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PH.D. THESIS

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Application of preventive measures in lightning protection

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Declaration

I declare that I created this Ph.D. thesis myself using the referred sources only. Each part which has been taken explicitly, or with similar content from other sources has been referred with the explicit source.

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Budapest, 11.01.2011.

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Information

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Tájékoztató

A jelen értekezésről készített hivatalos bírálatok, valamint a doktori munka védéséről készült jegyzőkönyv a védést követően a Budapesti Műszaki és Gazdaságtudományi Egyetem Villamosmérnöki és Informatikai Karának Dékáni Hivatalában érhetők el. (Budapest, XI. ker. Magyar tudósok körútja 2. Q épület B szárny)

Contents:

1. Introduction

Lightning, as a natural phenomenon was admired in the undeveloped societies since the Stone Age. Lightning was found in myths and in nearly all of the early religions. In the ancient religions, lightning and the thunderstorm were always preferred as weapons the supernatural's, weapons of gods. Lightning was Zeus' weapon [1], and also Thor, a god in Norse mythology wielded it [2].

The fear and admiration of the lightning was not without cause. The bright light and loud noise – even though only a momentary effect – was often taken as a sign. Strokes into populated areas left dead and destruction behind. Besides its deadly nature, lightning also served people sometimes. When a lightning stroke a tree, it often caught fire, and it was used to give warmth and to prepare meat.

In the middle ages, the human's thirst for knowledge grew stronger and scientists made progress in nearly every field of science. But until the middle of the 18th century, lightning remained an unexplained untamed natural phenomenon. The first man, who made scientific progress, explaining the electrical nature of lightning, was Benjamin Franklin. He proved his theory with an experiment [3], which was reproduced by other scientists as well. (In 1752, Francis D'Alibard, and in 1753 a Swedish scientist G. W. Richmann were those, who reproduced the experiment. G. W. Richmann's death was caused by a lightning stroke [4].)

Based on Franklin's research lightning rods were being installed in settlements to protect both people and their homes. This early type of protection was rather universal, since an installed rod (already containing the down conductor and the earthing) served to protect not only one, but several buildings against the lightning effects. Lightning protection became much more emphasized after some severe damages [5] occurred. It's also notable that the oldest lightning rods were mounted on churches[1] [5], [6].

This type of protection is referred to as primary lightning protection as it protects against the primary effects of lightning strike – the thermal and mechanical effects. Air termination systems are designed to provide a safe strike point for the lightning from where the lightning current may flow safely to the ground where the earthing system distributes it.

Even though the current flow does not endanger the buildings and people directly, the change of current and the E and H field generated by the lightning strike produces secondary effects. The secondary effects are the voltage surges and the induced voltages. With the rapid development of electronic devices these secondary effects became a more and more serious threat to these devices. Being aware of the danger surge protective devices were being build into the electrical systems of the buildings, the electrical outlets (or distribution networks) and later on into devices themselves.

Since the discovery of electromagnetic waves in the late 19th century the lightning phenomenon has been investigated in a different scope. Following the experiments of Hertz with electromagnetic waves and preceding Marconi's radio signal reception experiment in 1903 there were lightning detectors operating all over the world. The first lightning detector

[1] Before the use of the rods the church bells were rang to protect people from the lightning [4].

was built in 1895 by S. Popov (Russia), but his scientific achievement did not spread due to the language barriers. He was followed 1900 by E. Boggio-Lera (Italy) and then shortly by Gy. Fényi and J. P. Schreiber (Hungary). These lightning detectors (or more precisely 'counters') were in operation for only until about 1910 due to the rapidly increasing interference [7] (for more references see therein).

The next major step in lightning detection came when C.T.R. Wilson published his theory about thunderstorm electrification [8]. It was later followed by the first practical step, the invention of the direction finding (DF) technology just in twenty years [9]. Using these sensor types a complete network was built during the 80's covering the whole area of the US [10]. Such networks are being installed starting from the 90's all over the world. With these networks the lightning activity can be both registered and monitored with a relatively good accuracy. Hence they may be used for protection purposes as well.

Primary and secondary protection – as discussed above – use certain devices installed to the object to be protected. Their purpose is to protect the living and the goods from the effects of lightning strike. These devices are continuously protecting the object to be protected, thus provide constant protection.

In certain cases when the protection of the living is crucial or the protection of the goods may be too costly. In these cases primary and secondary protection is either non-cost efficient or may not be installed at all. The former is the case when the object to be protected is endangered only for a shorter time period; the latter is usually the case of crowds, or people at endangered locations. When conventional lightning protection methods are not feasible, new methods are to be used.

A new method introduced in this thesis denoted as ***preventive lightning protection***. The purpose of this thesis is to introduce the concept of preventive lightning protection and to give a theoretical description in some aspects.

This dissertation is composed of four theses. For practical reasons I deal with hazard forecasting and preventive actions in separate theses. The first thesis concerns forecasting methods, the second and third addresses the actions and risk calculation. The fourth thesis is only indirectly related to PLP, as it introduces a modular lightning model, which may be used to approximate exposedness to lightning strikes.

First, I define the event space approach as a method to describe the operation of PLP, and propose two forecasting methods for which the event space parameters are deducted. Current approaches in lightning protection only address forecasting and consider empirical data as the only source of describing its operation. As opposed to them the proposed methods are solutions on using forecasting and considering the preventive action parameters as well, and they include the calculations on approximating the performance of the protection.

The simpler method includes the use of fixed zones in which the presence of the thunderstorm cell should trigger the execution of the preventive action. This type of protection is realized by the so called 'zonal preventive lightning protection' (ZPLP). The other – more complex – method is that the thunderstorm cells are constantly monitored and based on their propagation speed and direction the need for execution of the preventive action is frequently evaluated. This requires complex evaluation methods, but also yields in much more accurate forecasting thus more efficient protection. In my thesis this method is denoted as the ‘high reliability preventive lightning protection’ (HRPLP).

The thesis deals with the preventive actions in a separate section, as they are key parts of protection, yet their properties should be discussed independently from forecasting as well. One of the most important features of preventive lightning protection is if it may be realized cost efficiently. This question usually does not arise in case of protecting the living, but in any other cases the parameters of protection shall be considered accordingly.

The preventive actions as means of protections have special features. While the air termination – down conductor – earthing system becomes a part of the object to be protected after it’s being installed, preventive actions are only in effect for a limited time period – for the existence of lightning hazard. Thus the costs of preventive actions are to be calculated differently.

In the current standards, the costs of protection are constant annual costs, thus PLP may not be fit to this approach. I propose methods to approximate the annual (non-fixed) cost of action executions taking into consideration the dynamism of PLP. The cost assessment of the whole solution (the fixed costs) is not in the scope of my thesis. Only a brief introduction is given on the other annual costs.

Planning of such a solution requires a method which takes into account the dynamic features of both forecasting and preventive actions. Preventive lightning protection is not included in the current standards due to its novelty, but its compliance with the standards is vital. The risk calculation methods in the standard are unable to handle risk in case of non-permanent protection methods, thus such methods as PLP cannot be included in the standards. Therefore I define a novel approach of risk calculation – the notion of the equivalent risk – to adapt PLP to the requirements of the current standards. I describe the application of this concept for PLP first in a theoretical perspective, then also through a practical example. Hence I provide compatibility for PLP with the international standards.

Also I extend the SCOUT method – a planning and auditing system for electrostatic applications – to include the planning tools for preventive lightning protection. The SCOUT system nowadays is generally used in industrial electrostatics. Its purpose is providing ample protection against electrostatic hazards. Yet it contains only the tools necessary for static (in time) hazards. To be able to handle preventive lightning protection I extend this method in my thesis. I include the use of forecasting devices, thus the SCOUT system will be capable of handling the forecasting-action type protection using various types of measurement equipments.

Besides the topics mentioned above I also discuss a modular lightning model concept in this thesis. In the research of lightning physics (micro physics, propagation etc.) certain sub-processes of lightning propagation were modelled individually. Nowadays due to the increasingly available computational resources it’s possible to realize more complex models describing the lightning phenomena more and more accurately. I propose a modular model structure which may contain many of the processes known from lightning physics as separate, exchangeable building blocks. Such a modular model is capable of describing the whole propagation process starting from the stepped leader development, to the return strokes and multiple strikes. I my thesis I show a simple implementation of the model which may be used to investigate the exposedness of certain building arrangements to lightning strikes. Thus this simple implementation may be used in planning of preventive lightning protection as well.

After the short introduction of preventive lightning protection in section 2, section 3 contains a more detailed explanation of the preventive lightning protection method and thesis 1, the forecasting methods used in preventive lightning protection. Section 4 describes thesis 2, the types of preventive actions and the approximation of their costs. Section 5 deals with thesis 3, the methods to define a new concept of risk for preventive lightning protection and the method's compliance with the standard [11]. Here also a method for planning and evaluation is introduced. The last thesis – a suggestion of a new lightning model structure and test results – is explained in section 6. There are many expressions which were not deducted in the according sections due to size constraints – these are included in the appendix, along with auxiliary calculations.

2. The concept of preventive lightning protection

The method described in the following section is a new method of lightning protection, which incorporates the application of preventive measures. These measures are application specific, in the sense that the same measures may not be feasible or optimal for the protection of both humans and different facilities.

Other methods use certain protection devices installed to the object to be protected, so in this case those are static protection methods. Since preventive measures include temporary measures this method is dynamic in this sense. Also as the preventive measures are executed before the actual hazard development, this protection method is denoted as *preventive lightning protection.*

2.1. Definition and the operation of preventive lightning protection

The preventive lightning protection method means avoiding damage of a lightning strike with special preventive actions. The preventive actions can be of various types, and the primary goal of preventive lightning protection is to decrease the risk of damage due to lightning for the duration of the thunderstorm. The preventive action shall be initiated before the beginning of the lightning activity, and shall be discontinued after the end of the thunderstorm [12].

If we assume that the object to be protected can be described with a risk value, which denotes the risk of damage due to lightning strike, then preventive lightning protection means the decrease of this risk value for a certain time period. This time period is the presence of a lightning hazard.

In preventive lightning protection *lightning hazard* means that a thunderstorm cell producing IC, CC and/or CG strikes is close to the object to be protected. The presence of a thunderstorm cell producing IC or CC lightning suggests that it will produce CG flashes later on, thus possibly damaging the object to be protected. When the thunderstorm cell already produces CG lightning, the threat is of course obvious.

The execution of the preventive action is timed with the help of lightning hazard detection systems. Hazard detection systems only include those systems which are capable of detecting lightning activity and/or cloud movement. However to realize adequate protection, the use of these systems is to be described properly. The system consisting of the lightning hazard detection devices and the rules, and principles of the use is further on referred to as *lightning hazard forecasting*, or *forecasting*.

Lightning hazard forecasting includes the *devices* which are used to monitor the cloud formation and thunderstorm propagation; the *ways of evaluating the data* – with the use of various information about the object to be protected and the properties of the applied preventive action – obtained from these devices; and the *signal* given to the user to execute or initiate the preventive action. The signal can be any kind of alarm which is given, or in case of automated systems an electric signal transmitted to the system responsible for the execution of the preventive action. So the purpose of lightning hazard forecasting is the timely warning of the future presence of lightning hazard taking into account the execution of the preventive measure. Also lightning hazard forecasting is responsible for the suspension of the preventive action, giving another signal to the user.

Fig. 2.1 shows the operation of preventive lightning protection. The risk value defined below is denoted as R_{npr}, this corresponds to the state when no lightning hazard is present, and won't develop in the future. (It is a risk calculated by principles the international standard [11].)

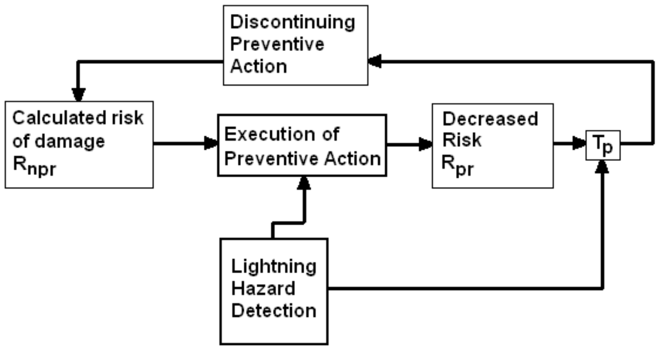

Figure 2.1.: The operation of preventive lightning protection [12]

If the lightning hazard detection system indicates thunderstorm cells in the vicinity of a certain area around the object to be protected (further this will be denoted as a Warning Zone – a part of the *zonal preventive protection* concept), then a preventive action is executed.

The *preventive action* is an action which decreases the risk of damage to the object to be protected for a certain period of time. This decreased risk value is denoted as, R_{pr} in Fig 2.1. This action can be of various types, as described in Section 4 depending on different properties of the object to be protected. It may consist of one single stage, or multiple stages – the latter is not always feasible, but has different advantages. The preventive action is in effect for a time period of T_p, while the lightning hazard is still present (reported by lightning hazard detection).

When the lightning hazard no longer exists – which is determined by the lightning detection system – the preventive action is discontinued and the risk of damage due to lightning strike 'increases' to the value of R_{npr} again. Note however that this risk value is only of theoretical meaning, since 'risk' is only defined during hazards. One has to take into account this risk value if the execution is not done in time[2].

2.2. Preventive lightning protection in lightning protection theory

Primary and secondary protection provides protection against damage due to lightning strike with the installation of different devices. Each of these protection methods require a 'compatibility' of the devices with the objects to be protected. For example lightning rods can't be installed onto people exposed to lightning hazard. If the different protection devices can't be installed to the object to be protected, then the appropriate lightning protection cannot be realized.

[2] The risk concept in case of preventive lightning protection is discussed in section 4.

Once the protection devices are installed, they become the part of the object to be protected permanently, as their dismantling would cause the loss of protection, and an increase in the risk of damage due to lightning strike. In this regard both primary and secondary lightning protection can be classified as a static protection method in time.

Preventive lightning protection on the contrary is a dynamic solution of lightning protection, since the protection is in effect only for the duration of the thunderstorm – the presence of the hazard. There are no devices permanently installed to the object to be protected. This means that an adequate realization of preventive lightning protection requires exact knowledge of the hazard and the ability to forecast the hazard. In static methods the only knowledge required is the knowledge of the hazard and devices applicable to the object to be protected.

Another very important difference between the static and dynamic solutions is the definition of the object to be protected. In the static solutions the object to be protected means 'a structure or service to be protected against the effects of lightning' ([11] IEC 62305-1 pp. 21). In preventive lightning protection the object to be protected means a structure, service or the living at a given location, where a lightning strike may yield damage. Note that the 'object to be protected' may include living per se.

Despite the many differences between the static and dynamic solution they may be used in conjunction to provide an adequate and cost effective solution.

2.3. The components of preventive lightning protection

The operation of preventive lightning protection is described by a sequence of events as shown in Fig 2.1. Thus preventive lightning protection consists of three main components which produce this sequence. These components are the *information*, *forecasting*, and the *preventive action*. All of these components are required to realize preventive lightning protection.

Information

In planning primary and secondary lightning protection the level of the hazard has to be known to find the adequate solution. Besides the level of the hazard, detailed knowledge of the object to be protected is also required to find the most suitable location for the installation of the protection equipment.

In preventive lightning protection more information is needed besides those obtained for the planning of primary or secondary protection. Since the nature of the protection is different, extra information is needed to choose the best preventive action and to plan the most effective solution [13].

The volume of the hazard is determined by following the principles of the international standard [11]. The risk of damage due to lightning strike without preventive lightning protection is first to be determined (the R_{npr} in Figure 2.1).

Meteorological and geographical information is also required to plan an efficient forecasting (for example to realize *zonal preventive protection*) and to choose an adequate preventive action. Gathering this information does not only require lightning protection specialists versed in the principles of the standard, but specialists who know the object to be protected to its details not only in the perspective of lightning protection, but of other hazards and special operational properties as well. This knowledge is required to determine the available preventive actions, and further risk and cost calculations are required to select the adequate protection (to see the importance of the information see Section 5).

Table 2.1.: Information requirements

	Forecasting	Preventive action
Information	The object to be protected: -Geographical information -Availability of forecasting equipment The area: -Annual number of thunderstorms per year -Average duration of a thunderstorm -Meteorological information	The object to be protected: -Environmental properties -Operational properties -Nature of lightning hazard -Risk of damage due to lightning strike

Lightning hazard forecasting (forecasting)

Lightning hazard forecasting is the key to the appropriate application of preventive actions. The alarm can be given in time to execute the preventive action (or a stage of the preventive action in case of multi-stage preventive actions – see section 4 on multi-stage preventive actions) based on the information provided by the lightning detection system and meteorological radars.

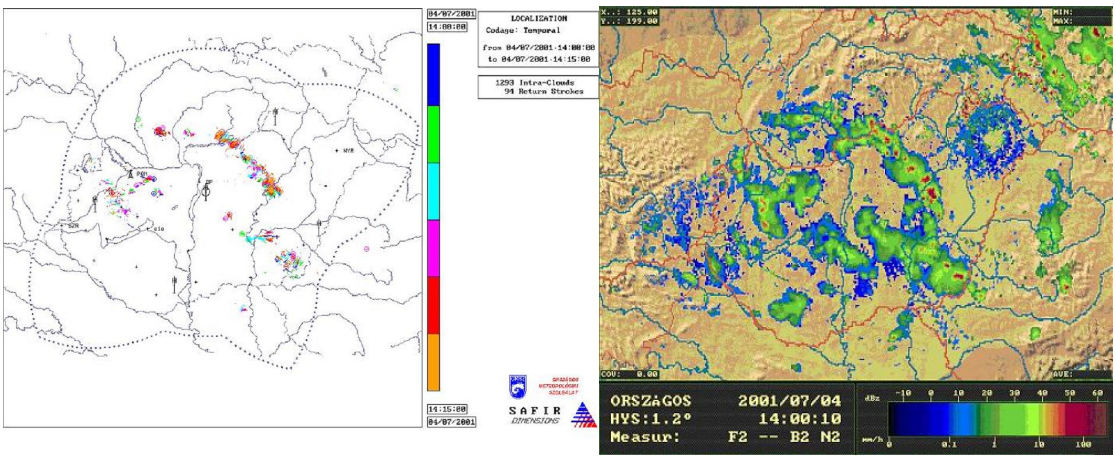

Figure 2.2.: Data of a lightning detection system and a radar system of Hungary [12]

The alarm can be of various types, starting from a simple audio signal, to a start signal for automatic equipment. It depends highly on the preventive action applied. The alarm to execute the preventive action is given only once. After that we assume that the preventive action has been executed. However since the preventive action has to be in effect only for a certain time (denoted as T_p in Figure 2.1.), another alarm has to be given, when no hazard is present anymore to suspend the action.

This concept means that preventive lightning protection can be realized only when constant monitoring of lightning hazard is present as a forecasting for preventive lightning protection.

In this case forecasting does not only mean the forecasting of the hazard, but the signalling upon the passing of the hazard.

Lightning hazard forecasting can be realized either with local monitoring equipment [14-16], or a lightning detection system used in conjunction with the meteorological radar as mentioned above [17], [18]. Each of the solutions has advantages and drawbacks, thus some solutions may require different forecasting equipment.

Table 2.2.: Different forecasting equipment

Type of forecasting	**Standalone device**	**Lightning detection network**
Cost	Low	High
Infrastructure required	Data acquisition and processing unit, alarm	Numerous units, and personnel
Maintenance requirement	Rarely	Often
Accuracy, range	Medium, short (<50 km)	Good, long (>>50km)

Standalone devices have a clear advantage over complex detection networks in the terms of cost and maintenance. These devices are mostly cheap, operate independently, and may be repaired or replaced easily. The data acquisition module and the data processing module are also cheap and it's capable of giving various types of alerting signals. Such a device can easily be attached to automatic devices, or may give audio or visual signals as well.

The drawback of a standalone unit is its limited range and accuracy [19]. Standalone units may be built using is a field mill, or a corona antenna. The accurate operation of the equipment requires good calibration and good positioning to avoid certain disturbances. Limited range in case of the standalone devices means that these devices observe the area above them, so the thunderstorm cell several kilometres away from them can't be observed with some types of devices. Their biggest advantage is that the process of thunderstorm cell development above the object to be protected can be monitored, since it causes measurable changes in the ground E-field [20].

On the contrary the lightning detection networks provide detailed data on the thunderstorm cells [21], [22], but they don't predict the start of the electric phenomenon inside the cloud, as the antennae receive only the strong electromagnetic waves. So if the first discharge of a thunderstorm is a CG lightning, then it can't be forecasted using a lightning detection system. But it can be predicted – or more accurately, the presence of the hazard can be determined – with a standalone device. However if CC activity precedes the CG strikes using a lightning detection network yields better results, although it yields bigger costs.

Preventive action

The preventive action is the tool of the protection itself. The preventive action is an action which temporary decreases the risk of damage to the objet to be protected due to lightning strike. The preventive action to be applied is always determined by the information gathered about the object to be protected and the nature of the hazard (type of possible damage, etc.). Because of this, there are no strict rules given to select the preventive action, but there are two criterions which have to be fulfilled by the preventive action.

One very important criterion is the *efficiency criterion*. It means that the preventive action has to decrease the risk of damage due to lightning strike to the object to be protected under the levels defined in the standard[3].

The other criterion is the *timing criterion*. The preventive action has to be executed in time, so upon planning the preventive action, the execution time has to be calculable for the actions. With this information the forecasting information is used effectively and the alarm is given in time.

A special case of preventive actions is the so called ‘multi-stage’ preventive actions. These actions are those which can be divided into several stages with well defined timing parameters. The goal of these actions is to increase cost effectiveness. If the action is divided into stages, then the costs are also divided. If the thunderstorm cell signalled by forecasting passes before endangering the object to be protected, then executing a preventive action may yield unnecessary costs. With executing different stages at different times, some cost can be saved (see *zonal preventive protection* for the use of forecasting in these cases, on multi-stage preventive actions see section 4).

[3] As according to the so called ‘tolerable risk’ [11]. A stricter condition involving the efficiency of forecasting is introduced in section 5.

3. Preventive lightning protection theory

1st thesis

I created the consistent theoretical framework of a novel method of lightning protection based on the use of forecasting and preventive measures developed in the Budapest school on lightning protection. The theoretical framework combines the methods currently applied in a broad probabilistic model. Two methods of preventive lightning protection are described, the zonal preventive lightning protection (ZPLP) and high reliability preventive lightning protection (HRPLP) [23], [16], [24], [25], [18], [26-29]**.**

Preventive lightning protection is a novel solution in lightning protection, but parts of this method are already in use. For example lightning detection networks are currently used for forecasting, and preventive measures are also used to some extent, but they're considered separately in most of the cases. As it is shown in later sections, the planning and use of forecasting and the preventive action in conjunction yields a better solution in terms of protection and/or cost.

The existing solutions however are not planned in this approach, so they can be considered rather as 'practices' than worked out solutions and are not compatible with the standards at all. A short summary is given of other approaches as well and preventive lightning protection is compared to them focusing mainly on the differences.

In this section I describe the different methods of forecasting and give a general description on the theory of preventive lightning protection. The efficiency is defined along the general event space[4] model of preventive lightning protection and the calculations are shown. Since the deduction of the results is rather complicated, the full deduction is found only in the appendices.

Two realizations of preventive lightning protection are discussed. The simplest and cheapest solution is the Zonal Preventive Lightning Protection (ZPLP – see Section 3.2), using the simplest hazard forecasting resulting in either good protection efficiency or good cost effectiveness. Its planning is an optimization problem using event space calculations and cost approximation. It is discussed in a rather theoretical point of view.

A more complicated method is the High Reliability Preventive Lightning Protection (HRPLP – see Section 3.3) which includes more sophisticated forecasting having increased cost effectiveness and protection efficiency. The event space approach is also applied for this method and the method is discussed in practical point of view.

A novel method introduced in preventive lightning protection is the Fuzzy Preventive Lightning Protection (FPLP). The theoretical explanation of this method is not in the scope if this thesis. See the research of Németh on FPLP [30] and also further case studies and applications [31], [32].

[4] In probability theory the event space is also denoted as 'sample space'. In this work I use the 'event space' terminology consequently.

This section contains the theoretical description of both ZPLP and HRPLP with practical examples as well. Also a comparison of ZPLP, HRPLP through a case study is found in appendix A2 [24].

The current applications of forecasting also include ‘efficiency’ calculations describing the accuracy of the forecasting, but they can be based on empirical data only, which is not available in some cases. Here the efficiency does not only mean the efficiency of forecasting, but also take into account the preventive measures used, which is novel compared to existing forecasting methods. Also the methods presented here provide approximations of the efficiency, for which no methods have been proposed.

3.1.Efficiency calculations

A method to evaluate preventive lightning protection and to compare it with primary and secondary protection is to calculate the efficiency of the protection. Since it is impossible to give an exact number of protection efficiency (as it can't reach 100%), the simplest method to describe efficiency is by using relative numbers or units.

The efficiency of preventive lightning protection is described by the following expression:

$$\eta = \frac{R_{npr} - R_{pr}}{R_{npr}} = \left(1 - \frac{R_{pr}}{R_{npr}} \right) \qquad (3\text{-}1)$$

In this expression R_{npr} denotes the risk value without protection, and R_{pr} denotes the risk value when the selected preventive action is executed. If we assume perfect hazard forecasting, then (3-1) describes the efficiency of the solution per se. Otherwise it is suitable to describe one individual action as well, thus various actions can be compared and most efficient – and cost effective – one can be selected.

