cells.')

if Basic_probability > 1:
    print('Error Basic probability: Spreadrate * time: ' +
        str(Basic_Spread_Rate*60*Timestep_min) + ' is > than Cellsize: ' + str(CellSize))
    print('For timestep ' + str(Timestep_min) + ' min, maximum usable spread rate is: ' +
        str(CellSize/(Timestep_min*60)) + '. Reduce spread rate, timestep or increase
        Cellsize.')
    quit()

Start_check = input('Continue simulation? Type: "Yes" ')
if Start_check != 'Yes':
    print('Operation cancelled.')
    quit()
else:
    print('Operation starting...')

#GRID STARTING POINT COORDINATES (Grid radius south, then 1/2 Gridradius west
South = geopy.distance.distance(meters=area_radius).destination((latitude, longitude),
    bearing=180)
South = [round(South.latitude,6), round(South.longitude,6)]
West = geopy.distance.distance(meters=area_radius).destination((South), bearing=270)
GridStart = [round(West.latitude,6), round(West.longitude,6)]
GridStart_lat = GridStart[0]
GridStart_lon = GridStart[1]

#====================== GIS DATA GATHERING
def elevation(lat, lon):
  ele = gmaps.elevation((lat, lon))
  print('Elevation')
  return ele[0]['elevation']

def FireWeatherData(lat, lon, date, time): #Latitude, Longitude, DateTime format
    YYYY-MM-DDTHH:MM:SSZ
  SMHI_DateTime = date+'T'+time+'Z'
  url = ('https://opendata-download-metanalys.smhi.se/api/category/fwia1g/version/1/daily/
```

```
        geotype/point/lon/' + str(lon) + '/lat/' + str(lat) + '/data.json')
    data = requests.get(url)
    FWIdata = json.loads(data.text)['timeSeries']
    for i in FWIdata:
      if i['validTime'] == SMHI_DateTime:
        FWI = (i['validTime'], i['parameters'][0]['values'], i['parameters'][1]['values'],
            i['parameters'][8]['values'], i['parameters'][9]['values'],
            i['parameters'][10]['values']) #Date, FWIindex, FWI, Temperature,
            Winddirection, Windspeed
    return FWI

def pop_cell_state(lat,lon):
    start_time = time.time()
    Water = ['(193, 225, 245)','(183, 227, 235)','(175, 223, 247)','(171, 219,
        251)','(183, 223, 239)','(179, 223, 243)','(175, 219, 247)','(171, 219,
        251)','(195, 231, 219)','(191, 231, 223)','(187, 227, 231)','(223, 231,
        235)','(215, 229, 238)','(195, 224, 246)','(191, 223, 248)','(175, 219,
        254)','(227, 232, 233)','(183, 221, 251)','(187, 222, 249)','(211, 228,
        240)','(203, 226, 242)','(171, 219, 255)','(203, 227, 243)','(207, 227,
        239)','(219, 231, 235)','(187, 223, 247)','(179, 219, 251)','(191, 223,
        247)','(199, 223, 243)','(170, 218, 255)','(211, 228, 239)','(219, 230, 236)']
    Forest = ['(198, 234, 219)','(203, 235, 211)','(199, 235, 219)','(215, 235,
        215)','(203, 235, 211)','(215, 235, 215)','(215, 235, 211)','(230, 234,
        225)','(228, 235, 224)','(227, 236, 223)','(222, 237, 218)','(220, 236,
        217)','(214, 238, 212)','(218, 237, 215)','(212, 238, 211)','(230, 235,
        226)','(246, 252, 246)','(208, 238, 208)','(213, 241, 213)','(239, 246,
        237)','(231, 247, 231)','(221, 236, 218)','(214, 237, 212)','(227, 235,
        223)','(220, 237, 217)','(231, 247, 231)','(208, 238, 208)','(225, 236,
        221)','(218, 237, 215)','(212, 238, 211)','(206, 238, 206)','(207, 239,
        207)','(223, 235, 219)', '(231, 235, 227)','(219, 235, 215)','(211, 239,
        207)','(215, 239, 211)','(219, 235, 219)','(211, 239, 211)','(223, 236,
        220)','(216, 237, 214)','(210, 238, 209)','(229, 235, 224)','(216, 237, 214)']
    Land = ['(248, 247, 246)','(237, 235, 231)','(238, 236, 233)','(244, 243,
        241)','(245, 244, 242)','(241, 239, 236)','(242, 240, 238)','(232, 234,
        227)','(239, 238, 235)','(248, 248, 246)','(235, 233, 229)','(235, 231,
        227)','(235, 235, 227)','(227, 231, 231)','(231, 235, 223)','(234, 234,
        228)','(239, 238, 235)']
    Urban = ['(238, 238, 238)','(238, 238, 238)','(237, 237, 237)','(236, 236,
        236)','(235, 235, 235)','(234, 234, 234)','(233, 233, 233)','(232, 232, 232)',
        '(231, 231, 231)','(230, 230, 230)','(229, 229, 229)','(228, 228, 228)','(227,
        227, 227)','(226, 226, 226)','(225, 225, 225)','(224, 224, 224)','(223, 223,
        223)']
    Road = ['(245, 246, 246)','(231, 230, 229)','(226, 225, 224)','(241, 242,
        243)','(236, 237, 238)','(253, 253, 252)','(234, 234, 228)','(255, 235,
```