If the preventive action decreases the risk considerably, then the effectiveness is high. If the preventive action does not mean a substantive decrease in risk, then the action is not very effective. Note however that the tolerable risk – defined in the standard – shall be reached in every case.

3.1.1. The event space of preventive lightning protection

To evaluate the preventive lightning protection it is important to define the possible events which may affect the object to be protected. In primary and secondary protection this so called ‘event space’ – as defined in probability theory – consists only of two components. A lightning strike (either direct or indirect) may, or may not cause damage to the object to be protected.

$$p_{dam} = \frac{\sum_i N_i P_i}{\sum_i N_i} \qquad (3\text{-}2)$$

This expression is a simplification of the notion that a lightning strike may cause damage several ways. N_i denotes one the occurrence (annual) of one individual type of damage, p_i denotes the probability of its occurrence. It means that the probability of damage is the weighted sum of the probability of all possible types of damage. It describes the event space of primary and secondary lighting protection.

Table 3.1.: Event space of primary and secondary lightning protection

Event	Corresponding probability
A lightning strike damages the object to be protected	p_{dam}
A lightning strike does not damage the object to be protected	$p_{ndam}=1-p_{dam}$

In preventive lightning protection however the event space is quite different, since it is a dynamic method. Even though the preventive action is in effect, damage may occur, but besides these events, the protection process produces other events. To focus the event space on the use of forecasting an ideal preventive action is assumed, so if the action is in effect, no damage may occur[5].

Preventive lightning protection uses alarms to give information about the future presence of the hazard. The event space of preventive lightning protection is created by the combination of two events: hazard development (does develop/does not) and timely alarming (given in time/not given in time (or at all)). In this simple model when an alarm wasn't given in time is taken as if it wasn't given.

Unlike in primary and secondary lightning protection the event space in preventive lightning protection is based on individual thunderstorm cells not on occasions of lightning strikes. This approach is reasonable since the alarm is given (or not given) based on thunderstorm cells approaching the object to be protected. The timing of the preventive action is also to be taken into account.

Based on this, the event space of preventive lightning protection consists of four events.

a) a thunderstorm cell gets near the object to be protected, hazard develops and an alarm was given in time
b) a thunderstorm cell gets near the object to be protected, but hazard does not develop (the cloud changes its propagation direction), still an alarm is given and the preventive action is executed
c) a thunderstorm cell gets near the object to be protected, hazard develop, but the alarm was not given in time, or wasn't given at all – the object to be protected didn't become protected
d) a thunderstorm cell gets near the object to be protected, but hazard does not develop. Due to the inaccuracy of forecasting, no alarm was given, yet it wouldn't have been necessary either.

[5] This assumption is required for the theoretical description; otherwise the event space becomes unnecessarily complex. The risk concept of preventive lightning protection incorporates the possibility of damages of course. See section 5 on the issues of risk.

These four events cover all the possible events in preventive lightning protection.

Event 'a' denotes an appropriate operation of preventive lightning protection. If a thunderstorm cell gets near the object to be protected, the preventive action shall be executed. If it is executed in time – the alarm was given in time –, then by the time the thunderstorm cell endangers the object to be protected, it is considered to be protected. Damage still may occur and it shall be handled by using the description methods and principles of the standard. I denote this event as an ***accurate alarm***.

Event 'b' denotes an inappropriate operation of preventive lightning protection. The thunderstorm cell gets near the object to be protected to trigger an alarm, but hazard does not develop. The reason for the existence of this event is the fact that the alarm is to be given before hazard actually develops to provide time for the execution of the preventive action. In the protection point of view this operation is appropriate, since the object to be protected isn't endangered, but the cost effectiveness decreases if this happens[6]. I denote this event as an ***unnecessary alarm***[7]**.**

Event 'c' denotes an inappropriate operation. In this case the preventive action is not executed in time – or not executed at all – and the object to be protected is exposed to hazard for a certain time. From the protection point of view it is a protection failure. I denote this event as a ***late alarm***[8]**.**

Event 'd' is only a theoretical event. It means that no alarm is given, and no hazard is present later. This event is fully omitted in the theoretical analysis of preventive lightning protection. This event occurs, when a thunderstorm gets near the object to be protected, does not endanger it, but due to the inaccuracy of the forecasting no alarm is given. I will show in later sections that in our applications we don't have exact information of the occurrence of this event. The ratio of this event compared to the other three is negligible, and the event does not contribute to the protection or cost efficiency. This event is denoted as ***no alarm.***

A probability value corresponds to each of these events. The next table summarizes the event space of preventive lightning protection.

Table 3.2.: Event space of preventive lightning protection

	Alarm was given in time	Alarm wasn't given in time
Thunderstorm cell endangers the object to be protected	(a) Accurate alarm - p_{aa}	(c) Late alarm - p_{la}
Thunderstorm cell does not endanger the object to be protected	(b) Unnecessary alarm - p_{ua}	(d) No alarm - p_{na}

[6] The preventive action may be costly, so they're assumed to have certain costs in each case. The cost of the actions and cost efficiency is described in section 4.

[7] Also note that when triggering the alarm the hazard may not develop later on. The probability of an alarm being accurate or unnecessary may be approximated when giving the alarm. This section also deals with this approximation.

[8] This event is also produced when a thunderstorm cloud develops near the object to be protected and the alarm is not given. As written earlier in section 2.3.2 some standalone devices are capable of predicting thunderstorm development. For a more detailed description see for example [33].

The following expressions apply to the probabilities defined in Table 3.2:

$$p_{aa} + p_{ua} + p_{la} + p_{na} = 1 \quad (3\text{-}3a)$$

$$p_{haz} = p_{la} \quad (3\text{-}3b)$$

$$p_{nhaz} = p_{ua} + p_{aa} + p_{na} \quad (3\text{-}3c)$$

The first expression means that these events form the full event space of preventive lightning protection. Practice shows that we have no information on no alarm cases and they don't influence nor the protection efficiency, nor the cost effectiveness. Thus p_{na} can be omitted simplifying the event space.

The other expressions define a classification of the event space. In (3-3b) – p_{haz} denotes that the thunderstorm cell will present hazard – it is shown, that the only hazardous event is the late alarm in the sense of protection. The other events (3-3c) – denoted by their occurrence probability p_{nhaz} – are non-hazardous events, but they influence cost effectiveness.

The probabilities can be calculated both empirically and in theoretically. When calculated empirically they are relative frequencies. This calculation follows the ordinary calculations of relative frequencies. For example the probability of unnecessary alarms is calculated empirically the following way (N_{ua} denotes the annual number of unnecessary alarms, $N_{totalevents}$ denotes the annual number of all the events – practically the annual numbers of thunderstorms handled by PLP):

$$p_{ua} = \frac{N_{ua}}{N_{totalevents}} \quad (3\text{-}4)$$

Naturally this calculation method requires empirical data, so it is not always applicable in planning, but it is always a suitable tool for the evaluation[9] of the preventive solution. The theoretical calculations follow the way of simple geometrical probability calculations, but using empirical data as well improves their accuracy as shown later in this section.

3.1.2. Efficiency calculations and the event space

In primary and secondary lightning protection the risk of damage is the parameter which describes the quality of protection. In preventive lightning protection this parameter wouldn't be enough to describe the quality of protection, since it is a dynamic method. The quality of protection does not only depend on the action taken, but also on the timing of its execution.

The preventive action decreases the risk of damage, but if the timing is not right, then the protection efficiency decreases and the risk may remain at high levels. The description of the

[9] Planning and evaluation is shown in details in section 5.

efficiency taking into account this effect is a type of problem yet unsolved in lightning protection[10]. The calculations here only use this method to discuss efficiency.

In this section I assume that the preventive action has been selected, and there's only one preventive action. In this case the efficiency is calculated using (3-1). However the probability of inappropriate operation is totally neglected (since this expression serves only for the individual evaluation of the preventive action, not the whole protection itself). If we take it into account then we shall include those cases into our calculations which include the inappropriate operation –only the late alarms are of importance, since these alarms degrade protection performance.

The risk of damage can be divided into two risk values; first when the preventive action is in effect and second when it's not. In the latter case the object to be protected is more exposed. For logical reasons I only handle the cases when the object to be protected is endangered by the thunderstorm. When no hazard is present, protection does not have importance, thus protection doesn't have meaningful performance parameters for those cases and no risk of damage either.

The risk taking into account the ratio of the accurate and late alarm can be described by their according risk values giving them the appropriate weight.

$$R_{pr} = R_A \frac{p_{aa}}{p_{aa} + p_{la}} + R_{npr} \frac{p_{la}}{p_{aa} + p_{la}} \tag{3-5}$$

In this expression the weighting of risks is based on the relative occurrence of the cases (p_{aa} and p_{la} denotes the probability of accurate and late alarms respectively). Only those cases are taken into account where lightning hazard develops. The risk of damage due to lightning strike if the action is in effect is denoted by R_A. If the action is not in effect, the risk of damage is higher, it's denoted by R_{npr}. If we substitute (3-5) into (3-1), we get an interesting – yet logical – result. I assumed that we have an effective preventive action, $R_A << R_{npr}$.

$$\eta = 1 - \frac{R_{pr}}{R_{npr}} = 1 - \left(\frac{R_A}{R_{npr}} \frac{p_{aa}}{p_{aa} + p_{la}} + \frac{p_{la}}{p_{aa} + p_{la}} \right) \approx 1 - \frac{p_{la}}{p_{la} + p_{aa}} = \frac{p_{aa}}{p_{la} + p_{aa}} \tag{3-6}$$

According to this assumption we get that in case of a good preventive action, the efficiency of the preventive solution depends mostly on the ratio of the accurate alarms, and the late alarms. In terms of protection efficiency the goal of planning is to find a solution when the probability of late alarms compared to the probability of accurate alarms is small.

Of course these expressions contain strong assumptions, thus they should only be used as guidelines in understanding the importance of forecasting in PLP. The detailed risk calculations are given in section 5.

This gives what logic would dictate: decrease faulty operation to increase efficiency. More than that (3-6) means that forecasting has a crucial role in preventive lightning protection not only by its place in the operation of the protection, but by its very strong influence on

[10] A possible solution is weighting the different cases with the according probabilities and thus calculating the risk as shown in section 5.

efficiency. The different forecasting methods and the according forecasting efficiencies are described in the following part of this section.

3.2. Zonal preventive lightning protection (ZPLP)

In zonal preventive lightning protection the zones have a very different meaning and role, than the zones in secondary lightning protection [11]. The zones do not represent theoretical (and practical) boundaries between different protection levels, but real areas defined around the object to be protected. One zone (Danger Zone) corresponds to the area around the object to be protected where the presence of the active thunderstorm cell endangers the object; other zones (Warning Zones) correspond to alarms given to execute different stages of the preventive actions. Using zonal approach is necessary to realize the operation shown in Figure 2.1.

As alarming plays an important role in preventive lightning protection, it is necessary to know when an alarm should be given. Lightning hazard forecasting is responsible for giving the alarm at the right time as early alarms reduce cost effectiveness, and late alarms reduce protection efficiency. During the discussion of the zones a perfect lightning detection system is assumed. However since when using a stand-alone detector, we can't assume it is perfect, the stand-alone detectors' use is briefly discussed in a separate section.

Danger Zones

The Danger Zone (DZ) is an area around the object to be protected. If the active thunderstorm cell enters the DZ, the object to be protected is endangered by the thunderstorm. By the time the thunderstorm enters this area, the preventive action is to be executed already. The DZ's size is determined by the size of the object to be protected, and the distance from it, where a lightning strike may cause damage due to secondary effects.

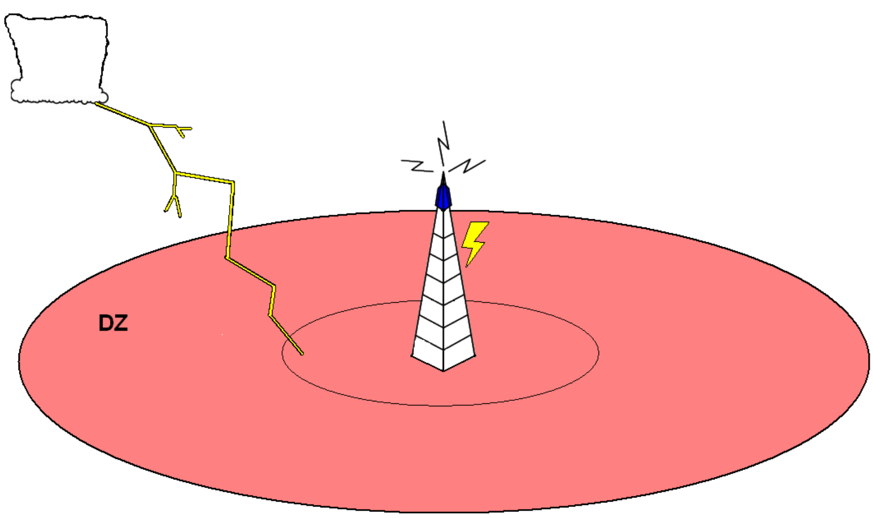

Figure 3.1.: Danger Zone of an antenna tower

$$r_{DZ} = r_{\sec} + r_{safe} \qquad (3\text{-}7)$$

The first term (r_{sec}) in (3-7) is the distance where a lightning strike may cause damage through secondary effects. The second term (r_{safe}) is the safety distance, which is the distance from a thunderstorm cloud where a lightning may reach. This depends on many factors including the altitude of the cloud, and soil conductivity.

> For example: If the object to be protected is an antenna tower, then a certain area around it can be defined in which a lightning strike causes hazardous voltage drop along the structure which may damage the equipment mounted on the tower. This is one part of the radius of the DZ. The rest of the DZ's radius is the distance from where a lightning could strike into r_{sec} causing secondary effects. The radius of the DZ in this case is the sum of these radii. It practically means that if an active thunderstorm cell is outside of this zone, it can't damage the antenna tower in any way.

In this regard divergent opinions are heard through practice about the safety distance from a thunderstorm cell ranging from 2 km to 10 km [34]. Since the size of the DZ is determined by the needs of protection, the freedom in determining the size of the DZ is relatively small. The distance where secondary effects may cause damage is to be calculated following the standard, and the safety distance shall be approximated uniformly, using a worst case value for maximal protection. Practically the difference between the DZs of different object is caused by their 'sensitivity' to secondary effects. One can use oversized DZs, but over a certain size it does not mean increase in protection[11].

> For example if the object to be protected is an area with people, then the secondary effects can be neglected compared to the safety distance. In this case the DZ consists only of the safety distance.

The radius in this case is measured from the object to be protected, and it is easier to measure it from the centre point of the object to be protected if possible. In other cases it is advisable to construct a line based on the shape of the object to be protected to serve as the base of measuring the radius of the DZ.

The DZ can be of various shapes practically chosen considering the area occupied by the object to be protected. In case of a building block it can be a square with round edges, or in case of an antenna tower it can be a circle (see Fig 3.2). The most important rule of planning the DZ is that it has to contain the area where a thunderstorm cell endangers the object to be protected. It can be modelled with a circular area, but in certain applications it may yield in a low efficiency solution.

[11] It may be calculated using the methods described in the standard.

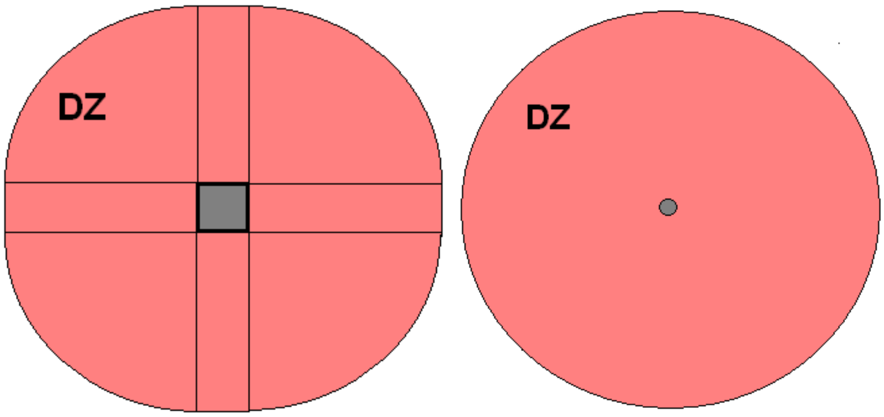

Figure 3.2.: Danger Zone of a building (square with rounded edges), and of an antenna tower (circle)

Warning Zones

The Warning Zone (WZ) is an area around the object to be protected. If the active thunderstorm cloud enters this area, the alarm signalling the execution of preventive action has to be given to provide enough time for the execution. Naturally the WZ is larger (sometimes substantially) than the DZ except for the case when the time required to execute the preventive action is relatively small, or zero. In case of instantaneous actions, it even may be omitted (the alarm is given upon entry to the DZ).

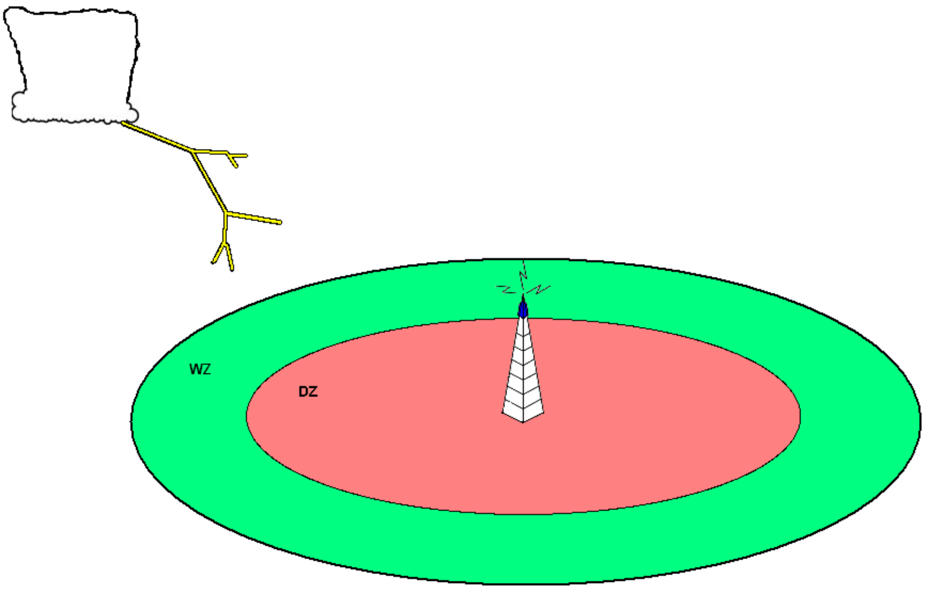

Figure 3.3.: Warning Zone of an antenna tower [18]

If the execution of the preventive action requires time, then at least one WZ has to be used. The shape of the WZ is the same as of the DZ. The radius of the WZ around the object to be protected can be calculated using the following formula.

$$r_{WZ} = r_{DZ} + t_{act} v_{storm} \tag{3-8}$$

The WZ radius is to be defined based on the DZ radius (3-7), the time requirement of the preventive action (t_{act}) and a selected thunderstorm cell velocity (v_{storm}). Of course the velocity of the cell is not constant, but an average value based on empirical data can be used during planning – or even a worst case value depending on protection efficiency needs.

> For example let's suppose that a DZ of a building consists of a radius where secondary effects may cause damage of 500 m, and a safety distance of 2 km (making a 2.5 km radius). The preventive action used in this building is an electrical switch off process which incorporates safety measures taking 5 minutes. Using (3-8) and approximating a worst case thunderstorm propagation speed of 60 km/h, we get an $r_{DZ}=2.5\ km$ and an $r_{WZ}=7.5\ km$.

By choosing a preventive action which can be executed quickly, it is possible to reduce the size of the WZ. The probability of unnecessary alarms is decreased if the ratio of the WZ and the DZ nears 1, but the probability of late alarms increase with it, if not a worst case thunderstorm cell propagation velocity[12] is applied in the calculations.

ZPLP and local detectors

In the previous sections ZPLP was generally discussed in terms of using lightning detection networks and meteorological radars as forecasting devices. However with the technologies currently available more and more accurate local detectors are accessible. These detectors can be applied with different approach to PLP.

In a recent article [19] Mäkelä et. al. described the application of local detectors in thunderstorm forecasting. Their approach is also a zonal approach, but does not fully comply with PLP. In the article the authors concentrate on the operation and accuracy of a local detector when both determining and calculating the different zones. Due to that, the zones in that approach are different.

Zone 1 (danger distance) corresponds to the DZ described in section 3.2.1 , as in this zone, the user is in danger of being struck by lightning (if an active thunderstorm cell is present). As in our approach the radius of this area is 10 km.

Zone 2 (tracking distance) corresponds to an area where the local detector is capable to determine the existence and distance of the active thunderstorm cell. When the cells are in this region, the user is alerted about its presence and distance. When this data is present, multi-stage preventive actions may be realized [25] and Zone 2 functions as multiple WZ-s. The size of this zone depends on the calibration of the local detector. The authors suggest a radius of 20 km (resulting in a total radius of 30 km). When used in ZPLP, the WZs should be within this zone.

Zone 3 (monitoring distance) is specific to the local detectors, as it denotes the area where the thunderstorm cell is sensed, but its distance is not accurately determined due to the accuracy of the detector. The presence of the thunderstorm cell is detected though. The authors suggest a size of less than 50 km (also taking into account Zone 1 and 2). The authors suggest not giving an alarm about the thunderstorm cell's presence, but in the forecasting perspective it's not practical as the users have to be alerted that the alarms may require more

[12] The highest measured thunderstorm cell velocity.

attention shortly. Of course the need for such an alarm is application specific, but in some cases it'd be practical. The application of such a zone is practical in the approach of HRPLP as well[13] .

When inducting local detectors to ZPLP, their properties are to be taken into account as well and this zonal approach – once inducted to the system of preventive lightning protection and planned according to the actions – is a useful and simple approach. Also it is a good benchmark of a given detector.

Currently there are only a few applications using local detectors. In some of those applications the WZ perimeter entirely consists of local detectors and the alarms are triggered based on the data of those detectors (mostly field mills). One of the most sophisticated solutions is realized at NASA (Launch Pad Lightning Warning System) [35], where 31 field mills serve as a complete WZ around launch sites to provide advance alarms. Further discussion of these of applications is not in the scope of this thesis.

Local detectors in ZPLP may be used as stand-alone detectors, or in networked operation. Simulations of Gulyás et. al. [16] showed that even when the ranging accuracy of a single sensor is poor; it can be used in ZPLP effectively as lightning hazard forecasting [16]. Also using simulation techniques can be used in planning a PLP using stand-alone local detectors. In the study mentioned above it was shown that by a proper choice of WZ size the probability of late alarms can be kept under 0.1, which is a very good result concerning protection efficiency – as it corresponds to exposedness, not damage directly.

3.2.1. Calculations of the event space in zonal preventive lightning protection (ZPLP)

The structure of the zonal protection partially determines the cost effectiveness of the solution. It is a logical conclusion that the larger the WZ, the larger is the ratio of the unnecessary alarms. This however does not mean that the probability of hazardous events, p_{haz} increases.

As described above the size of the necessary WZ is calculated taking into account the time required to execute the preventive action. Thus if we assume that the alarms are given in time, and the preventive action is executed, then the size of the WZ does not influence protection efficiency. In practice however thunderstorms can form near the object to be protected or the time between the alarm and the hazard development may not be enough to execute the preventive action. If a thunderstorm develops in the WZ or in the DZ, or the alarm did not come in time, then protection efficiency decreases. To approximate the ratio of these events, empirical data obtained from lightning detection systems is to be analyzed or theoretical calculations are to be carried out.

Late alarms can be produced different ways and thus they are difficult to analyze with simple probability calculations. The next section deals only with theoretical probability calculations of the p_{ua} and p_{aa}, while late alarms are dealt with in section 3.2.2.

[13] See section 3.3 for details. Due to the aims of this thesis the zonal structure at HRPLP is not emphasized, as the theoretical approach is discussed in details. The tracking distance of thunderstorm cells from the object to be protected is irrelevant in this case – as long as it's large enough.

Calculations of the event space parameters p_{aa} and p_{ua} in case of ZPLP

The probability of unnecessary alarms and accurate alarms can be approximated by using a simple method based on geometrical probability calculations[14]. The structure of zonal protection strongly influences the solution's cost effectiveness. In this section I assume that an alarm was given and the preventive action is executed in time, so I omit the possibility of late alarms. According to this assumption the event space is shrunk.

The calculations presented here obey the following criterion (assuming that an alarm was given):

$$p_{aa} + p_{ua} = 1 \tag{3-9}$$

Figure 3.4 shows the geometrical structure used in the calculation. The following assumptions were made in these basic calculations:

- The thunderstorm cloud is approximated with a circle
- The thunderstorm cloud is propagating in a straight direction
- The direction the thunderstorm cloud enters the WZ has flat distribution
- The distribution of the appearance of the thunderstorm cloud along the border of the WZ (further on denoted as 'z') has also flat distribution
- The thunderstorm cloud propagates with a uniform velocity

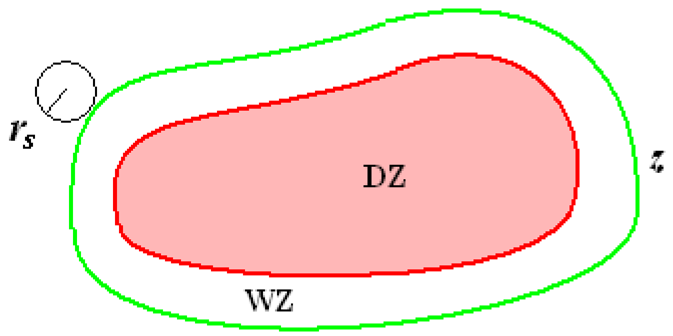

Figure 3.4.: Geometrical calculation of the probability of unnecessary alarm (universal DZ/WZ shape) [23]

These assumptions are made to simplify the calculations. Some of these assumptions are accounted for in section 3.2.3, and an extended model is shown including empirical data as well.