```
    161)','(255, 255, 255)','(250, 250, 249)','(252, 252, 251)']

url = 'https://maps.googleapis.com/maps/api/staticmap?center='+str(lat)+','+str(lon)+
       '&zoom=13&size=1x1&maptype=roadmap&key='+Google_API

response = requests.get(url)
img = Image.open(BytesIO(response.content))
img = img.convert("RGB")

color = str(img.getpixel((0,0)))

if color in Water:
    cell_state = 1
    P_den = 0
    type = 'Water'

elif color in Forest:
    cell_state = 2
    P_den = 1
    type = 'Forest'

elif color in Land:
    cell_state = 2
    P_den = 0.7
    type = 'Land'

elif color in Urban:
    cell_state = 1
    P_den = 0
    type = 'Urban'

else:
    cell_state = 2
    P_den = 0.99
    type = 'NA'
    if color == '(224, 224, 224)':
        print('Error getting pixel color. Coordinate: ' + str(lat) + ',' + str(lon) +
            ' returns ' + str(color))

    else:
        print('Missing color in palette for ' + str(lat) + ',' + str(lon))
        print(color)

end_time = time.time()
```

```
    total_time = (end_time - start_time)
    print('Populate: ' + str(total_time) + ' sec')
    return type, cell_state, P_den


#===================== EQUATIONS =================================

def BasicProb(cell_L, R, t):
    P0 = (R*60*t)/cell_L
    return P0

def PTop_cross(cell_L, fromcell_height, tocell_height, c1):
    theta = math.degrees(math.atan((tocell_height - fromcell_height) / cell_L))
    prob_t = math.exp(c1*theta)
    return prob_t

def PTop_diag(cell_L, fromcell_height, tocell_height, c1):
    theta = math.degrees(math.atan((tocell_height - fromcell_height) / (cell_L *
        math.sqrt(2))))
    prob_t = math.exp(c1*theta)
    return prob_t

def Pwind(V, Wd, c1, c2, fromX, fromY, toX, toY): #Wind speed, Real Wind direction
    (degrees, 0/360 = coming from North), correction factor 1, correction factor 2, from
    cell [X,Y], to cell [X,Y]

    deltaX = fromX - toX
    deltaY = fromY - toY

    degrees_temp = math.atan2(deltaX, deltaY)/math.pi*180

    if degrees_temp <= 0:
      degrees_final = 360 + degrees_temp
    else:
      degrees_final = degrees_temp

    theta = degrees_final - Wd

    ft = math.exp(V*c2*(math.cos(math.radians(theta))-1))
    Pw = math.exp(V*c1)*ft
    return Pw

def Pfwi (fwi):
    if fwi < 5:
```

```
        Pfwi = 0.40
    elif 5 <= fwi <= 11:
        Pfwi = 0.60
    elif 11 < fwi <= 17:
        Pfwi = 0.80
    elif 17 < fwi <= 22:
        Pfwi = 1.00
    elif 22 < fwi <= 28:
        Pfwi = 1.20
    elif fwi > 28:
        Pfwi = 1.40
    else:
        Pfwi = 1.01

    return Pfwi

def Pburn_cross(data_df, x, y, x1, y1):

    WindSpeed = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'windspeed'].tolist())[0]
    WindDirection = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'winddirection'].tolist())[0]
    Temp = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'temperature'].tolist())[0]
    Cell_Elevation = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'elevation'].tolist())[0]
    Neighbour_Elevation = (data_df.loc[(data_df['X'] == x1) & (data_df['Y'] == y1),
        'elevation'].tolist())[0]
    FWIindex = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'FWIindex'].tolist())[0]
    FWI = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y), 'FWI'].tolist())[0]