Thunderstorm clouds rarely have circular shape, but if we approximate the cloud with a circle, we get a worst case approximation to the probability of accurate alarms. The same applies to the cloud propagation direction, although this does not necessarily mean a worst

[14] The probability of late alarms may only be approximated by using empirical data as well.

case approximation. In case of smaller WZs this is an exact approximation, but in case of large WZs it may distort the results.

A flat distribution of the direction of approach is another simplification in the calculations, although it can be accounted for. It means that the cloud propagates in any direction with the same probability. This makes the calculation of geometrical probabilities feasible [36].

The uniform velocity assumption emphasizes only that it's not necessary to calculate with the velocity, and it also means that the planned WZ is appropriate and is planned according to (3-8).

The appearance of the thunderstorm cloud is a bit different matter. By assuming that the appearance along the border of the WZ has flat distribution, the results are quite distorted, since this assumption is not true in most of the cases. However for the comparison of zonal structures this assumption is adequate.

These assumptions simplify the calculation to geometric probability calculations. The method of the calculations is based on determining the probability at each point that the propagating thunderstorm cloud gets into the DZ later on. The propagation directions are between 0º and 180º denoting the angle the thunderstorm cloud propagates into the WZ when the alarm was given.

The geometric probability is to be calculated all around the border of the WZ (the curve representing the WZ is denoted as ‘z’) and its average is to be taken as the probability of accurate alarm (due to the assumption of flat distributions).

$$p_{aatot} = \frac{1}{z} \oint p_{aa}(z)dz \quad (3\text{-}10)$$

$$p_{aatot} = \frac{1}{n} \sum_{n} p_{aa}(z) \quad (3\text{-}11)$$

These expressions describe the probability of accurate alarms for a given DZ-WZ structure. (3-10) describes the continuous method, while (3-11) is a discrete model mostly used for the calculations as the analytic form of the WZ (curve z) may not be available in each case.

The probabilities in both of the expressions are the geometrical probability values, which describe the probability that the angle of propagation would lead the thunderstorm cloud into the DZ later on given that the thunderstorm cloud entered the WZ at a given point.

$$p_{aa}(z) = p(\alpha(z) < \alpha_{\lim}(z)) = \frac{\alpha_{\lim}(z)}{\alpha'(z)} \quad (3\text{-}12)$$

Expression (3-12) describes the geometric probabilities used in (3-10-11). α_{lim} denotes the angle within which the thunderstorm cloud would enter the DZ – thus lightning hazard would develop –, and α' denotes those propagation angles at which the thunderstorm cloud could have triggered an alarm. It is 180º in geometrical shapes, where the derivative of the curve z is continuous.

During the approximations of the event space parameters these geometric probabilities (using α_{lim} values) are to be calculated along the border of the WZ and their average is taken. Then combining the results obtained from calculating (3-10) with the condition given in (3-9) the probability of accurate alarms and unnecessary alarms is calculated.

These results are to be extended with the probability of late alarms (discussed in section 3.5) to describe the full event space – when no alarms are omitted.

The rest of this section shows the results of the calculations of (3-10) for simple DZ-WZ structures. The deduction of the calculations is found in the appendices, section A1.

Event space in case of simple DZ-WZ geometries

For the first example I assume a circular DZ, and WZ[15], and the thunderstorm is approximated with a circle of a given radius. In the following calculations the assumptions formulated in the previous section are valid. In these figures the higher the probability of accurate alarms, the higher the cost efficiency. These figures do not provide information on the protection efficiency.

Circular DZ-WZ arrangements

Circular DZ-WZ arrangements are symmetric, thus allow very simple calculations. In Fig. 3.5 the probability of an accurate alarm is shown versus the radius of the WZ assuming a DZ of 10 km (preserving the same DZ-WZ ratio the results apply to bigger DZ-s as well) and a thunderstorm cloud with the radius of 1 km.

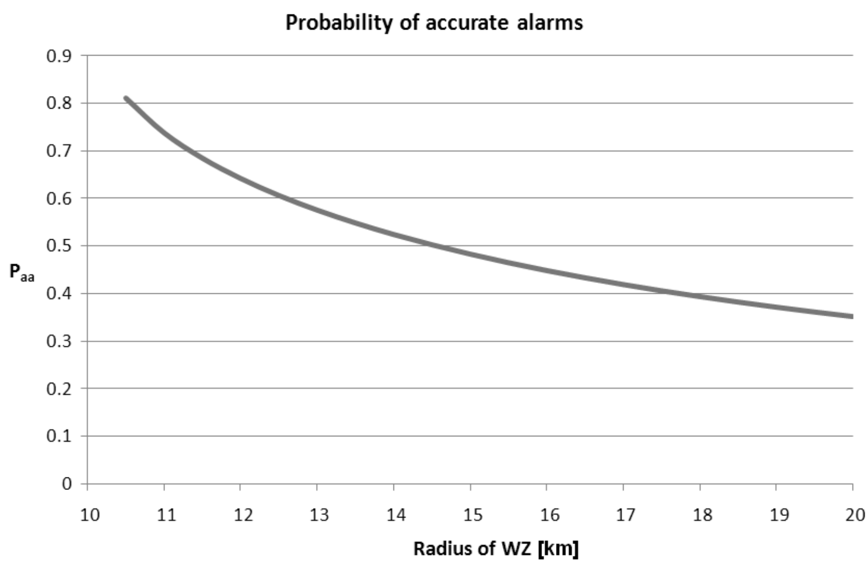

Figure 3.5: Probability of an accurate alarm vs. the radius of WZ

The result shows rather big values[16] at WZ/DZ ratios close to 1 (DZ = 10 km in fig. 3.5). This is logical, since if the WZ radius is not much bigger than the DZ radius, most of the alarms will be accurate. It is an important conclusion that even if the WZ is only of 1.5 times

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[15] This shape is typical for towers, or smaller buildings.

[16] Note that the condition $p_{aa}+ p_{ua} =1$ applies, so normalizing is required.

the radius as the DZ, the probability of accurate alarms decreases below 50%. Practically this means if the wind speed average is 60 km/h this means that an action which has a 5 minute long execution time is executed with a reason in every second case as per this worst case approximation.

Another important issue – which is not shown in Fig. 3.5 – is the influence of the thunderstorm radius. Larger thunderstorms cause unnecessary alarms less often, as the angle where the cloud gets into the DZ is bigger.

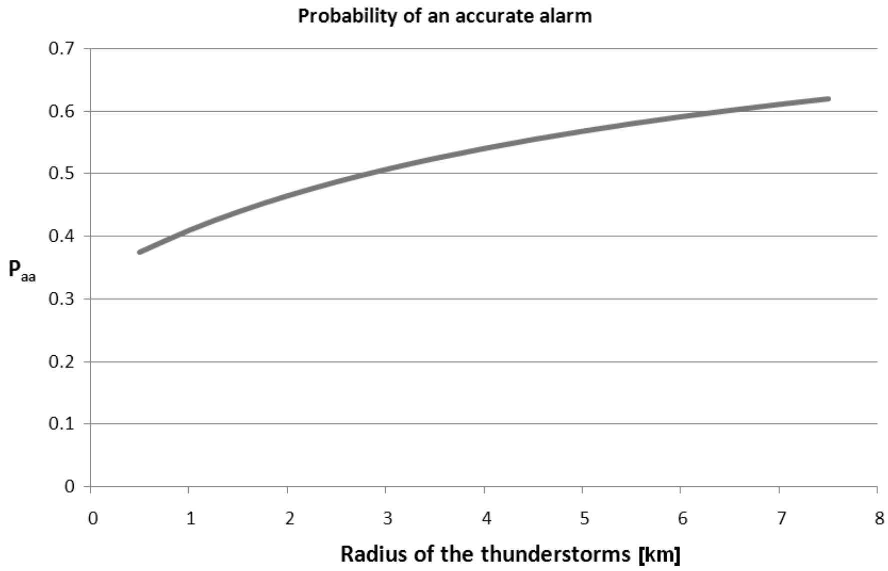

Figure 3.6.: Probability of accurate alarms vs. the radius of thunderstorm

To show the effect of thunderstorm radius the radius of the DZ is 2 km, and the radius of the WZ is fixed at the value of 4 km in Fig. 3.6. The thunderstorm cloud radius is shown from the values of 500 meters, to 7.5 km – nearly twice the size of the WZ. Through this interval the probability of accurate alarms is nearly doubled. Due to this strong influence, the applied thunderstorm radius has to be selected carefully (or multiple calculations should be carried out and weighting them in the end accordingly). The calculations are simple in case of circular DZ and WZ as it was shown in this example. More complex shapes however require more complex calculation methods. For example objects to be protected may be modelled by single lines, or multiple sections of lines. The calculations for these complex objects will be shown in the following.

Objects modelled with a single line

Several objects may be modelled with single lines, for example chemical pipelines, long radio antenna waveguides, long metal fences (where the distribution of lightning current may yield hazard), power lines [30], [37], [38] and sporting events such as rally tracks, or bicycle race sections in natural environment. The calculations of the probability of accurate alarms are much more complicated due to the geometry of the solution. The following results are for an object to be protected approximated with a simple line (it may be a single section of a power line with a substation terminating it at both ends [37]).

Results of these calculations show more interesting results than those of a simple circular arrangement. The radius of 10 km was used as a DZ and 1 km was used as a thunderstorm in all of the calculations.

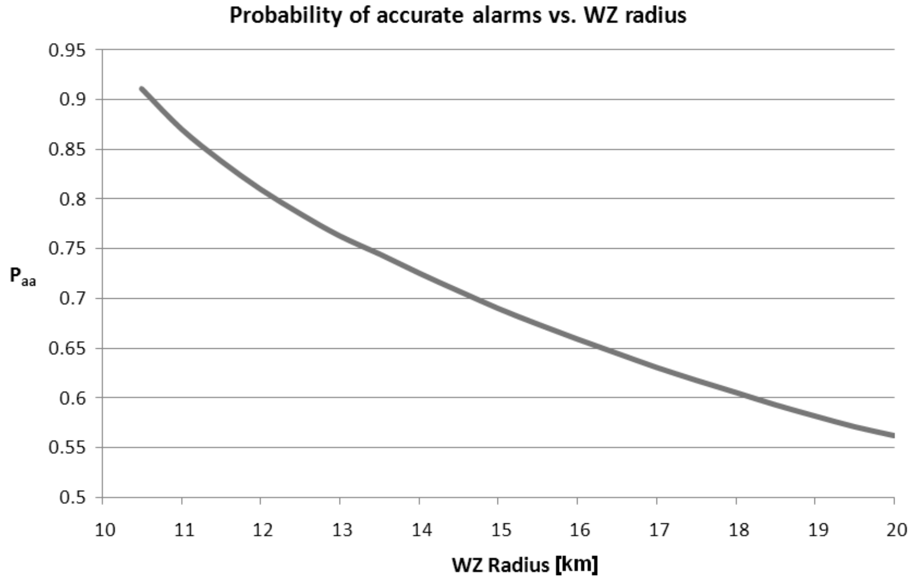

Figure 3.7.: Probability of accurate alarms vs. WZ radius.

The object (line) used in calculating the probabilities seen in Fig. 3.7 is 50 km long. An important result is that the probability of accurate alarms is considerably higher (more than 10 percent – comparing given WZ/DZ ratios) than in circular arrangements. Note that if the wind speed is taken as 60kmph and the execution of the preventive action takes 5 minutes then the probability of accurate alarms is nearly 70%.

In fact the longer the object, the higher the probability of accurate alarms. The same applies to the radius of the thunderstorm cloud as shown in Fig 3.8-9. Again a 5 minute long action is assumed, a DZ of 10 km and a WZ of 20 km is used.

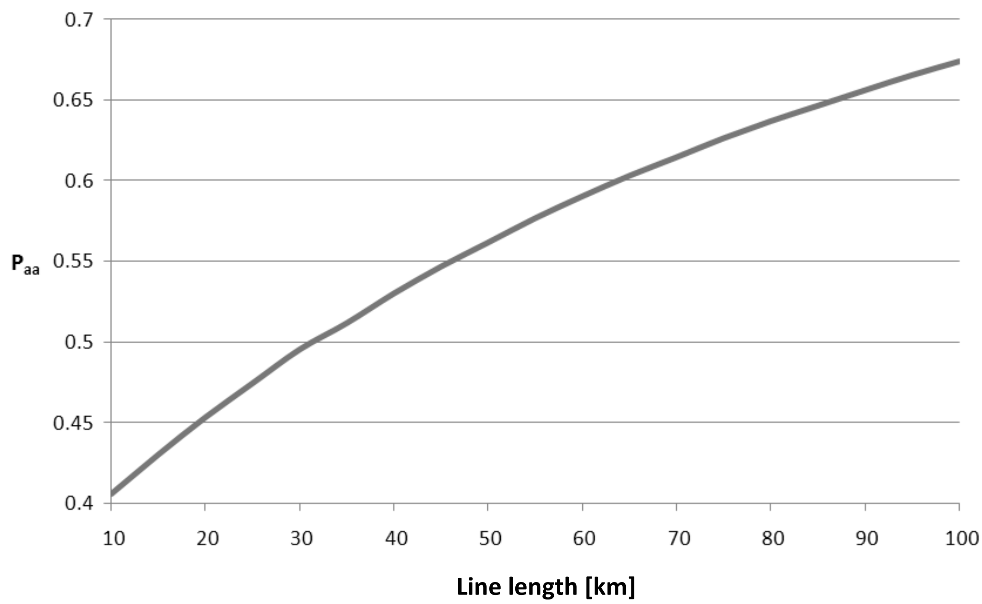

Figure 3.8.: Probability of accurate alarms vs. line length (km).

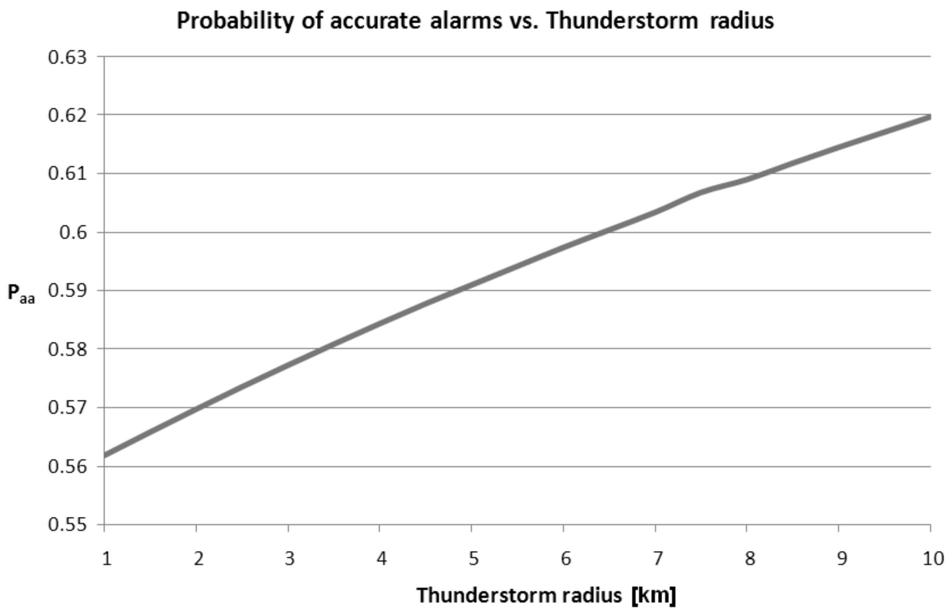

Figure 3.9.: Probability of accurate alarms vs. thunderstorm radius (km).

These figures show that efficiency is highest at longer lines and at large thunderstorm clouds due to the increasing probability of accurate alarms. We can summarize the effects of these factors when approximating the probabilities with linear functions. The approximations fit the data well (having a high R^2).

Table 3.3: Influence of different parameters on the probability of accurate alarms

Parameter (x_{eff})	Effect (*a [1/km]*)
WZ radius	-0.034
Line length	0.002
Thunderstorm radius	0.006

As Table 3.3 (the coefficients in the linear model) clearly shows, the WZ radius has the strongest effect on the efficiency in case of single lines. In circular arrangements, this effects is considerably smaller, below 0.01, the effect of thunderstorm radius is app. 0.006 per kilometre. Though smaller, the other factors have to be taken into account as well[17].

More complex geometries

In practice single lines may not be adequate to model objects. For example power lines may not be modelled by single sections in most of the cases, thus the complex arrangements have to be taken into account [30], [39]. The simplest case of multiple section power lines – or a power line with a curve – is the power line consisting of two sections [30]. Another good example for modelling objects to be protected with multiple sections of line is an exposed section of a rally track or bike competition.

[17] The effect is the increase in the probability of accurate alarms.

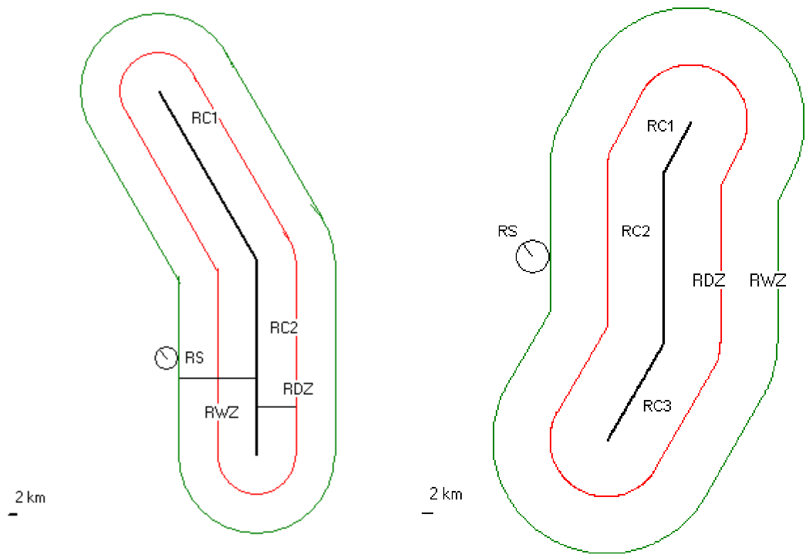

Figure 3.10: Complex geometries consisting of 2 and 3 sections

Figure 3.10 is an example of an object modelled with two straight sections of lines (left), and a longer one modelled with three straight sections (right). Appendix A1 deals with the analytical and numerical calculations of these solutions. Note that the analytic calculations are becoming more and more complex with the increase in the complexity of the arrangements, thus simulations provide an easier solution to determine the event space parameters. See appendix A1.1.3 for more detailed results on complex geometries.

3.2.2. The approximation of the probability of late alarms

During the calculations two very important assumptions are made, which have to be further investigated. The first such assumption is the wind speed uniformity. Of course when selecting a WZ radius, the assumed velocity of the thunderstorm cells has a strong effect on the protection. When the velocity of the thunderstorm cells is taken into account, then the protection is adequate only for thunderstorm cells moving with the velocity assumed, or slower than that. For these thunderstorm cells, the warning can be given in time. However for those moving faster than this assumed speed, we get late alarms[18].

In this section I assume that the lightning hazard develops, then I describe the conditional probability that a late alarm is given. If the velocity assumed is too low, then a higher probability of late alarms is experienced, but if a worst case approximation is used, an oversizing of the WZ can happen, thus cost effectiveness is reduced (more time was given to execute the preventive action), and the probability of unnecessary alarms also increases (but protection efficiency is improved).

The investigation of the effect of propagation velocity is important to see its contribution to the probability of late alarms. The probability that a thunderstorm cloud enters the WZ and then enters the DZ before the preventive action was executed (the WZ proved to be too small) is the integral of a part of the distribution function of the propagation velocity.

[18] Also note that thunderstorm cells may develop in the DZ or the WZ. For theoretical reasons, these cases are omitted in the calculations, but may be taken into account using empirical data.

$$p_{lava} = \int_{v_{crit}}^{\infty} p(v)dv \quad (3\text{-}12)$$

This gives the conditional probability of late alarms caused by the velocity assumption given that lightning hazard develops. The WZ radius has to be set to decrease (3-12) to an acceptable level.

If no cloud formation is expected inside the area of the WZ and the DZ, then (3-12) expression describes the probability of late alarms.

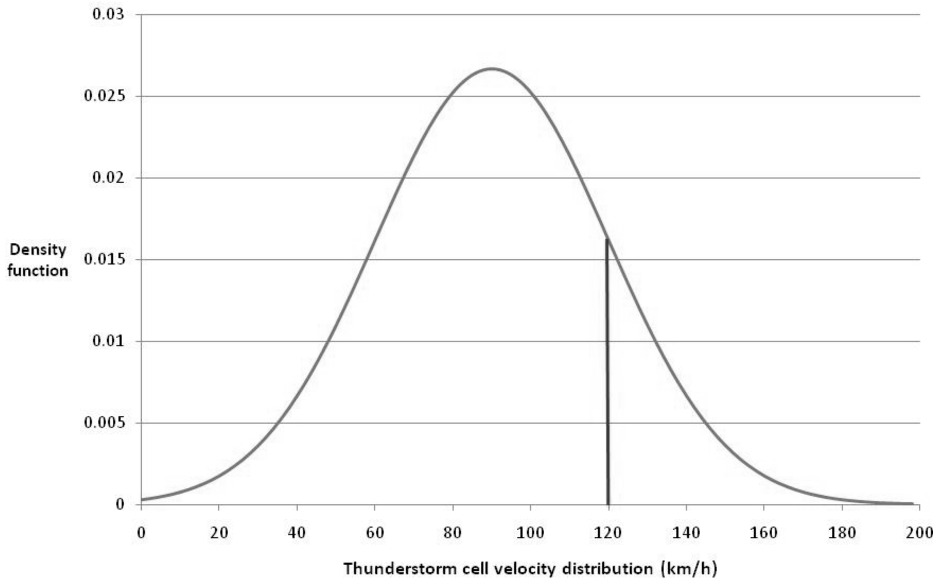

Figure 3.11: Example of possible propagation velocity distribution (density function of speed) [40]

An example is given in fig 3.11. for thunderstorm cell velocity distribution. In this example (normal distribution of wind speed with a mean of 90 km/h and variance of 30 km/h) if the WZ radius was set to a wind speed of 120 km/h (3-12) results in $p=0.15$ It means that 15% of the alarms will be late to some extent.

If we have information about the cloud formation inside the area of the WZ and DZ as well, then an approximation can be given on the probability of late alarms.

$$p(la \mid haz) = p_{dev} + p_{lava} = p_{dev} + \int_{v_{wind}}^{\infty} p(v)dv \quad (3\text{-}13)$$

In this expression p_{dev} denotes the probability of thunderstorm formation (or of a cloud becoming an active thunderstorm cell) inside the DZ. It is to be determined using empirical data. Practically this is the ratio (relative frequency) of the thunderstorms developing inside the DZ versus the total number of thunderstorms endangering the DZ.

The second assumption in these calculations is the fixed thunderstorm radius, and the approximation with a circle. Other approximation is also possible (ellipse, square) as thunderstorm cells have often different shapes than circles. The analytical calculation for these shapes yields very complicated results. In these cases simulation methods are to be applied. Also as (3-13) shows the probability of late alarm is mainly determined by the propagation velocity.

The approximation of the cloud shape influences only the probability of unnecessary alarms versus accurate alarms (cost efficiency), thus the protection efficiency **does not** decrease regardless of the shape assumed.

3.2.3. Calculation of the event space parameters including empirical data

As given in section 3.2.1, the following assumptions are made during the event space parameter calculations, which may be corrected by empirical data:

- Thunderstorm velocity distribution (approximated with one value)
- Thunderstorm approach distribution (flat distribution used)
- Thunderstorm propagation direction distribution (flat distribution used)
- Thunderstorm shape (circular is used in numerical calculations, elliptical could be used in simulations)

From these assumptions of course not all of them can be accounted for using empirical data. Thunderstorm shapes and sizes have a huge variation, sometimes only the upper and lower limits can be given to the size and shape, but not a really exact distribution. So total correction of this factor cannot be realized, an average shape and size should be used.

On the other assumptions however, empirical data can be used for correction. The easiest correction is made using the data from the velocity distribution. As shown earlier, data concerning the velocities is used to plan the WZ radius. In expression (3-12) it is shown that the thunderstorm cells moving faster than the velocity used in planning the WZ causes a late alarm. So practically with a density function of velocity available one only has to choose what probability of late and unnecessary alarm is acceptable.

The remaining assumptions play an important role in the probability calculation itself, as changing these assumptions would change the calculation method itself. For the sake of simplicity the use of data on the approach distribution is shown first, as that is merely an addition to the calculation.

Introduction of the approach distribution into the calculations

The 'approach distribution' is a continuous probability variable defined at each points of the WZ. It describes the probability that a thunderstorm cell enters the WZ at a given point. In numerical calculations, where discrete functions are used it shows the probability that the thunderstorm cell touches the WZ at a given point. I assume in the calculations of the probabilities of an accurate or unnecessary alarm that the alarm was given.

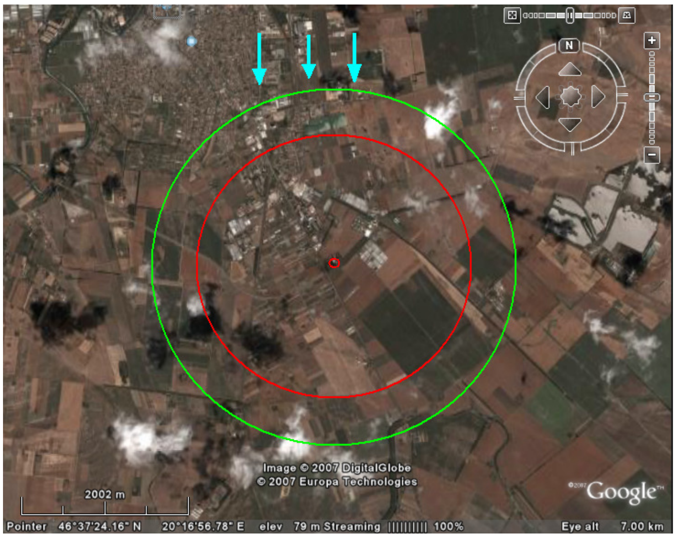

Figure 3.12.: The TV tower at Szentes with appropriate DZ and WZ for maintenance work

In Figure 3.12 an antenna tower is shown with the appropriate DZ and WZ[19]. The blue arrows in the figure show the directions where most thunderstorm cells arrive. This is related to the wind directions over this given area. In this example I assume the presence mainly of northern wind. In this case the approach distribution (further on denoted as $p_w(z)$) is approximated with the following function.

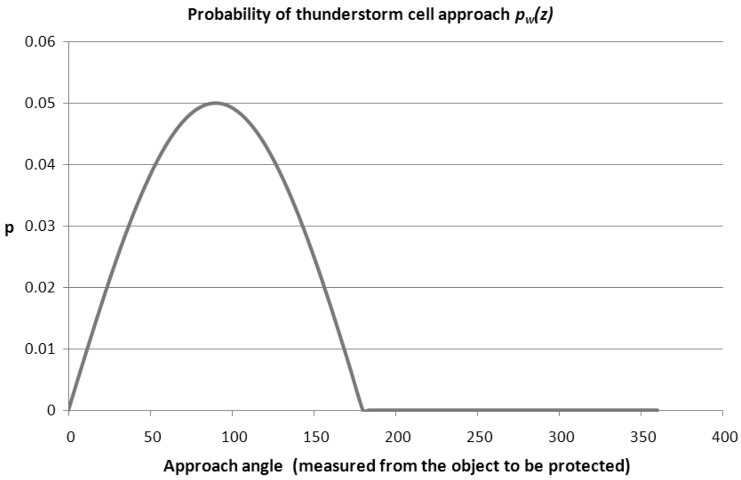

Figure 3.13.: The approach distribution density function (example)

In Figure 3.13 the x axis denotes the angle of point *z* on the WZ, 0 denotes the westmost point of the WZ. In an area where thunderstorms can propagate and form in any direction, the wind distribution is appropriate information to approximate the thunderstorm cell approach densities.

Using this data, the probability of accurate and unnecessary alarms can be described by weighting the probabilities at a given point of the border of the WZ by the probability a thunderstorm cell arrives at that point. This yields the following formula.

[19] I assumed a simple maintenance work and assumed a DZ of 2 km (it is the standard safety distance), and a WZ of around 2,5 km. This means that the workers have 30 seconds to suspend work assuming a thunderstorm cell velocity of 60 km/h. Tower height is 90m.

$$p_{aatot} = \oint p_{aa}(z) * p_W(z) dz \qquad (3\text{-}14)$$

The formula means that the probability of accurate alarms is described by weighting the probability of accurate alarms at the points of the border of the WZ by the distribution of the approach of the thunderstorm cells[20].

The integral practically gives a weighted average of the values, where the probabilities calculated with the method introduced in section 3.2.1, and are weighted with their occurrence probability. It is simpler to calculate this formula numerically. In this case the following formula is to be used.

$$p_{aatot} = \sum_{n} p_{aa}(z) * p_W(z) \qquad (3\text{-}15)$$

The formula means practically the same as (3-14) with the small exception that the sum is to be taken for *n* points. These points are the points the border of the WZ is divided into. The distances of the points should be equal to provide an accurate, yet simple calculation.

Introduction of the propagation direction distribution into the calculations

The propagation direction distribution is a probability function which represents the distribution of the thunderstorm cell propagation direction. In calculation terms it represents α in the range of α' when calculating (3-12). In the calculation of accurate alarms and unnecessary alarms this gives the angles approaching at which the thunderstorm cell could have triggered the alarm. Its range is between 0º-180º.

If some meteorological data is available concerning the distribution of this angle[21], then much better results can be obtained from the calculations. In the theoretical calculations flat distribution is assumed for this propagation angle (practically the direction), thus it was possible to approximate it with a geometrical probability calculation. With data available on the distribution, a function describing the accuracy of the alarm versus the propagation direction – denoted as $a(\alpha,z)$ – is to be calculated first[22].

Taking the example shown in fig. 3.12 with a WZ radius of 4.5 km, a DZ radius of 2 km, and a thunderstorm radius of 1 km, this function is the following for each points of z (as it has a circular shape). Here I assumed that the alarm is given in time.

---

[20] Note that the propagation direction of the thunderstorm cell after entering the WZ is still approximated with a flat distribution.

[21] It may be related to the approach direction distribution as well.

[22] $a(\alpha, z) = \begin{cases} 1 \text{ when } \alpha \text{ corresponds to accurate alarm} \\ 0 \text{ when } \alpha \text{ corresponds to unnecessary alarm} \end{cases}$

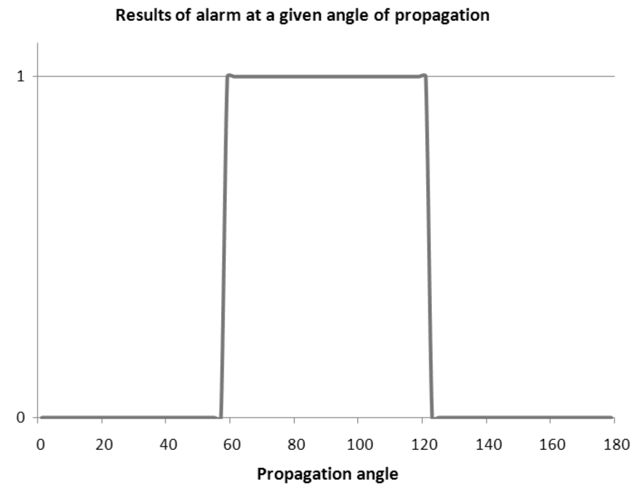

Figure 3.14.: Conditions for giving an alarm vs. propagation angle of a cell at a given point of the WZ

In this example the *α* where the alarm is first accurate is 59º, thus from that value $a(\alpha,z)$ has a value of 1, until the angle 180º-59º, after which direction alarms are unnecessary again, thus the values are 0 again. In circular arrangement of course this function is the same for all points of *z*. The purpose of simulations in these calculations is to determine $a(\alpha,z)$.

More complex DZ-WZ arrangements are significantly harder to calculate as $a(\alpha,z)$ is different at the points of the WZ. The calculations for both circular arrangements and objects modelled with single or multiple line sections are found in Appendix A1.

When this function is calculated, the probability of accurate and unnecessary alarms is to be calculated (still assuming that the alarm was given).

$$p_{aa}(z) = a(\alpha, z)\, p_{\alpha}(z) \quad (3\text{-}16)$$

$$p_{ua}(z) = \left(1 - a(\alpha, z)\right) p_{\alpha}(z) \quad (3\text{-}17)$$

$$p_{aatot} = \oint p_{aa}(z)\, p_W(z)\, dz = \oint \left(\int a(\alpha, z)\, p_{\alpha}(z)\, d\alpha \right) p_W(z)\, dz \quad (3\text{-}18)$$

The calculation method of (3-18) is the same as of the theoretical calculation (3-14). Applying (3-14) the probability of both accurate and unnecessary alarms is to be calculated at each points of *z*, the border of the WZ using (3-16 – 3-17). All of these functions are based on empirical data to obtain the best approximation for these parameters of the event space.

3.2.4. Summary of the probability calculations of the event space

As it was shown in Section 3.2 the calculation of the event space parameters is possible using theoretical considerations only, even though it's much less accurate and it can only be used as a comparison between different zonal protection solutions. A very important parameter however – the probability of late alarms – cannot be calculated using theories only. Thus when absolutely no empirical data is available, a test period has to be ran, or empirical data from other, similar areas has to be taken as a start, and regular re-evaluation of the solution is required.

To obtain a simple model of event space parameters, the following assumptions are made:

- Flat distribution of thunderstorm approach (at the points of the border of the WZ)
- Flat distribution of thunderstorm cell propagation directions
- A constant value of propagation velocity

The result of these assumptions is a simple model for the probability of accurate and unnecessary alarms.

$$p_{aa}(z) = p(\alpha(z) < \alpha_{\lim}(z)) = \frac{\alpha_{\lim}(z)}{\alpha'(z)} \tag{3-12}$$

With simple analytic methods (3-12) results in easily obtainable values, suitable for comparison purposes, or worst case approximations. Using empirical data these assumptions may be abandoned to obtain more accurate values. The only assumption which is to be kept is the constancy of propagation speed. The resulting formula is more complex, but the results are more accurate. They're capable not only for comparison, but also for an apriori approximation regarding the realized zonal protection.

$$p_{aatot} = \oint p_{aa}(z) p_W(z) dz = \oint \left(\int a(\alpha, z) p_\alpha(z) d\alpha \right) p_W(z) dz \tag{3-18}$$

Note that this calculation method yields values for an event space shrunk to accurate and unnecessary alarms only.

$$p_{aa} + p_{ua} = 1 \tag{3-9}$$

The event space also includes the probability of late alarms, which is calculated by taking the thunderstorms developing in the DZ and those propagating faster than which the WZ was planned for into account.

$$p(la \mid haz) = p_{dev} + p_{lava} = p_{dev} + \int_{v_{wind}}^{\infty} p(v) dv \tag{3-13}$$

The result of (3-13) is also a part of a shrunk event space taking into account the thunderstorms causing a hazard. To include all the probabilities in a combined event space they have to normalized, which results in (3-19).

$$p^*_{aa} = \frac{p_{aa}}{p_{aa} + p_{ua} + p_{la}}$$
$$p^*_{ua} = \frac{p_{ua}}{p_{aa} + p_{ua} + p_{la}} \tag{3-19}$$
$$p^*_{la} = \frac{p_{la}}{p_{aa} + p_{ua} + p_{la}}$$

The planned zonal protection is fully described by these probabilities. Both cost effectiveness and protection efficiency may be used to describe the realized solution. Note that in the evaluation periods (3-19) – and the according calculations – is to be recalculated both theoretically and empirically.

As this section shows the application of the WZ is a quite simple method of applying the conjunction of forecasting and preventive actions in lightning protection. However since the WZ is statically assigned, late alarms may occur. Also since the propagation direction and velocity is only a probability variable, cost efficiency may not be adequate. The advantage of this method is its simplicity. Only low resources are to be spent on forecasting and the alarming requirements are quite simple making ZPLP a cheaper, easily applicable method of preventive lightning protection.

3.2.5. Comparison with other approaches in the use of preventive measures in lightning protection

The use of preventive measures in the protection against lightning damage is not a novel approach. Watching for the strikes and listening to the roar of the thunder was used even centuries back, as it is currently used in Hungary in power line maintenance. This 'method' was based on the fear and amazement what surrounded the lightning as a natural phenomenon, not on the well-planned conscious use of preventive actions in conjunction with forecasting.

Practical uses including the use of technical equipment as a source of warning were documented in the last millennia [41], [42]. At that time of course lightning detection systems were not that accurate as those available nowadays. Also on different fields, easy principles were worked out to apply preventive actions – for example the 30-30 rule (of thumb) applicable for humans [43].

The first approach to use the available lightning detection systems as a tool for warning with a developed framework was presented in [44-46]. These frameworks were describing the use of forecasting as a warning tool for various applications. The framework was denoted as 'active lightning protection', which applies 'protective actions' as a method of protection.

This framework approached lightning protection from the side of forecasting, which is not adequate, since the tool of the protection is not the forecasting, but the actions themselves. Also the authors did not give adequate definitions neither to the method, nor the action. The definition for the 'active lightning protection' given in [46] is the following: '…Active protection involves the detection of the threat of overhead and/or nearby thunderstorms, coupled with a means to initiate various protective actions manually or automatically […].' (pp. 1)

This definition lacks the proper description of the 'protective actions' involved in the process and emphasizes the forecasting as a major issue of this method, but neglecting the importance and operation of the 'protective' actions.

Since the authors were analyzing this method on the forecasting side, they arrived at a conclusion of using certain zones as the method of forecasting in [17], [46]. The zone defined around the object to be protected was the 'Area-of-concern' (AOC) in that framework, also the area surrounding it was denoted as 'Warning Area' (WA). The definition of these areas found in [17] is the following: 'A particular location where warning information is needed is referred to as a Point of Interest, and that location is surrounded by an inner region that we call the Area of Concern (AOC). The AOC is then surrounded by a second region that we refer to as the Warning Area (WA). The WA is so named because the occurrence of CG flashes within the WA is used to provide the advance notice, or warning, of the possibility of CG lightning within the AOC.' (pp 3).

On the application side these definitions are not practical. It completely omits the definitions used in the international standards ('object to be protected') and aims at a point specific solution. For example in the case of objects covering large areas (power lines, football stadium, car race circuit, airport etc.) these definitions are not ambiguous.

Also on the theoretical side, the lack of CG lightning in the WA does not render CG strikes in the AOC impossible, so using such warning may lead to endangering the object to be protected.

Using these zones the measures for the evaluation of the protection (more likely the forecasting efficiency) were the quantities of 'probability of detection' (POD), 'failure to warn' (FTW), 'false alarm rate' (FAR). Their definitions were also found in [46] (also found later in [47]) is the following: 'We can look at the probability of having a specific amount of lead time, say 10 minutes, or the probability of having at least 10 minutes of lead time. The latter is what we are concerned with in this paper, and we define this as the Probability of detection (POD). While it is desirable to have lightning in the warning region always precede lightning in the AOC, this is not always the case in practice. Occasionally a storm develops directly overhead within the AOC or at least does not produce its first lightning until it reaches the AOC. Because these cases do not produce advance warning as defined by lightning in the warning region, they are referred to as Failure-to-Warn (FTW). Their probability is related to the POD, as we demonstrate in later sections of this report. In addition, some storms produce lightning in the warning region without ever reaching the AOC. From the statistical point of view, these storms are known as false alarms and their probability of occurrence is called the False Alarm Rate (FAR).' (pp. 3 in [46]).

These values are relative frequencies rather than probabilities, but of course given enough data they may be used to approximate probabilities – also 'probability' and 'rate' are used inconsequentially. They describe the application of a 10 minute warning. In the measures presented by this definition the notion of 'lightning hazard' is not defined as a possibility of CG strike to the object to be protected, but to actual CG activity in the AOC. From the protection point of view this means higher risk of damage, since the warning is only given when CG activity is observed, thus the active thunderstorm cells which have strong CC activity, but no CG activity yet, endanger the object to be protected when this warning method is used.

Also the notions to describe the events reflect that. 'False alarms' are the cases when the thunderstorm cell passing through the AOC does not produce a CG lightning (anymore). This does not mean that the alarm was false, since a thunderstorm cell is rendered to be inactive once the CC activity diminishes. So when such a cell passes through the AOC, the object to be protected is still endangered, so the alarm was not false at all!

The 'Failure to warn' in this case is only accurate when neglecting the operation of the actions following the warning. If the thunderstorm cell is already in the AOC when it produces its first CG strike, then it really is a failure to warn, but the authors do not emphasize the difference between different ‘failures’ (when the alarm is given when the CG strike is still 5 minutes away, or it is only 50 sec away). On the protection side this has to be cleared, but since this approach concentrates on the forecasting and does not take the parameters of the actions into account, it is incapable to consider these differences.

Differences in the approaches

Taking into account each of these inaccuracies of this approach, the framework of preventive lightning protection uses totally different notations and notions. The method of protection is the application of preventive actions – similar to the ‘protective actions’, but clearly defined –, but the emphasis is on the conscious use of forecasting and the preventive action. It’s crucial to forecast the warning according to the time requirements of the preventive action (10 minutes is sometimes too long – increases the costs of the protection – and is sometimes too short – decreases protection efficiency).

The ‘lightning hazard’ in preventive lightning protection means the possibility of damage to the object to be protected due to lightning strike. As shown in the previous section this includes both primary and secondary damages. *Lightning hazard* exists when an active thunderstorm is inside the DZ – no CG flash is required, CC and IC activity already signals the presence of an active thunderstorm cell.

The zones of protection – DZ and WZ shown in the last section – are also different from the AOC and WA. The DZ is different as it can be of any shape, may surround any area, and the notion of ‘endangerment’ is also different as described above. The WZ is also substantially different from the WA, as its function is to trigger alarms when active thunderstorm cells are entering it – again, no CG flashes are required. Also unlike in the definition of the WA – lacking the size requirements –, the size of the WZ depends not only on the forecasting method, but mostly on the time requirements of the preventive actions. Thus the preventive lightning protection integrates the preventive action properties as well.

The event space of preventive lightning protection also differs from the framework presented in [44-47]. The POD presented therein corresponds to the sum of the accurate and late alarms according to the event space. However it has the limitation of the given time requirements (10 minutes) and also only refers to CG activity. FAR is similar to the unnecessary alarms, but as described above the meaning differs significantly. Unnecessary alarms are produced if an alarm is given, but later on the thunderstorm cell does not enter the DZ. Once an active thunderstorm cell enters the DZ, the alarm is not to be classified unnecessary or even false even if no CG flash occurs. Late alarms may occur more frequently than FTW-s, since these alarms also occur in the case of CC activity as well.

Also in publications following the first appearance of the description of the event space of PLP [25], [37] (2007) the ‘successful warning’ (SUC) [47] (first mentioned in 2008) then later on ‘effective alarm’ (EA) [14] (2009) were introduced – both being similar to the notion of the accurate alarm – with the following definition: ‘…(1) the number of warning episodes having at least one CG flash in the AOC, (2) the number of episodes in (1) that were successful (see previous paragraph), and (3) the number of false alarm warning episodes (see previous paragraph). If we give these three quantities the names 'CGAOC', 'SUC', and 'FA',…' (definition of SUC in [47], pp. 4.) and '…Effective alarm (EA) is a warning that was previously triggered before a CG flash in the AOC;' (definition of EA in [14] pp. 508). Both of these definitions are somewhat similar to the accurate alarms, excluding the notion of endangerment. In the event space of preventive lightning protection, an alarm is classified accurate, when the active thunderstorm cell enters the DZ after the alarm was given. This includes cells producing CC and IC activity, not necessary CG activity.

One of the main differences between the measures used by other authors and those in preventive lightning protection is the notion of lightning hazard. While preventive lightning protection uses a theoretical definition, the other approaches use a practical, but not thorough (in terms of protection efficiency) definition.

Due to this discrepancy between the two approaches the different notations are kept and the calculations are made using these notations. Note however that the calculations found in this thesis can be realized for the framework presented by the other authors, but are not meant to, as the underlying theories differ significantly.

3.3. High reliability preventive lightning protection

In the previous part of this section I have shown that preventive lightning protection using the DZ and a constant WZ (ZPLP) can be realized and evaluated using the event space approach. If more detailed meteorological and lightning information (VHF, LF) is available then a solution with much higher reliability can be realized, though its cost may be considerably higher. I denote this method further on as High Reliability Preventive Lightning Protection (HRPLP) [18].

A serious problem in zonal preventive lightning protection is that it does not handle each thunderstorm separately when carrying out the preventive measures. It uses only a static WZ which may be good for one case, but may cause for example early reaction (extra cost) at thunderstorm cells with low propagation velocities, or a late alarm, decreasing cost effectiveness and protection efficiency.

In high reliability preventive lightning protection the concept of a WZ is entirely omitted, because this method concentrates on forecasting the hazard for individual thunderstorm cells. The concept of a DZ is still used in this solution of course. An area around the object to be protected is observed constantly and thunderstorm cells entering it or forming inside are monitored. The size of this area is practically chosen to be able to provide alarm for the fastest thunderstorm cells as well.

$$r_{obs} = r_{DZ} + \left(t_{act} + t_{samp}\right)v_{storm\max} \qquad (3\text{-}20)$$

For example with a DZ=5 km, t_{samp}=10sec t_{act}=5min, $v_{stormmax}$=200km/h the area to be observed has a radius of 22.2 km. The larger the area to observe, the larger costs it yields, since real-time observations are required.

In high reliability preventive lightning protection the thunderstorm cells are monitored individually, and the following information is gathered.

- Distance from the DZ
- Propagation direction
- Propagation velocity
- Size and shape

The last three properties of the thunderstorm clouds were approximated in ZPLP using empirical data. In this solution however these properties are constantly monitored and the preventive action is only carried out, when these properties fulfil the following criterions.

- The thunderstorm cell's path leads into the DZ
- The thunderstorm cell is close enough to the DZ

The first criterion is denoted as the direction criterion further on and the second as the distance criterion. Both of these criterions can be checked using the data from meteorological radar system and lightning detection networks [18].

The calculation of the direction criterion is the same calculation which is done during the simulations in the event space parameters in preventive lightning protection. A significant difference in this case is that a direction angle is given based on earlier observations (explained later). When this criterion is fulfilled, the distance criterion is to be calculated. Its calculation is the same as of the WZ radius except for that the thunderstorm speed is not an approximation of the average, but is calculated based on the observations.

The distance criterion for the alarm is the so called 'critical distance'. If the thunderstorm cloud gets closer to the DZ than the critical distance – and the direction criterion is also fulfilled –, then the preventive action is to be carried out immediately.

$$d_{crit} = r_{DZ} + \left(t_{act} + t_{samp}\right)v_{storm} \tag{3-21}$$

As seen in the expression the critical distance depends on the speed of the individual thunderstorm cell. The execution time of the preventive action and the sampling period is also to be taken into account to avoid late alarms[23]. This may be interpreted as a 'changing WZ', but this notion is wrong in the meaning that the WZ applies for all of the thunderstorm cells, while the critical distance is unique for each one.

[23] Note that (3-21) will be further refined in section 3.8 incorporating the inaccuracy of the thunderstorm cell location.

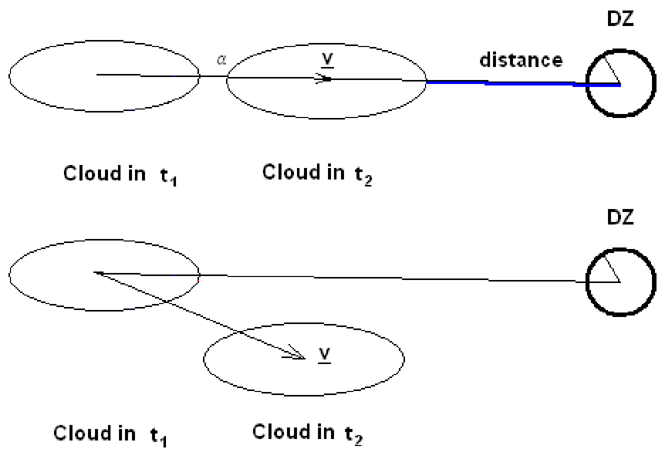

Figure 3.15.: The operation of high reliability preventive lightning protection [18]

In Figure 3.15 two cases are shown. The first case is when the thunderstorm cell is heading towards the DZ, and approaches it. The shape of the cell in this figure is an ellipsoid for the sake of simplicity. The distance criterion has to be calculated in this case using (3-21), and the execution of the preventive action is decided. The second case is when the direction criterion is not fulfilled, thus no action shall be taken.

A practical way of making these calculations is calculating the speed vector (v) of the thunderstorm cloud based on observations made in t_1 and t_2 (the difference is the sampling period) and making an extrapolation using that vector. If the vector placed anywhere on the perimeter of the thunderstorm cloud crosses the DZ after the extrapolation, then the direction criterion is fulfilled (and the alarm is to be given if the distance criterion is also fulfilled).

This can also be described (shown in Figure 3.16) as v having a given α angle – the direction angle – according to the line connecting the DZ and the thunderstorm cloud and based on the thunderstorm size, its limits, α_{lim1-2} can be calculated. (This concept is similar to the efficiency calculation of ZPLP.)

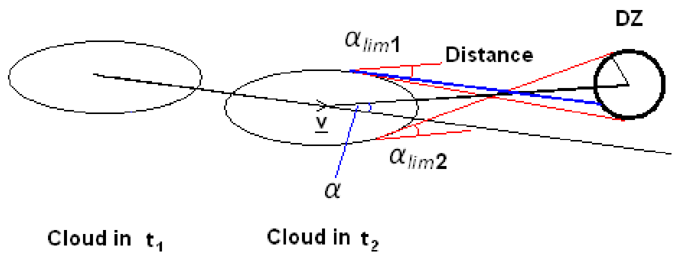

Figure 3.16.: Determining α_{lim1-2}, and the direction criterion [18]

If $\alpha < \alpha_{lim}$ (of course taking the appropriate limit), then the direction criterion is fulfilled, and the distance criterion is to be checked. In Figure 3.16 an example is given to determine the limit values. Two limit angles are defined, corresponding to a worst case scenario of propagation. In the case shown, according to the direction of v, α_{lim1} is the limit value to be taken into the calculation. In the example, the angle α is smaller than α_{lim1}, thus the distance criterion is to be calculated. Note, that the 'distance' taken into account in this case is the distance shown in Figure 3.16, the shortest distance in the path of the thundercloud, using the direction of v. In Figure 3.16 the line the distance is measured on is parallel to v.