    P0 = BasicProb(CellSize, Basic_Spread_Rate, Timestep_min)
    #print ('P0_cross = ' + str(P0))

    Pt = PTop_cross(CellSize, Neighbour_Elevation, Cell_Elevation, 0.063)
    #print ('Pt_cross = ' + str(Pt))

    Pw = Pwind(WindSpeed, WindDirection, 0.045, 0.191, x1, y1, x, y)
    #print('Pw_cross = ' + str(Pw))

    Pfw = Pfwi(FWIindex)

    Pden = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y), 'P_den'].tolist())[0]
```

```
    Pburn = P0*Pt*Pw*Pden*Pfw
    if Pburn > 1:
        Pburn = 1
        print('Adjusted Pburn to: ' + str(Pburn))

    print('Pburn_cross ' + str(Pburn) + ' Spread from: ' + str(x1) + str(y1) + ' to: '+
        str(x) + str(y))
    return Pburn

def Pburn_diagonal(data_df, x, y, x1, y1):

    WindSpeed = round((data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'windspeed'].tolist())[0],3)
    WindDirection = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'winddirection'].tolist())[0]
    Temp = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'temperature'].tolist())[0]
    Cell_Elevation = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'elevation'].tolist())[0]
    Neighbour_Elevation = (data_df.loc[(data_df['X'] == x1) & (data_df['Y'] == y1),
        'elevation'].tolist())[0]
    FWIindex = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y),
        'FWIindex'].tolist())[0]
    FWI = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y), 'FWI'].tolist())[0]
    Pden = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y), 'P_den'].tolist())[0]

    P0 = BasicProb(CellSize, Basic_Spread_Rate, Timestep_min)
    #print ('P0_diagonal = ' + str(P0))

    Pt = PTop_diag(CellSize, Neighbour_Elevation, Cell_Elevation, 0.063)
    #print ('Pt_diagonal = ' + str(Pt))

    Pw = Pwind(WindSpeed, WindDirection, 0.045, 0.191, x1, y1, x, y)
    #print('Pw_diagonal = ' + str(Pw))

    Pfw = Pfwi(FWIindex)

    Pden = (data_df.loc[(data_df['X'] == x) & (data_df['Y'] == y), 'P_den'].tolist())[0]

    Pburn = P0*Pt*Pw*Pden*Pfw

    if Pburn > 1:
        Pburn = 1
```

```
            print('Adjusted Pburn to:' + str(Pburn))

    print('Pburn_diagonal ' + str(Pburn) + ' Spread from: ' + str(x1) + str(y1) + ' to:
        '+ str(x) + str(y))
    return Pburn


#=====================CELLULAR AUTOMATON
def new_board(x, y):
    board = []
    for i in range(0, y):
        board.append([random.choice([0] + [1]) for _ in range(0, x)]) #UPDATE TO AND
            POPULATE WITH 0, STATE IS GIVEN IN DF
    return board

def get_cellstate(df, x, y, timestep): #return cell value from df
    timestep = timestep - 1
    cell_state = df.loc[(df['timestep'] == timestep) & (df['X'] == x) & (df['Y'] == y),
        'state'].tolist()
    #print('Get_cellstate:' + str(cell_state[0]) + ' Timestep: ' + str(timestep))
    return cell_state[0]

def assign_new_cellstate(df, x, y, timestep, state, dateTime):
    deltaTime = timestep * Timestep_min
    delta = timedelta(minutes = deltaTime)
    DateTime = datetime.fromisoformat(dateTime) + delta
    lon = df.loc[(df['timestep'] == timestep-1) & (df['X'] == x) & (df['Y'] == y),
        'longitude'].tolist()
    lat = df.loc[(df['timestep'] == timestep-1) & (df['X'] == x) & (df['Y'] == y),
        'latitude'].tolist()
    ele = df.loc[(df['timestep'] == timestep-1) & (df['X'] == x) & (df['Y'] == y),
        'elevation'].tolist()

    new_row = [x,y,lat[0],lon[0],state,timestep,DateTime,ele[0]]
    #print('Assign_new - New row:' + str(new_row) + 'XY:' + str(x + y) + ' Timestep:' +
        str(timestep))
    df.loc[len(df)] = new_row

    return df

def process_moore_neighbours(df_results, df_input, x, y, timestep):
    new_state = 2
```