In practice, the distance criterion should be calculated at each point of the thunderstorm cell, but the calculation requirement is reduced when only the points on the perimeter of the cloud are taken into account. If the distance criterion is fulfilled at any of those points, the alarm is to be given.

Of course thunderstorm clouds have various shapes and this method in this simple form covers only those which can be approximated with an elliptical or circular shape (the clouds approximated with circles can be taken into account easier, by extending the DZ, just as shown in the accuracy calculations of ZPLP). Approximating thunderstorms with these shapes is practical and fronts are easier to model with elliptic shapes. For the theoretical calculations the circular model is discussed in details. Just as in case of ZPLP the elliptical shapes may be used in simulations though, or real-time distance and direction calculations.

Modelling clouds for the calculations – the circular cloud model

In ZPLP the cloud was usually modelled with a circle. At that section this didn't require too much explanation, since the calculations were always based on existing data, so an approximation can be given. But in the real time application of HRPLP it's necessary to calculate the parameters of the event space (shown in the next section) in every sampling period. The basic idea of the calculations is the circular cloud model. The circular cloud model is a very simple model. More sophisticated models may be applied to fronts (for example elliptic shapes), but their discussion is not in the scope of this thesis. The aim here is to demonstrate a simple realisation of HRPLP, so the circular cloud model's simplicity makes it ideal for this purpose.

The circular cloud model means approximating an active thunderstorm cell with one or more circles. The circles are determined to fill the area of the thunderstorm cloud, thus the most area of the active thunderstorm cell is accounted for in the event space calculations.

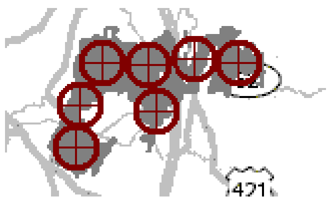

Figure 3.17.: A thunderstorm cell approximated with circles

In Figure 3.17 a thunderstorm cell is shown, which was taken from a meteorological radar system. As shown, a part of the thunderstorm is not covered by the circles. 'Circle packing' is a problem discussed from numerous aspects in mathematics. Good analytical solutions were given for filling circular [48] and rectangular [49] containers. Thunderstorm clouds are nor circular nor rectangular, so universal algorithms may be used [50]. Further review of circle packing is not in the scope of this thesis.

A practical approach may be to use circles with equal radius to represent the cloud, so this is assumed in the rest of this thesis. This simplifies both theoretical and simulation approaches considerably simpler.

In each sampling period the circular cloud model shall be created for the thunderstorm cell. Each circle represents a part of the active cells, so it's crucial to have circles which can be followed in time. The guidelines for the circular model are the following:

- the number of circles shall be kept constant
- the circular model creation shall create circles which cover most of the area of the thunderstorm cell
- circles may be removed from the model creation, when the cloud shapes change
- new circles shall be added, when the cloud shapes change

In Appendix A2 a theoretical case study shows the operation of HRPLP and the application of the circular cloud model. Using circles with the same radius yields a non-optimal cloud model. Still the results in the case study show that the efficiency is adequate.

Using a circular cloud model to describe cloud propagation

The simplicity of the circular cloud model is further emphasized, when the algorithms for HRPLP are considered. The circle is a symmetric shape, so modelling a cloud with circles eliminates several problems, like the 'direction' of an individual circles, and thus eases velocity calculations as well. When using the circular cloud model on a thunderstorm cell, the steps of the model formation are the following:

- determining the first circle
- attaching following circles
- when the covered area reaches a certain ratio, stop the process

There are several approaches in realizing these steps. The first step – determining the first circle – can be done either by progressing from one direction to another, or by calculating the biggest circle (if the cloud is modelled with circles of various sizes). The latter solution may lead to more complicated steps in the upcoming sampling times, while the former may lead to less optimal solutions.

Such modelling is used in geography – the circle tree [51]– but that solution does not consider time, and the change of an object, which was covered with circles. The circle tree gives an optimal solution for a steady object and thus it's a good method for model formulation. In HRPLP it's necessary to define circles, which can be 'found' in the next sampling time.

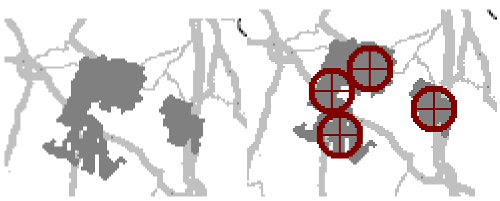

Figure 3.18.: Creating the circular model (simplified) for a cloud

Figure 3.18 shows a simplified circular model for a cloud. This model includes only circles with a fixed radius, so it's not an optimal solution, but it's easy to follow. The theoretical case study described in Appendix A2 shows the progression of a cloud and the application of such a simplified circular cloud model. In this model the N-S direction was chosen as the direction to assign the circles of the model. The northest circle was first placed, then the other two. The separate cloud was modelled with one individual circle.

With the progression of time, the shapes of the clouds change. The circular cloud model shall follow this change by adding more circles to the circular cloud model. Also the motion of the cloud shall be calculated by the change of the position of the circles in the circular cloud model.

Figure 3.19.: Creating the circular model (simplified) for a cloud

In Figure 3.19 the propagation of the cloud is shown, 5 minutes later than in Figure 3.18. The cell has grown, and a new part of it is forming. As seen in the figure, a new circle has been added to the model, to match the cloud motion. The cloud consisting of 3 circles remained almost the same in size, but it is moving northwards, as shown by the model.

To use this model in HRPLP, these circles are to be used to calculate the event space in each sampling time.

3.3.1. The notion and use of the event space in HRPLP

When making the decision of alarming also the event space is used. The causes of the events – and thus their probabilities – differ in some cases. A major difference is that in case of HRPLP the parameters of the event space are not universal as in the case of ZPLP. Since the alarming decision is based on multiple changing criteria in HRPLP calculating a universal event space would not yield useful results.

The approximation of such a solution based only on theories does not take into account neither the change of wind speeds and directions nor the constant availability of information.

The biggest advantage of HRPLP is that it handles thunderstorm cells uniquely, thus the event space is to be calculated for each thunderstorm cell, in each sampling period[24]. When giving an alarm the parameters of the event space – thus the probability of the upcoming event – are to be calculated.

In this event space there are no such events as no alarms, because there is no exact WZ. In preventive lightning protection this event was only added to make a coherent event space. The other important difference is the cause of unnecessary alarms.

In HRPLP unnecessary alarms occur when the thunderstorm cell changes it's heading while the preventive action is already being executed, or there's inaccuracy in the data

[24] Sampling period means the time when a sample is taken regarding the position of the thunderstorm cell. It can be either a meteorological radar picture, or data from a lightning detection network.

provided by the monitoring system. This inaccuracy is low, because the combined use of meteorological and VHF data gives detailed information [52], [53]. Due to that the no alarm event is entirely omitted (as seen in table 3.4).

Table 3.4.: Event space of HRPLP

	Alarm was given in time	Alarm wasn't given in time
Thunderstorm cell endangers the object to be protected	Accurate alarm - p_{aa}	Late alarm (increased cell speed) - p_{la}
Thunderstorm cell does not endanger the object to be protected	Unnecessary alarm (inaccuracy in data) - p_{ua}	-

The values and theoretical calculations given in table 3.4 are the approximations for the outcomes of individual alarming decisions. They highly depend on the accuracy of the lightning detection system. A simulation on the effect of the accuracy in HRPLP is shown in appendix A2, its use to calculate the event space is shown in the upcoming sections. The probabilities are to be calculated each time when the vector $\underline{v}$ is calculated and the decision of taking an action based on these calculations is to be reconsidered in each sampling period.

During planning though approximations are to be given about the solution to realize. The most practical way is to calculate an event space consisting of relative frequencies of events rather than probabilities. Of course such an event space can be calculated also upon planning to give an approximation on the performance of the solution. The next section shows how such an event space is to be calculated, as a first step in realizing the solution, and introduces the method to take into account the inaccuracies of the lightning detection systems during the calculation of the event space for the individual alarming decisions.

Calculations of the event space using existing empirical data for performance analysis

As mentioned before, the calculations of the performance of the system upon planning are done by using the existing empirical data. The empirical data is the CG lightning strike locations, VHF discharge location data recorded by the lightning detection network, and meteorological radar information if available.

Using the DZ calculated in the planning period theoretical 'test runs' can be done. Each of these test runs result in an event described in the event space (accurate, unnecessary or late alarm). In the end relative frequencies are available describing the event space. Of course the more data available for this approximation, the more accurate it gets.

$$p_{ua} = \frac{N_{ua}}{N_{total}} \tag{3-22}$$

This expression is just an example of the calculations, it shows that the probability of unnecessary alarms is approximated by the relative frequency of the unnecessary alarms during the test runs.

The test runs are mainly making decisions on alarming for the thunderstorm cells in the existing data using the rules of alarming in HRPLP. Thunderstorm cells closing in on the DZ are selected from the existing data and its propagation is analyzed. In each chosen sampling period an alarming decision is made and in the end, the occurring event is recorded (accurate, unnecessary or late alarm). Making such analysis on many thunderstorm cells results in each of the events having several occurrences and from this data the event space parameters can be approximated with the relative frequencies describing the performance of a HRPLP solution.

Elements of the event space in individual alarming decisions

The probabilities of the event space in this case require different calculations than in the case of ordinary preventive lightning protection. During the alarming decisions the upcoming events are considered: accurate alarm, unnecessary alarm, late alarm.

The inaccuracies may cause either of these cases. In most of the cases the alarming decision is quite clear, as the event space is dominated by only one of these events – depending on the propagation direction fulfilling the direction criterion. Mostly it's not difficult to decide if a given alarm would be accurate or unnecessary.

Late alarms are produced the same way as in ZPLP, except for that in HRPLP the increase of propagation speed may also cause them (there's no assumption regarding constant propagation direction). If the thunderstorm cell's propagation satisfies the direction criterion and the cell is closer than the critical distance, then a late alarm may be produced (provided that the propagation velocity does not decrease).

The decision regarding the alarm is made using the circular model and evaluating the event space for each of the circles forming the thunderstorm cell (fig. 3.19 shows such a cell). The alarming has to be decided using the event space parameters in a given sampling period and the preceding values. Inconsistent event space parameters may be caused by changes in the propagation direction of the cell. If the event space parameters predict accurate alarms constantly – the direction criterion is constantly fulfilled –, then the alarm is to be given

Unnecessary and late alarms due to inaccuracies

The probability of unnecessary alarms is related to the accuracy of the system. When considering the appropriate DZ area, the inaccuracy is to be considered as well (a bigger DZ is to be chosen) to maximize protection efficiency, but this also increases the number of unnecessary alarms (thus decreases cost efficiency).

The probability of unnecessary alarms is the probability that the alarm is triggered, while the direction criterion is miscalculated due to accuracy problems or changes in the propagation direction. The direction criterion is miscalculated when after a given position another position of the thunderstorm cell is calculated using inaccurate data.

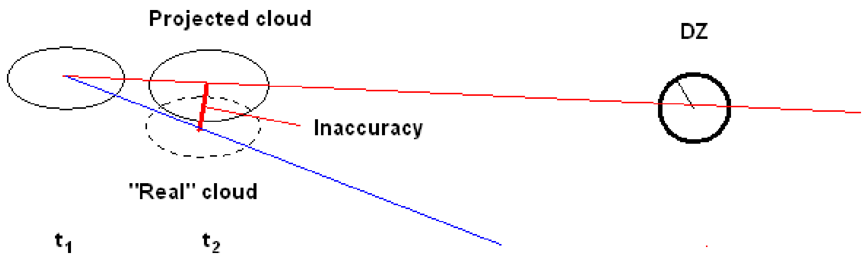

Figure 3.20.: Miscalculation of the direction criterion due to inaccuracy [18], [23]

In Figure 3.20 a typical way of how an unnecessary alarm can be produced is shown. The inaccurate detection at t_2 results in an inaccurate calculation of $\underline{v}$ and thus the direction criterion is fulfilled. If we assume that in this case the distance criterion is also fulfilled, then an unnecessary alarm is given. A simulation on the effect of system inaccuracy in determining the cloud in t_2 is shown in Appendix A3.

The single miscalculation of the distance criterion leads only an early alarm, but that should not be handled as an unnecessary alarm, as only cost efficiency decreases slightly in this case. Unnecessary alarms can be produced only if the direction criterion is miscalculated.

Late alarms on the other hand are mostly caused by the miscalculation of the distance condition once the direction criterion is fulfilled, or there's a rapid change in the propagation direction. Even though an alarm may be late, the occurring risk may not be significant.

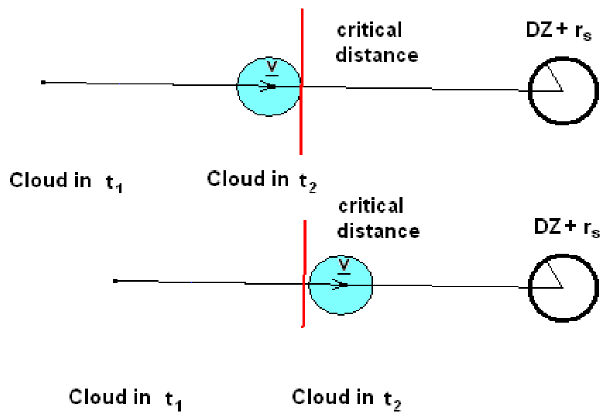

Figure 3.22.: Miscalculation of the distance criterion due to inaccuracy (circular cloud model)

In fig 3.22 the direction criterion is fulfilled so the event being an accurate or late alarm solely depends on the inaccuracy of distance criterion calculation. The upper part of fig. 3.22. denotes a case when the distance criterion is not fulfilled (if an alarm is given it is accurate, not late), while the lower region shows when the distance criterion is fulfilled despite the inaccuracies (an alarm given would be a late alarm).

If the alarm is given before the direction criterion is fulfilled, then no late alarm occurs. Inaccuracies may lead to cases shown in fig. 3.23. In this case the distance criterion is fulfilled and the inaccuracies may cause either an accurate or a late alarm.

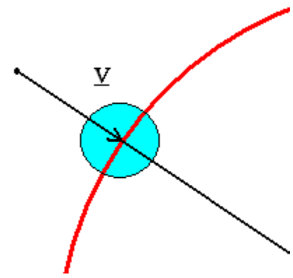

Figure 3.23.: Miscalculation of the distance criterion resulting in a late or accurate alarm

It may also be assumed that the direction criterion may also be fulfilled, so even besides the accurate and late alarms, unnecessary alarms may occur. All of these possibilities are to be considered when making an alarming decision and the calculations are to be done for each of the circles in the circular cloud model.

The calculation of the event space parameters during operation

During the operation of a HRPLP based system the alarming decisions are made based on the probability of hazard development (and the time left until it develops). The decision is to be based on the observation of cell progression. The event space parameters of HRPLP shall also be calculated during the operation, but then they have a different meaning.

The calculation starts with an assumption that the alarm is to be given. Then the probability of the assumed alarm being accurate, unnecessary, or late is to be determined. The resulting probabilities are apriori approximations, not relative frequencies (unlike the performance measures introduced above). The alarming decision has to be made based on these event space parameters.

The probabilities of the event space parameters can be calculated by taking into account the inaccuracies when determining v. A simple model of inaccuracy assumes that only the end point (P_2) of v was determined inaccurately. An example for the possible inaccuracy is shown in fig 3.24 – the distance condition is omitted in this figure.

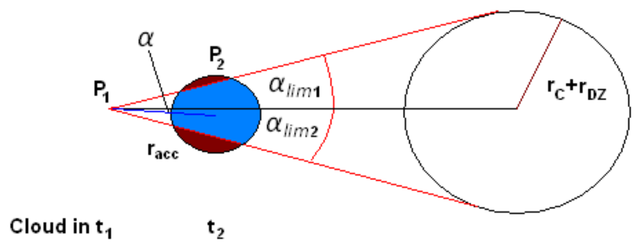

Figure 3.24.: Miscalculation of the direction criterion due to inaccuracy [18]

According to fig 3.24., the probability of an accurate alarm is the geometric probability of P_2 being in the blue area as if v points in this area and the thunderstorm progresses according to v, the cell would endanger the object to be protected later. When calculating the other event space parameters, the same geometric probability approach is used as given in (3-23).

$$p_{ua} = \frac{T_{c1} + T_{c2}}{r_{acc}^2 \pi}$$
$$p_{aa} = 1 - p_{ua} \qquad (3\text{-}23)$$

In the expression T_{c1} and T_{c2} denote the area marked brown in fig 3.24 and r_{acc} denotes the accuracy of determining P_2 – practically the accuracy of lightning detection. The most complex case is shown in fig 3.25.

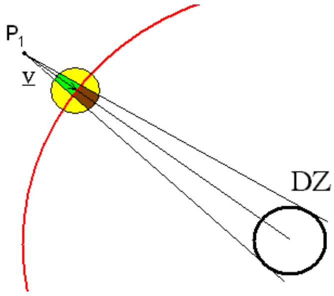

Figure 3.25.: Miscalculation of both distance and direction criterion

The area denoted with yellow corresponds to unnecessary alarms, the green area corresponds to the accurate alarms and the brown area corresponds to the late alarms. To calculate their probability the geometric probability approach is used. Also the inaccuracy of P_1 may also be included in the geometric probability calculations. (The starting point of $\underline{v}$ is also within a 'circle' around P_1, not exactly at P_1).

$$p_{ua} = \frac{1}{r_{acc}^2 \pi} \int T_{ua}(P_1) dP_1$$
$$p_{aa} = \frac{1}{r_{acc}^2 \pi} \int T_{aa}(P_1) dP_1 \qquad (3\text{-}24)$$
$$p_{la} = \frac{1}{r_{acc}^2 \pi} \int T_{la}(P_1) dP_1$$

Since these events form the full event space in HRPLP, so they sum up to 1. For the detailed calculations of $T_{ua}(P_1)$, $T_{la}(P_1)$ and $T_{aa}(P_1)$ see Appendix A3. In each sampling period all of these parameters are to be calculated for each circle in the circular model. Analytic solutions may be produced for circular cloud models, but for more complex shapes, approximation methods using simulation techniques may be used.

3.3.2. HRPLP and local detectors

Even though the accuracy of local detectors may be poor, still their use in HRPLP is indeed feasible. In a newer study Gulyás et. al. [16] showed that good algorithms implemented when using HRPLP do correct for the ranging errors of the local detectors. However these algorithms present a strong trade-off between cost and protection efficiency. If good protection efficiency is to be achieves, then usually alarms are given too early.

In the study a Monte Carlo simulation was executed to investigate the efficiency of the certain PLP methods. It was shown that regardless of the time required for the preventive action the probability of late alarm can be lower than 10%. Also it was found that raw HRPLP algorithms lead to higher probability of late alarms, so advanced algorithms are required.

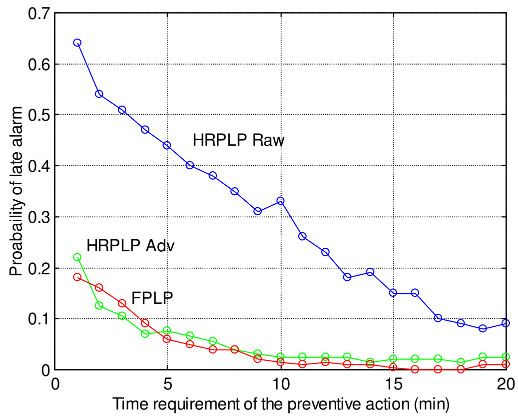

Figure 3.26.: Probability of late alarms with a local detector (simulated result) [16]

Note that the unnecessary alarms are not discussed in this study. Using empirical data the probability of unnecessary alarms may also be approximated. In Fig. 3.26 also a short comparison is given with Fuzzy PLP, which requires a complex system. Advanced HRPLP algorithms match the accuracy of FPLP and the early warnings are a weakness of both solutions. But if a local detector is used in the protection of people the early warnings are a negligible factor.

3.3.3. Short summary on HRPLP

HRPLP differs from ZPLP in several aspects. The thunderstorm cells are monitored individually and constantly, thus the zonal approach is not appropriate. Alarming decisions are made for individual thunderstorm cells.

Summing the events discussed in this section:

- The cloud is heading towards the DZ, and the distance criterion is fulfilled – an accurate alarm
- The cloud will not enter the DZ, but the distance criterion is fulfilled – an unnecessary alarm
- The cloud will enter the DZ, and the distance criterion has been fulfilled earlier, and no alarm was given – a late alarm.
- The cloud will not enter the DZ and the distance criterion is not fulfilled, nothing happens

In case of HRPLP the event space approach is used in two ways. The direct way is the part of the operation, which is approximating the upcoming event at each sampling period. The other use, the approximation of future performance is done with the existing empirical data.

Both applications of the event space approach were discussed in this section. As presented in previous figures, both the direction and the distance criterion are to be fulfilled to make the execution of the preventive action necessary. Based on the thunderstorm cell data the possible outcome of giving an alarm is calculated – practically this is the event space. This gives information at a given moment if the alarm given at that moment will be accurate or not.

But to give an overall view of a solution's performance, an approximation of the event space parameters is to be given. It is easily done using existing empirical data which gives a guideline during planning and evaluation.

3.4. Summary of the proposed forecasting methods – advantages and disadvantages

The framework proposed here offer a solution on the use of forecasting and preventive actions as a method of lightning protection. Preventive lightning protection is a novel approach in the sense that its main assumption is that the forecasting tools and the preventive actions are to be selected, used and planned in conjunction to provide an adequate solution.

The advantages of the proposed framework for preventive lightning protection is that it contains all the calculations required to give apriori approximations and aposteriori evaluations of the performance of the solution to be realized. The methods themselves – ZPLP and HRPLP – are particular types offering solutions with various characteristics.

Zonal PLP is the simplest solution proposed here. Its main advantage is its simplicity and thus its low cost. ZPLP is ideal for using local detector as a device for forecasting, but it may be used with lightning detection networks as well. The drawback of this method is the relatively high number of unnecessary alarms – thus the annual action cost of this method is much higher than that of HRPLP (and FPLP). Still this method is easy to plan and to realize.

High Reliability PLP on the other hand involves quite complex calculations in case of both planning and operation. However it provides higher protection efficiency and better cost efficiency. It is applicable with lightning detection networks, but is less cost efficient with local detectors, as the direction of propagation may not be detected.

Despite that the calculations cover performance measures and also the operation – in case of HRPLP – the proposed framework is constrained by the available empirical data. All the apriori approximations presented here rely highly on empirical data. In case of ZPLP system performance highly depends on the propagation of the cells (speed and direction). To be able to take that into account during planning a large amount of data is required. Worst case approximations can be given of course, but still that may not be accurate enough. In case of most of the countries though there are data regarding earlier lightning activity and thunderstorm cell propagation, so the empirical data can be obtained.

Preventive lightning protection as presented here is more than merely giving a warning, or doing something once the hazard is obvious. Its main novelty is that combining forecasting and actions results in a better solution (both cost wise and protection wise) than using them alone. In the following two chapters the preventive actions and the issue of risk is investigated. The former is vital for planning the solution, and the latter enables evaluating preventive lightning protection using the terminology of the international standard, thus provides compatibility with it.

4. The structure and cost of preventive actions

2nd thesis

Protection against the effects of lightning is realized in preventive lightning protection with preventive actions, not with various protective devices. As long as the preventive actions are in effect, the risk of damage due to lightning strikes is decreased. These actions are not constantly in effect. In this thesis the preventive actions are classified by their different properties. The aim of this classification is that using the actions in conjunction with hazard forecasting would be able to be planned more efficiently. In case of the preventive actions the approximation of the annual costs is very important as it contributes to the annual cost of the solution. In this thesis I describe a method with which it's possible to approximate the annual costs of action execution. The cost-time functions of the preventive actions are assumed to be known and the cost assessment of the actions and hazard forecasting is not in the scope of this thesis [12], [54], [38], [13]**.**

The means of protection when applying preventive lightning protection are the preventive actions. As described before, these actions aren't permanently in effect, but only for the duration of the thunderstorms. They shall be initiated before the lightning hazard develops, and suspended once it has diminished [12].

In this thesis I classify the preventive actions by certain properties. This classification clearly describes the different properties of the preventive actions and thus helps in selecting the adequate preventive action for an individual solution.

Besides classifying the preventive actions, this thesis also deals with the apriori approximation of costs. These costs comprise the cost of forecasting and the execution of preventive actions. Forecasting costs are easily determined and are constant in preventive lightning protection. Costs of the preventive actions on the contrary vary depending on the number of storms and the hazard forecasting efficiency. This thesis also deals with the approximation of the costs due to the execution of preventive actions. It's concluded that the costs are mostly influenced by forecasting efficiency.

The methods of assessing the action costs and the forecasting costs are not in the scope of this thesis. It is assumed that the costs of the preventive actions have already been assessed and does not address forecasting costs at all. The purpose of this analysis is to demonstrate how the operation of preventive lightning protection influences annual action costs.

It is important to mention here that the methods introduced in this section may be used for other existing solutions (discussed earlier) as well. Approximating annual costs is very important in those applications as well, since the dynamism of a protection relying on forecasting is difficult to take into account. No proposals have been given on how to deal with such protection methods in this aspect, and without the cost calculation methods a lightning protection system may not be evaluated by the principles of the standard and thus cannot be planned adequately.

4.1. Classification of preventive actions

In the planning stage of preventive lightning protection the suitable actions are selected first then the forecasting parameters are tuned together with the parameters of the action [13]. Upon exploring the available preventive actions it's practical to examine the different properties of the object to be protected. Usually the suitable preventive actions are determined by the object to be protected. If humans are to be protected by the means of preventive lightning protection, then the most common way to realize protection is the removal of people from endangered places. On the other hand in certain applications a change of the endangered place is a viable solution[25]. After the object to be protected is thoroughly examined, the possible preventive actions are to be determined. Finally the most appropriate preventive action should be selected.

Preventive actions can be classified by different properties which influence protection efficiency and costs. These properties are the following:

- time requirements (instantaneous or non-instantaneous)
- object to be protected (living or non-living)
- number of stages (single-stage, multi-stage)

Time requirements of an action mean its execution time. The execution of an action can be instantaneous or it may take a certain amount of time. Execution means the process when the action is realized resulting in a decreased risk of damage to the object to be protected. The execution finishes only after the object to be protected is in the protected state. Instantaneous actions are usually disconnections of electrical equipment while for example removal of personnel or suspension of industrial processes does require some time to be executed.

Time requirements strongly determine the protection efficiency and the cost efficiency of preventive lightning protection. When several minutes are required to execute a preventive action, there may be numerous unnecessary alarms yielding unnecessary costs for the user. Also when a late alarm occurs, the protection efficiency decreases, since the object to be protected may remain endangered for several minutes[26].

The ideal preventive action is instantaneous. In case of such preventive actions there are no late or unnecessary alarms. The action is executed only when the thunderstorm hazard actually develops and is thus always accurate.

Actions also differ by what they're used to protect. A very important field of application in preventive lightning protection is the protection of people at endangered locations. Thus the preventive actions may protect both the living and objects. A striking difference between PLP and other lightning protection methods is that this type of protection can be applied directly to the living. In both primary and secondary lightning protection the direct application of protection is the installation of certain devices to the object to be protected. Naturally there's no device which could be installed to for example several thousand people.

Besides these properties, the structure of preventive actions is also an important property. Preventive actions may be built up of different stages if the action itself can be divided into

[25] For example some football stadiums have retractable roofs. If the roofs are closed before the thunderstorm nears the stadium, then people are less exposed [55].

[26] Thesis 3 (section 5) describes the risk calculation taking into account the late alarms.

other actions [37]. This is practical, because the costs of preventive actions are lower, if they're only partially executed in case of unnecessary alarms. This is explained in the next sections.

For example when alerting people of lightning hazard, the preparation for removal and the removal itself are two different actions. In this case the preventive action may be divided into these parts. Other actions are however only one-stage actions, such as disconnecting electrical elements.

Single-stage actions are actions that can't be divided into different parts. Removal of people from endangered places is sometimes such an action, but this also depends on the location and the current activity of people at that location. For example the protection of car race viewers is a single stage action, as their removal from the stands is a single action itself.

Multi-stage preventive actions are practical due to their ability of cost reduction. The event space in this case may be described for each stage of the action with according conditional probabilities. So the event space calculations are to be modified accordingly using the expressions introduced in section 3. The same method shall be used for both ZPLP and HRPLP.

However when approximating the costs of protection, it's very important to describe the event space parameters and certain distributions for each action stage. Multi-stage preventive actions usually generate lower costs, as in case of unnecessary alarms, not each stage of the action is executed.

The properties of the object to be protected usually determine these properties of the preventive actions. Each of these properties influences one of the most important parameter of preventive lightning protection; its cost. The preventive actions and the forecasting are planned together to maximize protection efficiency and minimize costs. This thesis describes the apriori cost approximations of protection.

Note that currently there are solutions for lightning warning as described in [56]. These warning methods concern warning efficiency only, but mainly disregard many aspects of the actions applied. Also cost considerations are mentioned therein, but mostly cost assessment is done using existing empirical data. This section deals with cost approximation, so it's assumed that the cost assessment has already been done in some way. Also on cost assessment see [30].

4.2. The costs of preventive lightning protection

In case of any protection measure, the key feature is the cost of protection. The cost of protection is compared to the assumed costs of damages, and if it proves to be lower, then the protection is realized. This also applies to lightning protection (as written in the standards [11]) and preventive lightning protection.

However while primary and secondary protection only yield certain one-time investment and maintenance costs, preventive lightning protection has varying annual costs. The annual costs of preventive lightning protection are comprised of the costs of the forecasting system and the execution of the preventive actions.

$$C_{anprev} = C_{anforec} + C_{anact} \qquad (4\text{-}1)$$

The forecasting system has constant costs ($C_{annforec}$), its calculation is not in the scope of this thesis. The system is constantly in operation, or when a third party forecasting service is used, the costs are also given as annual or monthly costs. Costs of preventive actions on the other hand are not that unambiguous (C_{anact}).

4.3. Describing the costs of preventive actions

One of the most important features at action selection is its cost. When determining the available preventive actions their cost may be described by one individual value – that's the case of instantaneous actions – or by a cost-time function depending on the action type. The cost-time functions describe the costs of an action starting from its execution to its suspension. The operation of protection can be divided into three parts corresponding to the processes of the preventive action.

The first part is the execution of the action. Once an alarm is given, the action – or at least a stage – is being executed yielding certain costs for the user. Its cost – also the length of this process – is constant. The second part of the function is the active part, when the action is in effect. The duration of this part depends on the presence of lightning hazard. This varies for the thunderstorms, but approximations are possible. When data is available, the average length of the thunderstorms is to be used. The last part of this function is the suspension of the action. This process is also constant in terms of cost and length.

The cost of the action execution is described by the so called ‘cumulative cost function’. The cumulative cost function describes the total action cost when the action is in effect for *t* time units (second, minutes). This function is used in cost approximations. The assessment of this function is not in the scope of this thesis, a theoretical function is used in the following using a rough approximation only.

The cumulative cost function

The *cumulative cost* function describes the total action cost versus time. It consists of constant terms and a variable term. The constant terms correspond to the execution and suspension. If the action is executed, but the lightning hazard diminishes at the time it is executed – so it’s immediately suspended –, then the cost of the action is only the cost of execution and suspension. When the lightning hazard is present longer than that, the costs are also increased by the costs in the active period – described by the variable term. For the sake of simplicity the terms are denoted as ‘Execution and suspension’ and the ‘Active stage’ referring to action status.

$$c_{pvcum}(t) = \begin{cases} C_{exec} + C_{susp} & t \le t_{exec} \\ C_{exec} + C_{susp} + c_{active}(t) & t_{exec} < t \end{cases} \qquad (4\text{-}2)$$

Expression (4-2) and Figure 4.1 shows the cumulative cost function of airplane refuelling. Figure 4.1 has been created using the costs described by the ACRP [57]. As (4-2) shows the only time dependent term ($c_{active}(t)$) is the costs in the active region. Once the action is executed, it has to be suspended as well. Both of these costs occur at each execution[27].

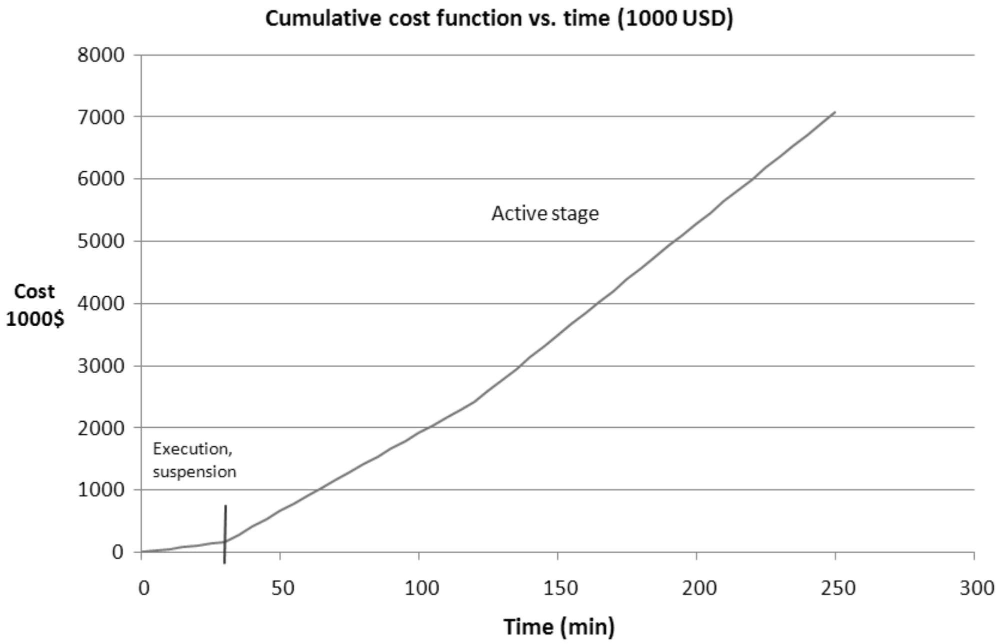

Figure 4.1.: Cumulative cost vs. time function of airplane refuelling (based on data in [57])

The only time dependent term is the costs occurring during the activity of the preventive action. This differs in each application and it is to be assessed by the user.

Upon planning preventive lightning protection the users shall calculate these functions to be able to approximate the costs of protection. As seen in the former example the process of describing the possible preventive actions is quite complex. Still these steps are necessary to be able to approximate the annual costs of preventive lightning protection.

4.4. Approximation of the annual costs of preventive actions

In general the costs of protection are determined by the forecasting costs - real-time data from lightning detection networks and meteorological stations, or using forecasting services – and the action costs. While forecasting costs are given by the data provider, annual action costs can only be approximated.

$$c_{pv}(t) = C_{pv}(t) + C_{pv0} \quad (4\text{-}3)$$

[27] Note that in the document supplied by the ACPR no direct execution/suspension costs are mentioned. This is not uncommon at these applications as the execution and suspension is realized by the crew, thus it does not yield significant costs.

Each time an alarm is triggered the action is executed. It is in effect until the lightning hazard is present (the thunderstorm cell is still in the DZ). Since this varies, the cost of protection is non-constant as shown in (4-3) [12]. C_{pv0} denotes the constant cost, which is known upon planning its further analysis is not in the scope of this thesis. Expression (4-3) describes a time dependent cost, which is to be calculated annually, resulting in (4-1).

Expression (4-4) is the cumulative cost function of a preventive action, an extended version of (4-3). The time dependent term in (4-4) denotes the actual cost of the action. Figure 4.1 shows a cost-time function of a preventive action corresponding to both (4-3) and (4-4).

$$C_{pv}(t) = C_{exec} + C_{susp} + C_{active}(t) \tag{4-4}$$

Once this function is calculated, the other calculations used at the calculations of the event space are to be applied to provide the approximation. The goal of these calculations is to approximate the cost of protection at accurate, late and unnecessary alarms as in these cases the preventive action is executed.

There are two approaches to approximate the cost of preventive lightning protection. A simplified version does not require extensive calculations, but yields a less accurate approximation. The complex calculation is done parallel with the event space calculations.

Simplified action cost approximation

When approximating the annual cost of preventive lightning protection, the annual cost of preventive actions is approximated by using the event space parameters. The event space parameters[28] describe the operation of protection. These are calculated first during the planning process, where approximations are used depending on the forecasting method used.

Table 4.1.: The event space of preventive lightning protection

	Alarm was given in time	Alarm wasn't given in time
Thunderstorm cell endangers the object to be protected	Accurate alarm - p_{aa}	Late alarm - p_{la}
Thunderstorm cell does not endanger the object to be protected	Unnecessary alarm - p_{ua}	No alarm - p_{na}

The event space contains three events, where the action is executed; the accurate, late and the unnecessary alarms. For the sake of simplicity the no alarm event is omitted – it does not yield costs. For the approximation one more data is needed, the duration of the thunderstorms. This is usually described by a distribution function, which can be obtained from the meteorology services along with other data which are required during planning.

If the average thunderstorm duration is given and the event space is known, the following expression yields the approximated annual cost:

[28] For the complete description see section 3.

$$C_{anact} = N_t * \int p_{thdur}(t) c_{pvcum}(t) dt = N_t * C_{avg} \quad (4\text{-}5)$$

The first term (N_t) denotes the number of thunderstorm cells triggering an alarm and thus inducing the execution of the preventive actions. This is approximated based on empirical data. The second term is the resulting average cost for one alarming event. This term is the weighted sum of the cost for actions with given duration ($c_{pvcum}(t)$). The weighting function is the probability distribution of thunderstorm duration ($p_{thdur}(t)$ denoting the density function) – the duration of the preventive action in effect. Of course this cost is not separated based on the corresponding events (see later).

As it's seen in (4-5) this calculation method is quite simple. The parameters required are the thunderstorm duration statistics and the cumulative cost functions. Both of these data is already available at this stage of planning. The resulting cost (C_{anact}) is the annual cost of actions, which gives a part of the total annual costs, as described in (4-1).

This calculation method is capable to approximate the costs, but is not capable to describe the cost efficiency of the solution. The alarm type (accurate, late or unnecessary) is not included in this calculation, thus the unnecessary costs can't be calculated this way.

Action cost effectiveness

When an alarm is triggered it may indicate real danger (accurate alarms and late alarms), or it may be unnecessary. Unnecessary alarms are produced, when a thunderstorm cell enters the WZ, but does not cause hazard later on, or – in HRPLP – the thunderstorm cells change their heading due to the changes in the wind.

Section 3 has shown that the unnecessary alarms may be approximated, but the length of these alarms was not in the scope of that section. The longer an alarm is in effect and the longer the preventive action is in effect, the larger costs it yields. When considering protection the cost effectiveness of the solution is to be considered.

In terms of PLP the cost effectiveness means the ratio of the annual costs related to accurate alarms and total costs[29].

$$\eta_{cost} = \frac{C_{annec}}{C_{antotal}} = \frac{C_{annec}}{C_{anunnec} + C_{annec}} \quad (4\text{-}6)$$

Calculating (4-6) yields a number between 0 and 1 – it can explicitly be transformed into percentages. The costs corresponding to accurate and late alarms can be calculated using (4-5) for the cases when the alarms are accurate. If the cost efficiency is 0, then there are no costs associated with accurate alarms, but there are some associated with unnecessary alarms. Since

[29] Note that the term of cost-effectiveness analysis is used in various scientific fields [58-62]. In ordinary methods the cost-effectiveness is associated with the input-output, or cost vs. alternative cost comparison. In PLP these kinds of approaches are only useful to determine if PLP is a viable alternative to primary and secondary lightning protection. Since this thesis deals with the theoretical approaches used in PLP, the use of cost-effectiveness analysis in protection type selection is not discussed here.

the same cost-time function applies in each case, this corresponds to $p_{aa} + p_{la} = 0$, so there are only unnecessary alarms, neither of the alarms would've been necessary. In other words the protection is not required at all or the PLP does not protect the object to be protected at all (there were late alarms only and in these cases the preventive action wasn't executed at all).

If the cost efficiency is 1, then the total costs are the same as the cost produced by accurate and late alarms (alarms signalling real hazard). In this case all alarms signal real hazard, so the protection is perfect – but of course only in terms of cost effectiveness[30].

Cost effectiveness may be generally formed to be used in decision making, based on the methods described in the standard. The standard approaches cost efficiency as the comparison of damage costs and protection costs. For PLP this approach is formalized the following way.

$$\eta = \frac{D_c - D_{cpr}}{D_c} = \left(1 - \frac{D_{cpr}}{D_c}\right) \quad (4\text{-}7)$$

$$c_{pv}(t = 1yr) < (1-\eta)C_d \text{, where } C_d = \sum_i P_i * C_{di} \quad (4\text{-}8)$$

Expressions (4-7; 4-8) [12] describe preventive lightning protection's cost efficiency in terms of protection and damage costs. Expression (4-7) describes the protection efficiency of an individual action D_c representing damages without protection measures, D_{cpr} representing damages with a preventive action. In case of a good preventive action, this value is near 1.

Expression (4-8) describes the criterion for the application of protection according to the standard. If the annual costs of protection are smaller than the annual cost of damage (C_d) modified by the efficiency of the action, protection is to be realized.

In the following sections the former definition of cost effectiveness is used. The latter definition however helps in the induction of PLP to the standards.

Complex calculations of annual action costs

Besides having a certain probability of unnecessary alarms, the unnecessary costs are also determined by the duration of these alarms. If the unnecessary alarms are in effect only for a short time, then they may yield only small costs, so a higher rate of unnecessary alarms may be acceptable for the use to minimize the probability of late alarms – thus maximize protection efficiency. However it's necessary to take these costs into consideration upon planning forecasting and selecting forecasting type (ZPLP or HRPLP).

These calculations are practically done along with the calculation of the event space. This section describes the theoretical background to approximate these costs and gives a short example of how the calculations are used in ZPLP.

When approximating the annual costs of protection the following events are taken into considerations (producing an alarm, thus triggering the preventive action):

[30] That does not mean that the protection efficiency is adequate, but that there are no unnecessary alarms. As described in section 3.1.2 the protection efficiency is determined by the late alarms and accurate alarms in case of good preventive actions.

- accurate alarms
- late alarms
- unnecessary alarms

The annual costs of PLP are approximated by multiplying the individual cost types with their occurrences:

$$C_{anact} = N_{ts} * (p_{aa}C_{acc} + p_{ua}C_{unnec} + p_{la}C_{late}) \quad (4\text{-}9)$$

The annual number of thunderstorms endangering the object to be protected (N_{ts}) determines how many times the protection may be activated and costs may occur. The costs in the second term (C_{acc}, C_{unnec} and C_{late} denoting costs of accurate, unnecessary and late alarms) are weighted by their occurrences (the event space parameters p_{aa}, p_{ua} and p_{la}) resulting in an "average" cost for one thunderstorm.

Calculations of these costs are different for ZPLP and HRPLP as a result of the different use of forecasting. Thus the calculation methods will be shown for both PLP types.

Action cost calculations in ZPLP

Calculations of accurate alarms cost

Costs associated with accurate alarms may be calculated by applying the existing meteorological data and the cumulative cost function. The thunderstorm duration distribution (p_{thdur}) is known upon planning, as it is calculated from meteorological data used for planning. The cost of an individual accurate alarm is calculated with the following expression.

$$C_{acc} = \int p_{thdur}(t) c_{pvcum}(t + t_{exec}) dt \quad (4\text{-}10)$$

In (4-10) the cumulative cost function $c_{pvcum}(t)$ is "shifted" in the integral with the time required to execute the preventive action and weighted with the density function of thunderstorm duration $p_{thdur}(t)$. This is necessary as the "duration" of the thunderstorm refers to the time spent in the DZ. In each case the action is executed (since this alarm is accurate), so the execution and suspension costs are always to be calculated with. Every other minute the thunderstorm cell spends in the DZ contributes to the "active" stage of the preventive action (in the cumulative cost function).

Calculations of late alarms cost

The approximation of late alarm costs is more difficult, as their existence is only roughly approximated in case of the thunderstorm cells developing in the DZ or WZ. Those cases are to be taken into account using existing empirical data. For the sake of simplicity these are omitted in this calculation. The other cause of late alarms is the high speed of the thunderstorms.

$$C_{late} = \int p_{thdur}(t) c_{pvcum}\left(t + t_{exec} - \frac{r_{WZ}}{v_{storm}}\right) dt \tag{4-11}$$

The last term in the parameter of c_{pvcum} denotes the 'lateness' of the alarm as it takes into account the applied WZ size r_{WZ} and the velocity of the thunderstorm cell v_{storm}.

The difference between late and accurate alarms in terms of cost is that the late alarms are in effect for a shorter time period. This time period depends on the speed of the thunderstorm cell, which can be written as a function of the thunderstorm duration as well. An easier worst-case method of this approximation neglects the last term and may use (4-10) instead. Using (4-11) is practical and accurate only when there is ample data available.

As seen in the parameters (4-11) applies to ZPLP. For HRPLP the late alarms are mostly caused by thunderstorm cells developing in the DZ, thus they can be approximated by using empirical data.

The most difficult type of alarms to take into account is the unnecessary alarms. In these cases the thunderstorm cell does not even touch the DZ, but – in case of ZPLP – travels through the WZ, or – in case of HRPLP – changes its heading. So in this case a more thorough approximation is required for each forecasting method.

Calculation of unnecessary alarms cost

When using ZPLP, unnecessary alarms are produced when the thunderstorm cell enters the WZ, but does not cross the DZ. As shown in Section 3.2 the probability of unnecessary alarms is approximated using the DZ-WZ size and geometrical probabilities. These methods can also be used in approximating the costs of unnecessary alarms.

In ZPLP when a thunderstorm cell touches the WZ, an alarm is given. The alarm is in effect as long as the thunderstorm cell is passing through the WZ (and possibly the DZ). When calculating the costs, the time the thunderstorm cell spends in the WZ is to be taken into account. This is calculated by using the distribution of the thunderstorm cell velocity and the distance through the WZ.

$$t_{cross}(\alpha, z) = \frac{d_{WZ}(\alpha, z) + 2r_s}{v_{storm}} \tag{4-12}$$

When the thunderstorm cell enters the WZ, it has to travel though the WZ to allow the suspension the preventive action. Upon approximating the costs the averages are used for both the thunderstorm size (r_s) and the thunderstorm velocity (v_{storm}). Using (4-12) the cost can be approximated for the whole WZ, but it's also necessary to include the thunderstorm occurrence probabilities ($p_{storm}(z)$) and the distribution of propagation direction ($p_{prop}(\alpha,z)$). The distribution of propagation direction is only taken at the angles where the alarm would be unnecessary. The approximated cost for an individual unnecessary alarm is thus formulated as the following.

$$C_{unnec} = \oint_z \int_\alpha p_{storm}(z) p_{prop}(\alpha, z) c_{pvcum}\left(t_{cross}(\alpha, z)\right) d\alpha dz \tag{4-13}$$

The calculation method is the following:

At each point of the WZ (curve z) calculate the average cost the preventive action using the distribution of action time for each propagation angle where the alarm would be unnecessary, weigh them with the probability of the given propagation direction – using the propagation distributions (wind direction distributions) – and weight this product with the probability of the occurrence of the thunderstorm cloud at a given point of the WZ perimeter.

Note that when applying any distribution the $\int_{-\infty}^{\infty} p(x)dx = 1$ condition holds, so no other weighting is required.

This method applies in ZPLP as it follows the calculations of the event space using the same approximation and empirical data. HRPLP is different in this regard as well, as in this case the probability of both unnecessary and late alarms is considerably lower.

Action cost calculations in HRPLP

The most important advantage of HRPLP over ZPLP is its lower rate of unnecessary and late alarms. Thus the costs of preventive actions occur mostly because of accurate alarms and the cost effectiveness is closer to 1. Note however that the forecasting costs in this case are considerably higher than those of ZPLP, because HRPLP requires constant monitoring and real-time calculations.

The costs in the case of HRPLP are also calculated using (4-1 – 4-4;4-6, 4-7) – since these expressions describe PLP generally. Simplified calculations are also possible using (4-5).

Cost approximations in case of HRPLP are done using empirical data (just as the calculations of the event space – see section 3.8). This empirical data is obtained from lightning detection networks and meteorological radars and is required for advance planning. When selecting preventive actions and determining the appropriate alarming criterions (direction and distance criterion[31]) the empirical data is used to determine the resulting event space.

As the event space is calculated the distribution of thunderstorm hazard duration ($p_{thdur}(t)$) is described. This distribution may be used to describe the cases of late alarms and accurate alarms. The alarm duration for unnecessary alarms can also be described with a distribution ($p_{uadur}(t)$), which is approximated also using empirical data. The costs are calculated taking into account these three kinds of alarms.

$$C_{anact} = N_{ts}\left((p_{aa} + p_{la})\int p_{thdur}(t) c_{pvcum}(t)dt + p_{ua}\int p_{uadur}(t) c_{pvcum}(t)dt\right) \tag{4-14}$$

Expression (4-14) describes the costs in a similar way as (4-9). The first term in the sum corresponds to the accurate and late alarms. I suppose that the late alarms are similar to the

[31] Both direction and distance criterion are described in section 3.3.

accurate alarms in the sense that the thunderstorm duration distribution corresponds to these two events. The second term in the sum deals with unnecessary alarms, which have shorter duration – in case of HRPLP – than the accurate or late alarms. The sum is multiplied by the annual number of thunderstorms and the probabilities in the sum are weighting the integrals, as their sum gives 1.

This expression also shows that the calculations for HRPLP are based on empirical data rather than theoretical approximations.

Costs of multi-stage preventive actions

Multi-stage preventive actions are to be considered as many preventive actions executed based on each other. A given stage can only be executed if the preceding stage has already been executed.

The costs generated by such preventive actions may be calculated step-by-step for each execution stage, but this method can be simplified. A given stage of a preventive action may be interpreted as a separate preventive action.

In case of ZPLP it means, that since each stage has its own WZ, the WZ of the next stage may be defined as the DZ for the previous section. This holds because if the thunderstorm cell enters the WZ of stage I., it is executed, and if the thunderstorm cell enters the WZ of stage II the alarm at WZ I was 'accurate'. The alarm may prove unnecessary later on, but for that stage, it was an accurate alarm.

Taking this into account the cost calculations for ZPLP may be repeated for each stage of preventive actions using (4-1 - 4-14). Note that in this case the cumulative cost function has to be divided into parts corresponding to each stage. Another – simpler – alternative of these calculations is handling the multi-stage actions as a single-stage action. Calculations with this assumption yield a worst-case cost approximation using the first stage only.

In case of HRPLP the multi-stage actions are actions which have an according distance (and direction) criterion for each stage. HRPLP yields a more cost effective solution than ZPLP, still multi-stage actions may further improve this. Similarly to ZPLP if the first stage has been executed, the following stages will only be executed once their corresponding distance (and direction) criterion is fulfilled.