```
if x == 0 or y == 0 or x == (NoCells_X-1) or y == (NoCells_Y-1): #IF EDGE, KEEP THE
    SAME STATE
        assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)
else:

    if get_cellstate(df_results, x, y+1, timestep) == 3:
        Pburn = Pburn_cross(df_input, x, y, x, y+1)
        new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
        new_state = new_state[0]
        if new_state == 3:
            print('Newstate XY1: ' + str(new_state) + ' Timestep: ' + str(timestep))
            assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

    if get_cellstate(df_results, x+1, y+1, timestep) == 3 and new_state == 2:
        Pburn = Pburn_diagonal(df_input, x, y, x+1, y+1)
        new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
        new_state = new_state[0]
        if new_state == 3:
            print('Newstate X1Y1: ' + str(new_state) + ' Timestep: ' + str(timestep))
            assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

    if get_cellstate(df_results, x+1, y, timestep) == 3 and new_state == 2:
        Pburn = Pburn_cross(df_input, x, y, x+1, y)
        new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
        new_state = new_state[0]
        if new_state == 3:
            print('Newstate X1Y: ' + str(new_state) + ' Timestep: ' + str(timestep))
            assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

    if get_cellstate(df_results, x+1, y-1, timestep) == 3 and new_state == 2:
        Pburn = Pburn_diagonal(df_input, x, y, x+1, y-1)
        new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
        new_state = new_state[0]
        if new_state == 3:
            print('Newstate X1Y_1: ' + str(new_state) + ' Timestep: ' + str(timestep))
            assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

    if get_cellstate(df_results, x, y-1, timestep) == 3 and new_state == 2:
        Pburn = Pburn_cross(df_input, x, y, x, y-1)
        new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
        new_state = new_state[0]
        if new_state == 3:
            print('Newstate XY_1: ' + str(new_state) + ' Timestep: ' + str(timestep))
            assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)
```

```
        if get_cellstate(df_results, x-1, y-1, timestep) == 3 and new_state == 2:
            Pburn = Pburn_diagonal(df_input, x, y, x-1, y-1)
            new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
            new_state = new_state[0]
            if new_state == 3:
                print('Newstate X_1Y_1: ' + str(new_state) + ' Timestep: ' + str(timestep))
                assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

        if get_cellstate(df_results, x-1, y, timestep) == 3 and new_state == 2:
            Pburn = Pburn_cross(df_input, x, y, x-1, y)
            new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
            new_state = new_state[0]
            if new_state == 3:
                print('Newstate X_1Y: ' + str(new_state) + ' Timestep: ' + str(timestep))
                assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

        if get_cellstate(df_results, x-1, y+1, timestep) == 3 and new_state == 2:
            Pburn = Pburn_diagonal(df_input, x, y, x-1, y+1)
            new_state = np.random.choice([2,3], 1, p=[(1-Pburn), Pburn])
            new_state = new_state[0]
            if new_state == 3:
                print('Newstate X_1Y1: ' + str(new_state) + ' Timestep: ' + str(timestep))
                assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

        if new_state == 2:
            assign_new_cellstate(df_results, x, y, timestep, new_state, DateTime)

    return df_results

def process_rules(board, df_results, df_input, timestep):
    #Board rules, update per timestep
    for x in range(0, len(board[0])):
        for y in range(0, len(board)):

            cell_state = get_cellstate(df_results, x, y, timestep)

            if cell_state == 1: #Cell not containing fuel -> keep state
                assign_new_cellstate(df_results, x, y, timestep, 1, DateTime)

            elif cell_state == 2: #Cell contains fuel
                process_moore_neighbours(df_results, df_input, x, y, timestep)

            elif cell_state == 3: #Cell burning -> burnt fuel, state 4
```

```
            assign_new_cellstate(df_results, x, y, timestep, 4, DateTime)

        elif cell_state == 4: #Cell burnt out -> keep state
            assign_new_cellstate(df_results, x, y, timestep, 4, DateTime)

        else:
            print('Error for cell: (' + str(x) + ',' + str(y) + '), Timestep: ' +
                str(timestep) + ' in process_rules.')