The costs of HRPLP with multi-stage actions may be approximated also by handling multi-stage actions as a single stage action, but that also gives a worst case approximation. The approximation is based on empirical data in this case as well, not on theoretical approximations.

When taking each stage as a separate stage, (4-14) is to be calculated for each stage, so the meteorological and lightning data is to be processed accordingly to obtain the necessary distributions. Also the cumulative cost functions are to be divided to the according parts as well.

The result of using multi-stage actions is the decrease in costs, because the alarms, which would later prove unnecessary yield smaller costs, as not each stage of preventive action will be executed, thus smaller cost is generated. Note that in case of actions which are not costly, the multi-stage actions do not really mean an advantage.

5. Risk calculations in lightning protection, extension of the SCOUT system

3^rd^ thesis

Taking into account its tools, preventive lightning protection does not fit among conventional lightning protection methods, thus planning such a method is not feasible with the principles of the international standards. The key notion of the international standards is the risk concept, which is adapted to preventive lightning protection in this thesis. I introduce the notion of the 'equivalent risk' which is a key concept in including preventive lightning protection into the standards. For the planning of preventive lightning protection I propose an extension to the SCOUT system to be able to handle this method. The SCOUT system is a novel method of protection against electrostatic hazards. It includes the planning and auditing methods for static protection solution. In this thesis I propose its extension with dynamic methods, thus with this method the planning of preventive lightning protection is possible. I also describe a detailed planning algorithm which fits into the SCOUT system [63], [40]**.**

This section deals with the methods and issues of planning preventive lightning protection, and the necessary definitions and calculation methods of risk are introduced to allow the induction of PLP into the international standards. The planning algorithm introduced here describes the order of planning steps and the information dependencies which are required to plan preventive lightning protection.

In this section a novel approach to risk is presented well, since preventive lightning protection cannot be described with currently proposed methods. Here I define a new type of risk – the equivalent risk –, which takes into account the dynamism of a protection method (in this case PLP). The definition proposed here is a practical definition and is independent on what risk approach is it applied to, since it includes a probabilistic approach (what all risk definitions include as well). Also the introduced risk calculation method is added to the SCOUT system, a novel approach to electrostatic protection.

Definitions of risk

In lightning protection the risk of damage due to lightning strike is the most important measure which describes the quality of protection. The adequacy of a solution is determined by calculating the risk of damage due to lightning strike. The risk defined in the standard [11] results in an annual cost.

Another approach to risk calculation has been presented before the issuance of the standard by T. Horváth [64], [65]. Its main focal point is the frequency and extent of damage, thus the protection efficiency of the realized protection is emphasized. Unlike risk in the standard, this risk does not have a dimension. The annual number of lightning strikes, the equivalent area of the object to be protected, the lightning parameters, and the protective devices' parameters are all taken into account in this calculation method. Various methods are applied during the calculation. The equivalent area is determined by the principles of the standard, mainly influenced by the area and the height of the object to be protected. When calculating the strikes to the object to be protected the electrogeometrical model [64], [65] is used taking into account the lightning parameter statistics of the area[32].

$$N_f = N_g A_{eq} \tag{5-1}$$

$$N_i = P_i N_f \tag{5-2}$$

$$D_i = N_i S_i W_i \tag{5-3}$$

$$D_c = D_i + D_a \tag{5-4}$$

$$R_D(t) = 1 - e^{D_c t} \tag{5-5}$$

In these expressions we see one definition of risk proposed by Horváth [64], [65][33]. Taking into account each of the factors described above (in expressions 5-1,5-2), the resulting risk is derived from a Poisson process (5-5). The actual risk to be considered is the annual value of (5-5), practically calculating the risk with *t=1 year*.

In the standard however another definition is used emphasizing the cost of damage. Also we may find two definitions for risk. As a notion it is defined as 'value of probable average annual loss (humans and goods) due to lightning, relative to the total value (humans and goods) of the object to be protected' ([11] IEC 62305-2 pp 29.). As a calculated value it is defined as 'The risk R is the value of a probable average annual loss. For each type of loss which may appear in a structure or in a service, the relevant risk shall be evaluated.' ([11] IEC 62305-2 pp 45.).

$$R = NPL \tag{5-6}$$

The last expression ([11] IEC 62305-2 pp.71) means that the risk depends on the number of events per year, the probability that an event – in this case a lightning strike – causes damage, and the consequent loss. Note that this is distorted by the use of cost of the object to be protected. Also note that the 'linear' nature of this risk approach may even result in R being larger than 1, which raises doubts about its adequacy. Modelling risk by using a Poisson process (5-5) however gives a better approach.

The former expressions (5-1 – 5-5) mean that risk depends on the interception efficiency rather than the actual cost of damage. Both of these approaches can be used to calculate risk values, and preventive lightning protection fits in whichever concept.

The standard defines the so called 'tolerable risk' (R_T), which is a guide value for planning lightning protection. It is calculated by calculating (5-6) for a year. This value never reaches

[32] Due to size restrictions, the total description of the theoretical background of risk calculation is not included in this thesis.

[33] The notation in these expression is the following:
N_f – the annual number of strikes to a building [strokes/year]; N_g – ground flash density [strokes/year]; A_{eq} – equivalent area [m^2]; P_i –interception failure coefficient [%]; N_i – annual number of interception failures [1/year]; S_i – sizing failure coefficient [%]; W_i – weighting factor; D_i – damage caused by sizing failure; D_a – damage caused by interception failure; D_c – damage caused by lightning;

0, as perfect protection does not exist. There's always risk of certain damage, although this value should be as low as possible. Tolerable risk means the risk value where the protection is to be classified adequate according to the standard. The following table summarizes the tolerable risk values for certain type of damages.

Table 5.1.: Tolerable risk values [11] **IEC 62305-2 pp. 59.**

Type of loss	R_T[34]
Loss of human life	10^{-5}
Loss of service to the public	10^{-3}
Loss of cultural heritage	10^{-3}

Tolerable risk is also a guideline and minimal criterion for preventive lightning protection, since a solution can only be classified acceptable if it satisfies the requirements defined by the tolerable risk concept. In this regard too, PLP complies with the current principles of lightning protection. As in primary and secondary lightning protection, the protection measures influence the probability of damage in PLP as well.

However evaluating preventive lightning protection only by using the tolerable risk concept for the preventive actions is inaccurate. In the aspect of protection the late alarms are also to be taken into account, as they decrease protection efficiency, thus increasing the risk of damage.

5.1.Preventive Lightning Protection and risk assessment

In PLP the hazard development has to be forecasted and the preventive actions are to be executed before the hazard actually develops. When it is not executed in time, the risk of damage is increased. Since the standards do not deal with dynamic protection methods, the risk calculations are to be revised and extended. There are attempts to include temporary operation into the standards, but due to the problems with the current risk concept further research is required in this direction [66].

The probability of the failure in case of PLP depends partially on the preventive actions applied and on the forecasting used. In PLP the preventive action decreases the risk of damage by decreasing the risk of a lightning strike to the object to be protected and/or its vicinity.

A simple model of PLP risk calculation – the two level risk calculation model

Either method of PLP is capable of protecting an object to be protected only if the preventive action is executed in time. Generally this happens when the alarm to execute the preventive action is given in time. The risk of damage is decreased if the preventive action is executed, at the time the thunderstorm cell reaches the danger zone.

[34] The unit of risk is intentionally omitted. According to the standard the unit of risk is EUR/year. This may be helpful in making economic decisions, but its scientific meaning is somewhat confusing. When using the risk described by (5-5) however a relative cost is used, thus risk retains its dimensionless behaviour.

Combining forecasting with preventive actions results in a complex solution which requires two level risk calculations during planning [40]. The first level is the calculation of the ‘exposedness’ of an object to be protected – that is the risk of damage due to lightning strike without any means of protection – and the risk of damage in case of the preventive action being in effect. The risk values for executing the preventive actions can be described as a function of time to provide a complete description.

The second level of calculation addresses the quality of forecasting by taking into account the late alarms (see section 3 and [25], [23]), when the actions are not in effect when they would’ve been required to.

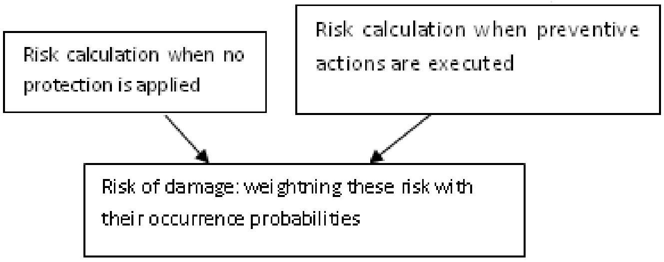

Figure 5.1.: Two level risk calculation in case of preventive lightning protection (simplified model). [40]

This model is a simplified model of the risk calculations. In the following sections the application of this model is introduced for PLP. When calculating the risks the different forecasting methods are not taken into account. In case of both ZPLP and HRPLP the general idea of the application of this model is the same.

Analytical description of the two level risk calculation model

When we can describe the distribution of the forecasting time, the risk of damage due to lightning strikes can be explicitly calculated. Suppose that ZPLP is realized to protect an antennae tower, while maintenance work is in progress.

Denote the risk of loss of human life outside the maintenance period of the antennae tower with R_{pr}, as no special protection methods are applied, and denote the case when somebody works on the tower with R_{npr} as in this case the maintenance worker is not protected.

When calculating the risk values according to the standard, this protection can’t be described with either of these values. Consider the case when the thunderstorm cloud enters the DZ before the worker climbs down from the tower. In this case R_{npr} should be applied, since the worker is still in danger (even though only for a while). If the worker is able to leave the worksite before the hazard develops, then the other risk value, namely R_{pr} describes the situation.

The resulting risk should include the prediction efficiency of hazard forecasting. If one wishes to calculate the risk of damage in case of preventive lightning protection it’s necessary to take into account both cases – when the forecasting was timely or late – and weighting them according to their occurrence. The weights are calculated using the elements of the event space of preventive lightning protection.

$$R_{prev} = p_{prot} R_{pr} + p_{nprot} R_{npr} \tag{5-7}$$

In this expression p_{prot} denotes the probability that upon a given event – development of the lightning hazard – the preventive action was executed in time, thus the object to be protected is considered to be protected. Similarly p_{nprot} denotes the cases when there wasn't enough time to execute the preventive action, so the worker wasn't protected.[35]

Expression (5-7) describes the simplest model introduced in fig. 5.1. In this model the notion of 'hazard' is either existing or non-existing. This model does not deal with the different levels of hazards associated with the progress of the execution of the preventive action – the 'lateness' of an alarm.

The probabilities in expression (5-7) depend on the time distribution of the alarms before the lightning hazard develops. If they're given in time, then the alarm is accurate, else the alarm is late – these notions are those defined in the event space approach (section 2). Consider the case, when applying ZPLP a fixed WZ is selected and the execution time of a preventive action is known and is constant. In this case if the wind speed distribution $p(v)$ – v denotes thunderstorm velocity in [m/s] or [km/h] – is known, then the probabilities can be calculated explicitly.

It depends on the applied WZ in case of ZPLP. When planning ZPLP the WZ is planned according to the preventive action's execution time and an artificially selected parameter, the critical speed, v_{crit}. It describes the thunderstorm velocity above which the realized protection produces late alarms. Its detailed description is found in section 3.2.2.

$$p_{nprot} = p_{la} = \int_{v_{crit}}^{\infty} p(v)dv \tag{3-12}$$

If the speed of the thunderstorm cell is greater than what the WZ was planned for (v_{crit}), then the object was not protected. By integrating the wind speed distribution above this value yields the probability of late alarms[36], as (3-12) shows. Calculating the integral from 0 to the critical value results in the probability that the accurate – in this regard, it should be referred to as 'timely' – alarms.

The complex model of PLP risk calculations – the continuous model

The limitations of expression (5-7) are that it assumes a preventive action not having any time requirements. However this entirely omits that when there's a late alarm, the preventive action is still executed and the object to be protected is exposed only for a shorter time period. In this case the level of hazard also decreases, as the execution progresses.

In reality the preventive actions which are simple flips of switches – namely disconnecting certain elements – not having any time requirements, are not too common. The most

[35] Technically these probabilities are obtained by restricting the event space of preventive lightning protection to the late and accurate alarms, and normalizing these values to 1.

[36] Omitting the development of thunderstorm clouds in the DZ.

important field of preventive lightning protection – protecting human lives – always involves preventive actions with certain execution times. This has to be examined in terms of risk as well.

The equivalent risk

We can describe the process of executing a preventive action with a time function of risk. In other words it can be interpreted as the 'momentary' according risk values in the function of time.

The equivalent risk means the annual risk calculated by the IEC62305 for the particular conditions as a function of time if we'd abandon the preventive action at a given moment, and wouldn't finish, nor undo it. The equivalent risk is denoted as $R_{eq}(t)$. This function is continuous, takes the value of R_{npr} at $t=0$ and takes R_{pr} at $t=t_{act}$ – the execution time of the action. Its shape between these two points depends on the action itself.

The following figure shows an example for the equivalent risk as a function of time for a preventive action having certain time requirements.

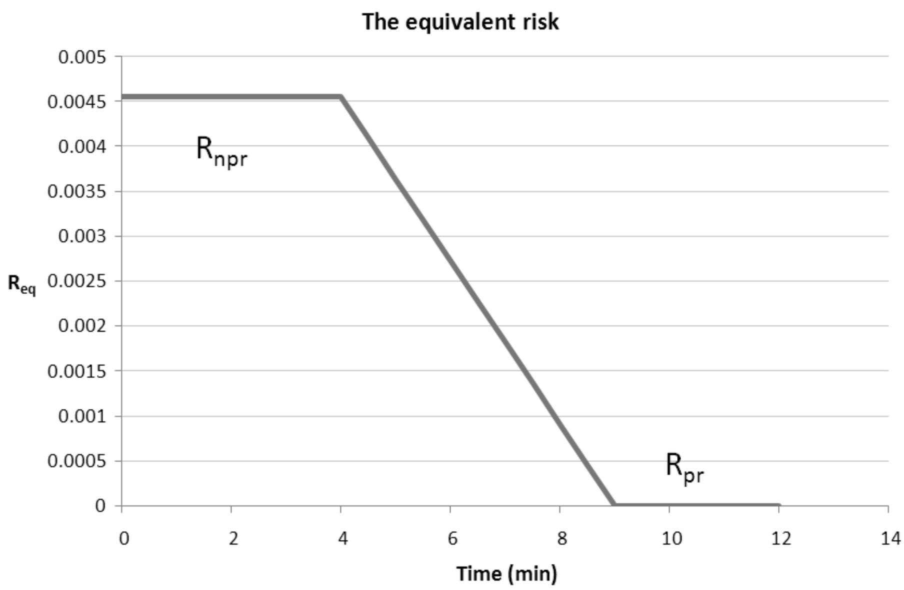

Figure 5.2.: Equivalent risk vs. time function of a preventive action [40]

This figure shows the equivalent risk vs. time function of an action. The *x* axis denotes the time passed after beginning the execution of the action. Fig. 5.2 shows the example of the action executed in case of antennae maintenance (work suspension and returning to safety). The first four minutes do not mean decrease of risk (this value is denoted as R_{npr} – not protected) as it corresponds to work suspension, the workers gather their tools used (they're up on the antennae) and disconnect their safety rig. The following five minutes denote their actual removal from the antennae and returning to safety. After nine minutes the workers are considered safe (this is denoted as R_{pr} – protected).

This figure shows that even though if a thunderstorm cloud enters the DZ of the line 7 minutes after starting the preventive action is denoted as a late alarm in terms of PLP, the risk of damage is considerably lower than if the workers would be still up at the antennae. So considering this case as a complete failure of protection is incorrect, just as considering it as a proper case. These features of preventive actions are to be included in the risk calculations for preventive lightning protection.

Extending the two level calculation model with the equivalent risk

So expression (5-7) has to be extended in the cases where the preventive action has a given execution time – it's not executed instantaneously – and the changes in the equivalent risk aren't instant. In other words the probabilities which weigh the equivalent risk values are to be described as a function of time as well!

To be able to do this extension we have to assume that we know the distribution of the time left to execute the preventive action after the alarm is given – $p_{ex}(t)$. Ideally this value shall always be bigger than (or equal to) the execution time of the preventive action. In case of ZPLP this is easily calculated from the thunderstorm cell speed distributions – in HRPLP on the other hand it may be approximated comparing the changes in the velocity of the thunderstorm cell.

Also we shall differentiate between different delays in the alarms. For example if an alarm is given so that there are still 7 minutes left until the hazard develops, then this case present a much lower risk than if after the alarm it's only 2 minutes left to execute the action. To take account of this, the average risk shall be calculated from the equivalent risk.

$$R_{AVGex}(t) = \frac{1}{t_{act} - t} \int_{t}^{t_{act}} R_{eq}(\tau) d\tau \qquad t < t_{act}$$

$$R_{AVGex}(t) = R_{pr} \qquad t \geq t_{act} \qquad (5\text{-}8)$$

In (5-8) t_{act} denotes the time required for the execution of the action. This expression describes the risk which occurs if a given time is left for the execution of the preventive action. So if the alarm is given the same time as the thunderstorm enters the DZ, then the risk is calculated taking the average of the equivalent risk for the action. If the alarm was given in time, then (5-8) results in the risk occurs if the action has been executed.

If these two functions – $p_{ex}(t)$, the probability distribution of the time left until hazard development and $R_{AVGeq}(t)$, the average risk function – are calculated, then the resulting risk for the given solution is formulated as follows:

$$R_{prev} = \int_{0}^{\infty} p_{ex}(t) R_{AVGeq}(t) dt \qquad (5\text{-}9)$$

This expression addresses the risks involved in both late and accurate alarms (depending on alarm time). The integral goes from 'zero seconds' – that is when the alarm is given at the moment the thunderstorm cloud enters the DZ – to infinity. Of course in practice the distribution of time left for execution ($p_{ex}(t)$) sets the interval of the integral.

Also since the average equivalent risk is defined with two functions for two intervals, (5-9) should be split into two terms as well to emphasize those cases when the preventive action is executed in time and when it's not. Splitting the integral (5-9) results in the following expression:

$$R_{prev} = \int_{0}^{t_{act}} p_{ex}(t) \frac{1}{t_{act} - t} \int_{t}^{t_{act}} R_{eq}(\tau) d\tau dt + R_{pr} \int_{t_{crit}}^{\infty} p_{ex}(t) dt \qquad (5\text{-}10)$$

The second term is the simpler one in this case. It denotes the case when the alarm was given in time – thus the average equivalent risk always takes R_{pr}. It's exactly the same term as seen in expression (5-7). Integrating $p_{ex}(t)$ results in p_{prot} in this case. The first term denotes the case, when the alarm was not given in time, so in the last minutes of the execution of the action the lightning hazard is already present. In this case (as mentioned before) the 'residual' equivalent risk (time function) is averaged to give an according risk value, and that is weighted with the according probability of a certain interval of time for execution.[37]

5.2. An example of the application of the continuous model

In this example workers were up on the antennae tower doing their maintenance work. The preventive action was their removal from the worksite to safety. In this section a numerical example is presented, assuming that ZPLP is realized. The equivalent risk function and the wind speed distribution are assumed to be the following:

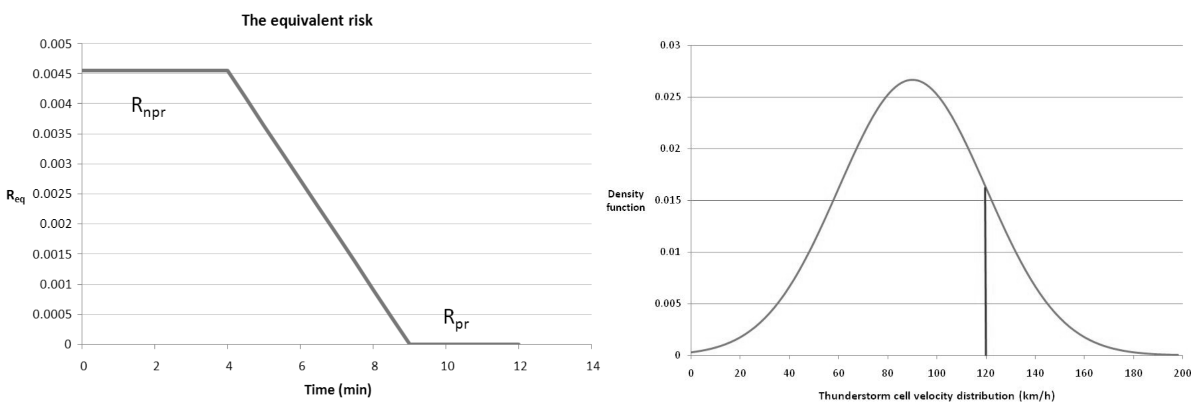

Figure 5.3.: Equivalent risk vs. time function and thunderstorm cell velocity distribution [40]

The equivalent risk function shows, that the preventive action requires 9 minutes. From this function 5-9 can be calculated. The WZ was planned so that when a thunderstorm slower than 100 km/h approaches the workers may get into safety in time – giving them exactly 9 minutes in this case. This results in a 15km wide WZ around the DZ. Supposing, that the thunderstorm speed (or wind speed) distribution is a normal distribution given in fig 5.3, the distribution of the time for action execution can easily be calculated. Then with these expressions available, expression (5-10) is calculated.

[37] Note that even though these expressions contain solely integral calculations, the practical realisation of the calculations would contain summing operations, as usually data is available as discrete functions.

In fig 5.4 the risk values calculated to the different thunderstorm speeds are shown. This figure can be drawn with using the time of the alarm before hazard development as the X axis, but in this case the similarity to the thunderstorm speed graph is more spectacular.

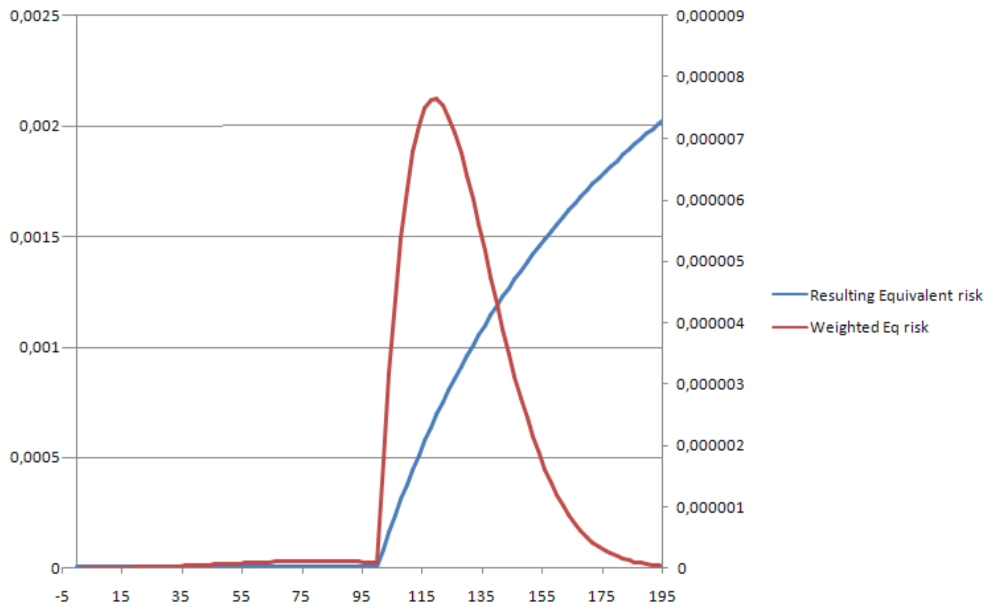

Figure 5.4.: Resulting (left axis) and weighted (right axis) equivalent risk vs. thunderstorm speed distribution

Fig. 5.4 shows the calculation steps of the model proposed. First the equivalent risk is calculated which is the result of either accurate or late alarms. This denotes the first integral term in (5-10) and the R_{pr} if the alarm was given in time. The next step is weighting this risk value with the thunderstorm speed distribution function, or with the distribution of time for action execution. The result of this weighting is with the current data (given equivalent risk vs. time and thunderstorm speed distribution function) results in $R=1,516*10^{-4}$.

This value is above the values defined in the standards – the tolerable risk values –, so a stricter alarming is required. If both the action and the thunderstorm speed distribution remains the same, changing the WZ size improves protection efficiency. It's summarized in the following figure.

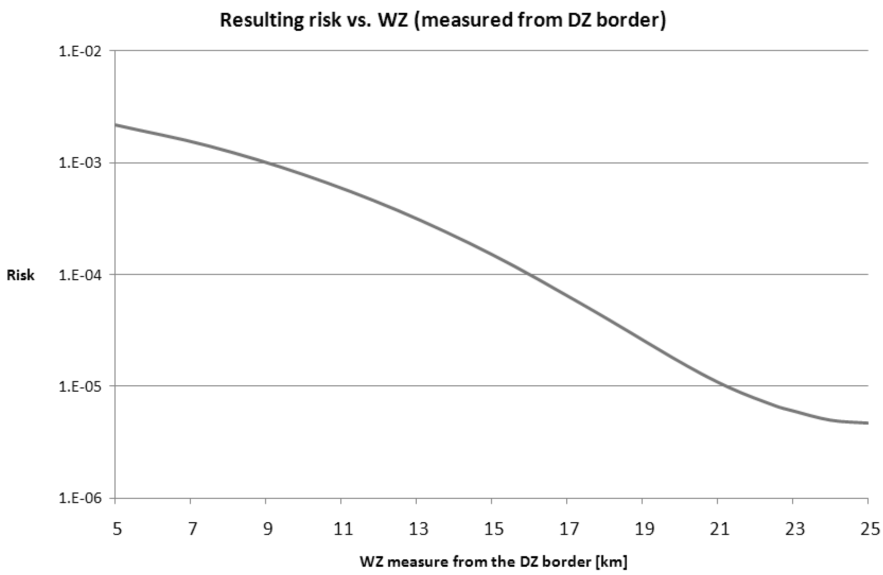

Figure 5.5.: Resulting equivalent risk vs. the WZ (measured from the border of the DZ)

Fig 5.5 shows that in case of $r_{WZ}=r_{DZ}+15km$ and assuming the thunderstorm speed distribution shown in Fig 5.3 the solution does not satisfy the requirements of the standards. With the given parameters, a WZ above 21.2kms would be sufficient according to the standard, as it would result in risk levels below 10^{-5} – the tolerable risk of loss of human life.