    return df_results

def create_input_df(board):
    #Converting the Board to DataFrame and populate with geoData.
    print('Preparing input data...')
    start_time = time.time()
    rows = []
    X_jump = GridStart
    Y_jump = GridStart
    FWdata = FireWeatherData(latitude, longitude, Date_string, Time_string)
    Date, FWIindex, FWI, Temp, WindDirection, WindSpeed = FWdata
    FWIindex, FWI, Temp, WindDirection, WindSpeed = FWIindex[0], FWI[0], Temp[0],
        WindDirection[0], WindSpeed[0]
    #print('FWI: ' + str(FWI) + ', FWIindex: ' + str(FWIindex) + ', Temp: ' + str(Temp) +
        ', WD: ' + str(WindDirection) + ', WS: ' + str(WindSpeed))
    Input_step = 1
    for x in range(0, len(board[0])):
        for y in range(0, len(board)):
            el = round(elevation(Y_jump[0], X_jump[1]),1)
            map_cell_state = pop_cell_state(Y_jump[0], X_jump[1])
            #-- FIX INITIAL CELLSTATE, 1-4 different?
            rows.append([x, y, Y_jump[0], X_jump[1], map_cell_state[1], 0, DateTime,
                map_cell_state[2], el, Temp, WindDirection, WindSpeed, FWIindex, FWI])

            #Next latitude point calculation
            Y_jump = geopy.distance.distance(meters=CellSize).destination((Y_jump),
                bearing=0)
            Y_jump = [round(Y_jump.latitude,6), round(Y_jump.longitude,6)]

            print('Step: ' + str(Input_step) + ' of ' + str(Total_cells))
            Input_step = Input_step + 1

        #Next longitude point calculation
        X_jump = geopy.distance.distance(meters=CellSize).destination((X_jump),
            bearing=90)
```

```
            X_jump = [round(X_jump.latitude,6), round(X_jump.longitude,6)]
            Y_jump = GridStart

    df = pd.DataFrame(rows, columns=['X', 'Y', 'latitude', 'longitude', 'state',
        'timestep', 'datetime', 'P_den','elevation', 'temperature', 'winddirection',
        'windspeed', 'FWIindex', 'FWI'])
    df.at[(df['X'] == round((NoCells_X/2),0)) & (df['Y'] == round((NoCells_X/2),0)),
        'state'] = 3
    end_time = time.time()
    print('Input dataframe created in ' + str(round(end_time - start_time,2)) + ' sec.')

    return df

def create_results_df(df):
    #Create the results DataFrame based on input DataFrame.
    CA_results = df.drop(columns=['P_den', 'temperature', 'winddirection', 'windspeed',
        'FWIindex', 'FWI'])
    return CA_results

#================ ACTIVITY ===================
board = new_board(NoCells_X, NoCells_Y)
CA_inputdf = create_input_df(board)
print(CA_inputdf)

today = datetime.now()
dt_string = today.strftime('%Y.%m.%d-%H.%M.%S')
CA_inputdf.to_csv(str(dt_string)+'-'+str(Name)+'_inputdata.csv', encoding='utf-8')

CA_resultsdf = create_results_df(CA_inputdf)

print('Starting simulation...')
totalstart_time = time.time()
for i in range(1, (NUM_ITERATIONS+1)):
    start_time = time.time()
    CA_resultsdf = process_rules(board, CA_resultsdf, CA_inputdf, i)
    time.sleep(0.1)
    end_time = time.time()
    print('Timestep ' + str(i) + ' of ' + str(NUM_ITERATIONS) + '. Time elapsed: ' +
        str(round(end_time - start_time,2)) + 'sec for ' + str(NoCells_X*NoCells_Y) + '
        cells.')
    print('Total estimated time remaining: ' + str(round((NUM_ITERATIONS*(end_time -
        start_time)) - (i*(end_time - start_time)),2))+ ' sec.')
    print('--------------')
```

```
totalend_time = time.time()
print('Total compute time: ' + str(round(totalend_time - totalstart_time,2)) + ' sec for
    ' + str(NUM_ITERATIONS) + ' timesteps, ' + str(NUM_ITERATIONS*Timestep_min) + ' min
    simulated time for ' + str(NoCells_X*NoCells_Y) + ' cells.')

today = datetime.now()
dt_string = today.strftime('%Y.%m.%d-%H.%M.%S')
CA_resultsdf.to_csv(str(dt_string)+'-'+str(Name)+'_results.csv', encoding='utf-8')
print('.csv datafiles stored')


CA_resultsdf['datetime'] = CA_resultsdf['datetime'].astype(str)
CA_inputdf['datetime'] = CA_inputdf['datetime'].astype(str)

config = {
    'version': 'v1',
    'config': {
        'mapState': {
            'latitude': latitude,
            'longitude': longitude,
            'zoom': 13
                }
            }
        },

vis = Visualize(api_key=MapBox_API, style='satellite', read_only=False)
vis.add_data(data=CA_resultsdf, names='Simulation results')
vis.add_data(data=CA_inputdf, names='Simulation input')
vis.config = config
html_path = vis.render(open_browser=True, read_only=False)
```