When planning preventive lightning protection these calculations – along with the event space calculations and cost assessment shown in earlier theses – are to be followed to determine the adequate preventive action and forecasting parameters. This short case study has shown that by using the methods described in this thesis a solution using preventive lightning protection can be planned according to the standards.

In the following sections some remarks are given regarding HRPLP and this approach to risk calculation is added to SCOUT, a novel planning and auditing system for various applications in electrostatics. Also the detailed planning algorithm is given for preventive lightning protection.

5.3. Risk calculations in High Reliability Preventive Lightning Protection (HRPLP)

In HRPLP the use of the preventive action is dynamic in the sense that the alarming decision is based on monitoring the storm progression, so it depends on multiple factors, not on a static area.

It is difficult to determine system efficiency, but apriori approximations can be calculated if earlier lightning detection network data is available. Both p_{prot} and p_{nprot} can be empirically calculated using data about the progression of past thunderstorms – also this would help the calibration of the alarming system.

If some preliminary data is available apriori calculations of risk are also possible following the steps introduced in this thesis. Expression (5-10) can be calculated with that data explicitly, thus the risk of damage for that solution is given with the same assumptions in effect as in ZPLP. Note that the resulting risk values for all past thunderstorms and alarming events should be averaged to approximate the risk associated with the solution.

On the application side, the concept of accepted risk can be used in the alarming decisions as well. The following figure shows the case when different preventive actions are set to be executed. The decision in this case depends on multiple factors depending on the different properties of the preventive actions [32].

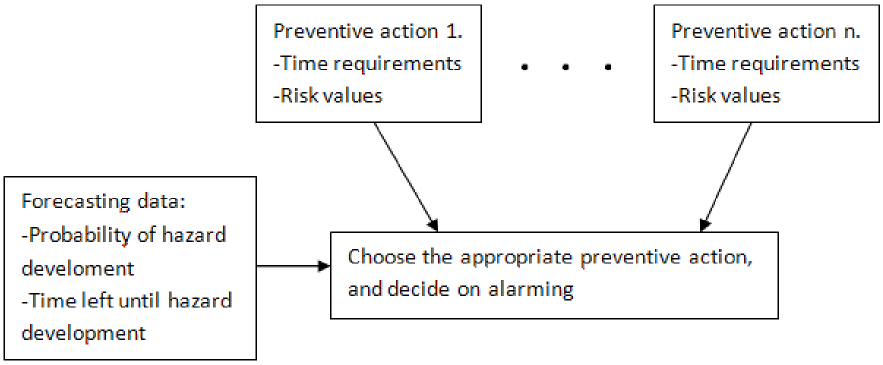

Figure 5.6.: The decision making process in case of multiple possible preventive actions [40]

Since in HRPLP the decision for alarming is revised in every sampling period, the risk calculation should be repeated along with this revision. This results in having a certain risk value for each time period besides having a probability of hazard development. This calculation process is complex, but with the tools available nowadays it can be applied real-time.

In HRPLP multiple preventive actions may be used depending on the properties of the object to be protected. In this case [32] the momentary probability of hazard development is taken into account and an action is selected from the set of the preventive actions also using fuzzy logic [31].

5.4. SCOUT – a method of dynamic protection

Another question frequently arises when planning protection solutions is the methodology of how individual protection types are to be selected, the levels and means of protection, and the sustainability of safe operation.

An answer to this – recently given - is the SCOUT System [67], [68], which is an aid to both decision makers and evaluators in planning and auditing the protection. Risk is deeply involved in solutions like that, but the dynamic methods in protection aren’t yet defined in the SCOUT system. In the next section we’ll give a brief review of the inclusion of dynamic protection with the SCOUT system.

In industrial processes the protection against certain types of hazards is realized differently. Using the SCOUT system – an emerging method on the field of static hazards – gives aid in decision making when facing electrostatic hazards.

SCOUT (**S**tatic **CO**ntrol with **U**p-to-date **T**echnology) System means a procedure of risk assessment based on audits, which does not only include aid for planning, but also includes guidelines for decision makers, and auditors. This universal method is capable of handling any type of static hazards, and due to its generality, it's capable to handle almost any kind of processes.

One of the novelties of this system is that it contains not only the preparations required for decision making, but also the tools to audit the solutions realized.

In case of dynamic methods (such as PLP) – where the protection mechanism is not a permanent protection, but is based on timely forecasting – even the SCOUT system can't offer an ambiguous solution since the notion and the calculation of risk can't include such methods due to the limitations of the risk calculations, and assessment methods currently in use. The risk calculations for PLP – shown in this section – can be adopted into the SCOUT system per se, as the notion of risk complies with the international standards.

The preaudit, choice of solutions and the post audit in the SCOUT system

The first process in SCOUT which involves risk calculations is the preaudit process, where the need of protection is determined.

Figure 5.7.: Determining the need of protection – risk assessment component used in the SCOUT system (also used generally) [69]

The strategies of the stakeholder (risk taker) are also taken into account and the resulting risk levels are compared to the accepted risks. Thus it becomes clear, if there's a need for protection at all. In the next step, possible solutions are worked out. The possible solutions are evaluated using risk calculation methods, the viable solutions are determined and their costs are estimated.

After the risk values have been calculated, the other properties of the possible preventive actions are examined – the cost and time requirements. The forecasting properties are omitted at this stage, since they're already included in the calculations of risk. The decision maker then chooses the most suitable method.

Figure 5.8 summarizes the choice made by the decision maker as described before. The resulting choices for the decision maker can be formulated in many ways. It can either be a cost per year, or simply the risk values. It depends solely on the preferences of the decision maker.

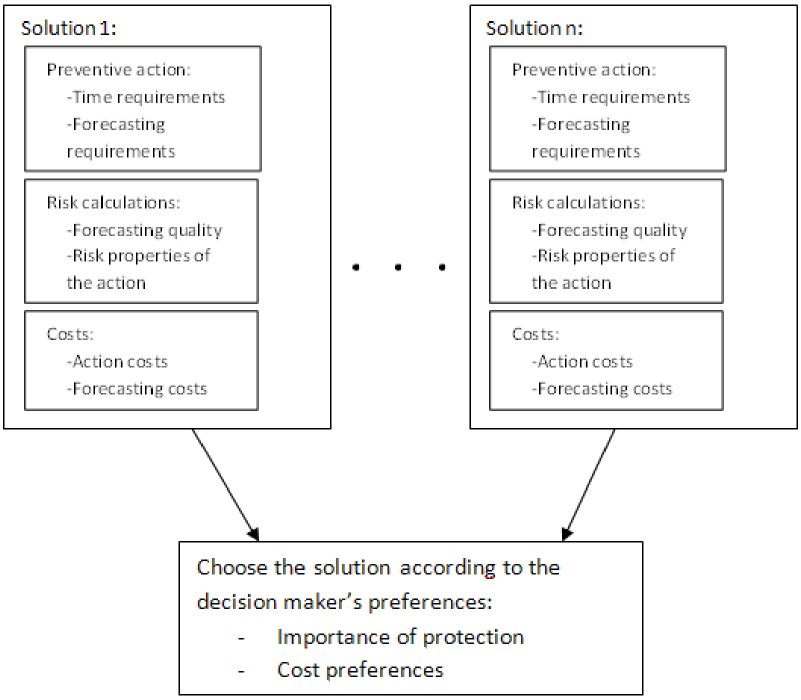

Figure 5.8.: The choice mechanism offered by the SCOUT system [40]

During the postaudit the realization of the protection is revised. This means that the empirical risk values are to be calculated and compared with the apriori calculations and the technical realization of the solution is also revised. The former includes data collection and calculation, while the latter is more technical in the terms that it deals with the actual realization – the presence and quality of the forecasting and alarming system, the execution of the preventive action(s) etc.

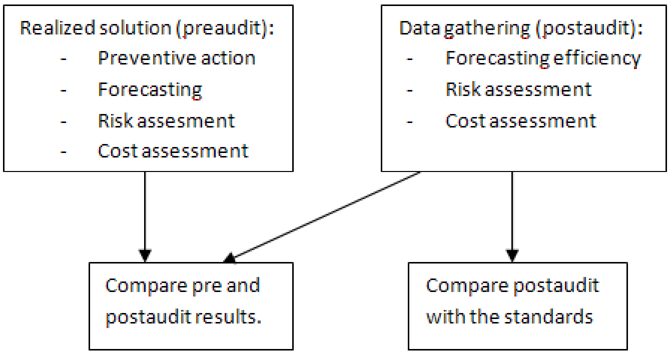

Figure 5.9.: The postaudit process in the SCOUT system [40]

Figure 5.9 shows the postaudit – or evaluation – process. An important part of a successful audit is the availability of planning information – namely the calculations which based the selection of an individual preventive action containing risk, cost and execution time calculations.

Also empirical data is required for the audit. In case of preventive lightning protection it shall include the properties of forecasting – the event space parameters [18], [25], [23] – measured empirically, and also a recalculation of.

Then these values are to be compared with each other and with standard requirements. Comparison with each other is important to classify the planning of the solution (if it was adequate based on present information) and comparison with standards is required to determine if the solution is proved to be in accordance with the standards.

This section showed how a dynamic method can be planned and audited with the SCOUT system through the example of preventive lightning protection. This is an important extension to the system as dynamic methods can be applied on other fields as well, not only atmospheric electricity.

Preventive lightning protection may be planned and evaluated with the use of the SCOUT system, but since the SCOUT system offers a general solution to these problems, the planning algorithm of preventive lightning protection is still to be discussed. The evaluation – or post-audit – methods given in the SCOUT system however can be used per se as a tool to evaluate the performance of PLP – regardless of forecasting method.

5.5. Detailed planning algorithm for PLP

The goal of planning in PLP is to determine the possible combinations of preventive actions and forecasting as possible solutions as introduced in the framework of the SCOUT system (Fig. 5.7). The decision makers require the data describing the performance of an individual action and the corresponding forecasting methods to decide on the solution to apply.

Evaluation or post-audit on the other hand means the supervision of the existing preventive lightning protection. The purpose of the evaluation is to check the efficiency and cost effectiveness of the system. Upon planning preventive lightning protection several theoretical considerations are taken into account, and usually limited information is available regarding the expected performance of forecasting. Costs and cost effectiveness are to be checked as well.

The process of planning

The goal of the planning process is to examine the possible solutions. They consist of the proper action description and the forecasting method. These descriptions include efficiency calculations and cost estimates as well. When the solutions are available, the decision maker may select the one to realize according to his own preferences.

During the planning process the basic structure of preventive lightning protection is followed.

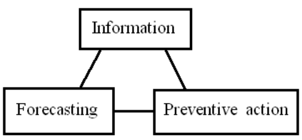

Figure 5.10.: The structure of preventive lightning protection

This structure is also applied during planning as shown in fig 5.11. The first step preceding the calculations is gathering information on site regarding geographical location, available forecasting solutions, and some object specific information. The geographical information includes the description of the location of the object (height, earth surface features, soil parameters etc.) and the meteorological data (lightning detection network data and meteorological radar data for the calculations, annual stormy days, lightning strikes etc.). The available forecasting solutions may be using lightning detection networks, meteorological radars or installing new devices.

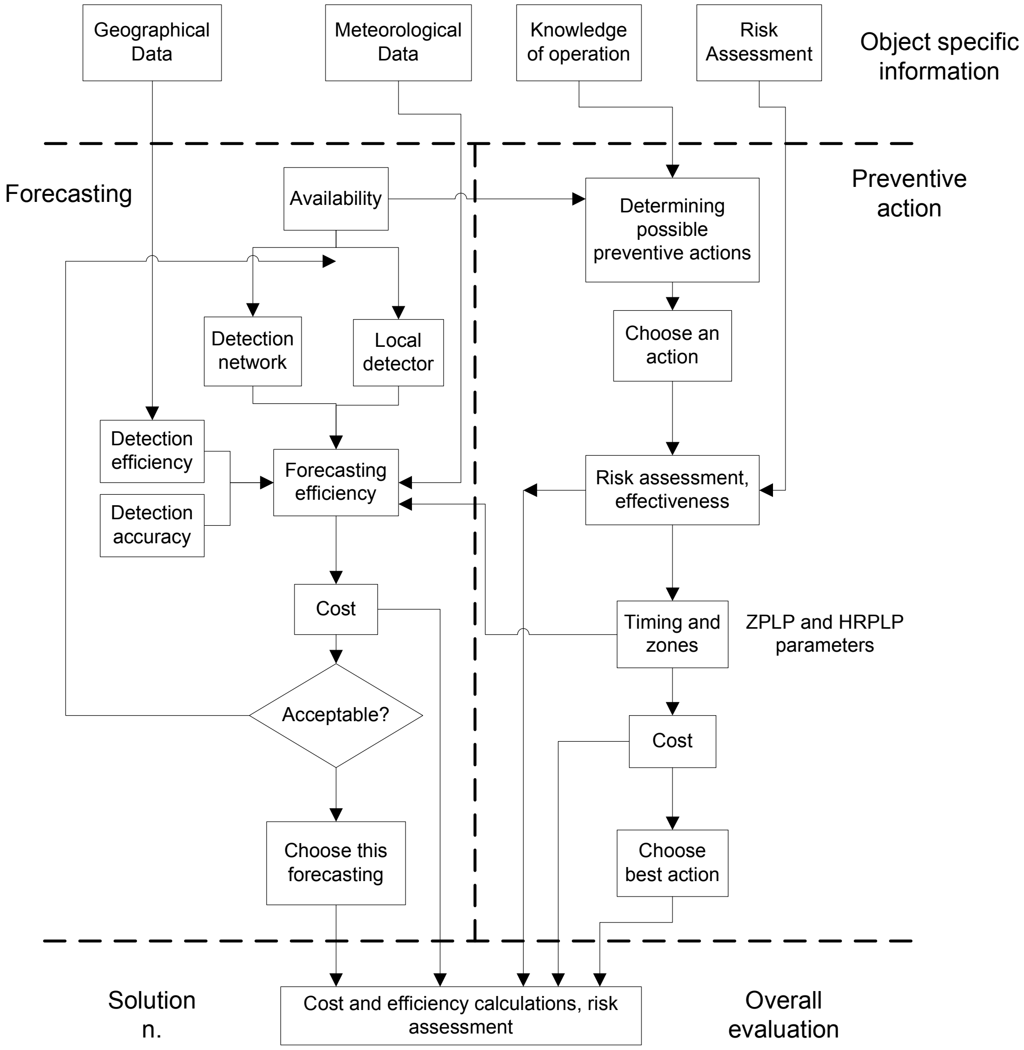

Figure 5.11.: The complete planning process [13]

Object specific information includes the data regarding the operation of the object to be protected and the according risk calculations. Operational data is required to determine the set of possible preventive actions[38]. Also the object to be protected has to undergo the process of risk calculations defined by the standards giving a result being below, or above the tolerable risk levels (in the latter case PLP is required).

[38] In case of antennae tower maintenance this set is the removal the worker from the endangered location by removing the worker from the tower entirely, or moving the worker into the interior of the tower. In case of an open-air mass event there may be many methods to protect people.

The next steps are evaluating the available forecasting, and determining the best preventive action. These steps are not always sequential steps, as the preventive action directly influences the efficiency of forecasting through the zonal protection and HRPLP – namely the sizes of the different DZ and WZs [25] and possible preventive actions are limited by forecasting capabilities.

Forecasting is realized either with a lightning detection network, or (one or multiple) local lightning detectors used in conjunction with meteorological radar systems. In the case when no forecasting can be realized, preventive lightning protection is not applicable.

A key property of forecasting is its efficiency. The forecasting efficiency is mainly influenced by the detection efficiency and accuracy [21], [25]. The detection efficiency denotes the ratio of the number of detected thunderstorms and the overall number of thunderstorms. It's very difficult to define, since the existence of a thunderstorm is verified by the lightning detection networks and meteorological radars, but some estimation exists [70], [71]. Detection accuracy on the other hand means the real location of a thunderstorm cell (the aerostatic activity classified as an active thunderstorm cell) versus the detected location. This is usually estimated with the CG strike locations (detected vs. real). Some systems claim to have better than 500m accuracy for CG strikes [53], [71]. Further than that the structure of zonal protection is also a key influencing factor (DZ and WZ sizes, multiple WZs etc.).

In some cases the lightning detection networks are not the best choice for forecasting. For example if the object is endangered by topographic thunderstorm [72] then a local detection instrument measuring changes in the electric field may prove more effective than a sophisticated lightning detection network (note that such devices cannot locate lightning strikes further away)!

The efficiency is to be calculated taking into account these properties, and the event space model parameters [25], [23] – the theoretical performance of forecasting – have to be calculated as well. After the calculation of the efficiency of the forecasting, its cost shall be considered. If a suitable forecasting is realized in terms of detection efficiency and cost, then this shall be chosen. However since the goal of planning is to find the best combination of forecasting and preventive action, this choice has to be made for every – in other ways suitable – preventive action.

The selection of the applied preventive action is also connected to the availability of forecasting. Even a less efficient preventive action may prove to be the most cost effective solution. In this regard planning of preventive lightning protection is an optimization problem of cost and efficiency.

If only local detection is available, then only preventive actions with very low execution times are to be chosen. Withdrawing workers from worksites is a good example for an action like this [73]. When lightning detection networks are to be considered as a forecasting tool, longer execution times are also allowed, for example the preparation of multiple electrical switching, or suspending industrial processes.

After the possible preventive actions are determined, their protection efficiency shall be calculated and depending on the required timing parameters the efficiency of forecasting shall be calculated. These data is used then to calculate the risks and compare it to the tolerable risk values found in the standards, and to estimate the cost of the actions with the methods introduced in this and the previous section.

The final step of planning is summarizing the results of the calculations as a possible solution. The solution includes the forecasting parameters, the accurate description of the preventive action (also including its efficiency, equivalent risk functions) and the cost estimation for both.

As the result of the planning process the set of solution is made available for the decision maker and the optimal solution (the criterion for the optimal solution is set by the decision maker) is selected.

As described in the SCOUT system, regular post-audits are required, depending on system properties. The post-audits are evaluations of the realized solution.

The goal of evaluation is the comparison of the values given from the calculations during planning with actual empirical data (according to fig 5.8). If the empirical data justifies the efficiency calculations then the solution is adequate. If the empirically calculated efficiency is lower than the theoretical efficiency – which in fact is calculated taken into account some empirical data available [25] – then it shall be considered if the protection is effective enough.

The evaluation process starts with the recollection of the calculations used during planning for the realized solution. The necessary calculations include the efficiency and cost estimates for the whole solution and separate efficiency calculations for forecasting and the selected preventive action.

The next steps are the calculation of the forecasting efficiency based on the empirical data from the active period. This includes the number of alarms (also the type of alarms) and the event space parameters. They are in this case relative frequencies, but shall be handled as probabilities for the purpose of risk calculations. Also if it's available – and necessary – the delays between hazard development and finishing execution of the preventive actions are useful information. It is used if the execution of the preventive action has certain time requirements. If there are late alarms, then their 'lateness' is to be described and their cause – improper data on thunderstorm speed distribution, improper size of the WZs – is to be found and corrected.

The resulting risk is to be recalculated with the obtained empirical data and is to be compared with standard values and the estimates given during the planning period. If the calculated values prove to be better or equal, then the realized protection is good enough. If the efficiency proves to be worse than the calculated values then the solution's compliance with the expectations of the standard shall be considered. If it is below the required level of protection (the risk is higher than the tolerable risk), then the solution has to be revised, and new forecasting methods and/or preventive actions shall be used.

6. Stochastic modelling of lightning strike point with the Open Source Lightning Model (OSLM)

4th thesis

During the planning of lightning protection the exposedness of different objects and structures are approximated by certain physical and probabilistic models or by simulations. I propose a model structure (OSLM), which –unlike currently used models – does not aim to describe the sub-processes of the lightning strike independently, but describes the whole process starting from the stepped leader development through the changes in the ground E-field to the return current flow. The essence of the OSLM model is its structure as most emphasis is given to its modularity. The sub-processes of the lightning development are described by different applied models. There may be many applied models for one individual sub-process, so these applied models are 'exchangeable' in the model enabling the researcher to compare the effect different applied models. I also introduce a possible implementation of this model including simple applied models. This implementation is used to illustrate the model for a building in terms of exposedness, thus helps in planning preventive lightning protection [74]**.**

In lightning research the use of computer simulation gained importance in the last decade due to the huge development in computer technology and models. The first model simulations were done three decades ago and since then made steady progress, but the rapid increase in computing capacity and data storage resulted in much more complex models being applied nowadays.

Numerous laboratory experiments and simulations were done to investigate the lightning phenomenon [64], [75-77],the breakdown of air [78-80] (for more references see [81] and a thorough comparison see [82]), and also to investigate Franklin rods [83]. These experiments helped understanding lightning physics, but had their limitations. For these experiments high voltage equipment is needed and the researcher is limited to ordinary laboratory conditions. A major advantage of computer models compared to laboratory experiments is that they are cheap. The only thing required for a test run is a computer with sufficient computing capabilities and the necessary time for the calculations. Another feature of this approach is that the parameters of the model experiment can be changed almost instantly, while in the laboratory the researcher is limited to instrument capabilities and the laboratory conditions. Since both the breakdown of air and the propagation of the stepped leader are affected also by different properties of the air, laboratory conditions are a true limitation.

As a result of these studies, the acquired knowledge was used to construct complex lightning models, which are capable of describing lightning propagation and attachment. With such models building exposedness and shielding efficiency may be investigated. Such models were used to test for example the exposedness of wind turbines [84] or other complex buildings [85].

In this section I introduce a novel model structure of leader propagation and lightning attachment – the Open Source Lightning Model (OSLM). The purpose of this model structure is to integrate a part of the knowledge available about lightning into a model, which may help in simulating the efficiency of different down conductor models.

The novelty in the structure of the model is modularity, which means that different models of leader propagation and input parameters are 'exchangeable'. Thanks to this the different models about lightning physics and empirical results may be compared. In its current implementa5tion it's only purpose is to test different arrangements and generate data on the probabilities of exposedness. The data can be used for comparison purposes only.

First I will briefly review the currently used lightning propagation models, then I describe the structure of the OSLM. Finally I show some test results of a simple implementation of the OSLM comparing results with other models.

6.1. Existing lightning propagation model types

There are mainly three groups of lightning models: physical models, stochastic models, and electrical equivalent models.

The physical models are the models, which are based on the laws of physics only and describe the discharges by calculating the different properties of leader propagation. The first such model was used to simulate stepped leader propagation and air ionization [75]. Also a purely physical model was developed to approximate striking points [64], [86], [87]. These models use the Maxwell's equations to compute the space charges and the potential gradient in air, when determining the leader progression direction. The velocity of the stepped leader is calculated partially by using Maxwell's equations or by using other approaches[39] .

In a recent paper Borghetti et al. presented a paper which describes a complex propagation model including the charge distributions, stepped leader propagation and upward leader development as well [88]. The authors have used a finite-element method to calculate E-field and potential distribution and use a complex model for the leader charge distribution. A similarly complex propagation and inception model was introduced recently by Cooray and Becerra [89].

Both of these models are purely physical models and they both concentrate on the final stages of downward leader propagation, and the interception. The practical use of these models presented by the authors was the investigation of the lateral distance next to tall structures protected from the lightning strike. Their results will be compared with results obtained using the OSLM later in this section.

Since they are physical models, their advantage is their drawback at the same time, which is their deterministic behaviour. When testing shielding efficiency, the physical models always predict nearly the same striking point for all test runs. Due to this they don't describe reality adequately. The reason for this is the starting conditions of the simulation. It is too complicated to account for all the properties of air and the charge distribution in the cloud etc.

[39] Based on energy calculations rather than supposing the electrical environment as the only influental source of particle motion.

To account for this, probabilistic models were created. These models do not approximate the environment with probabilistic functions, but they approximate the behaviour of the discharge as random, which may be based on real physical parameters.

The simplest model types do not consider electrical processes at all when determining the propagation direction of a lightning discharge – for two such models see [90], [91]. Total randomness is again not an adequate description of reality, still the authors in these referred models used their model to test the efficiency of LPS. Both models use the electrogeometrical model in a probabilistic way. The peak current is chosen randomly, and the different properties of the lightning discharge (jump length, orientation distance) are determined using to this value.

An approach taking into account electrical phenomena is for example using the electric field along the leader as a function correlated to the propagation direction [92], [93]. It's also possible to use the stochastic view in the micro-processes of discharge formation and progression [93].

The drawbacks of these models are that they sometimes may lead to surreal lightning paths, or exclude existing lightning propagation patterns due to the input parameters and boundary conditions defined in the model. Also it is hard to approximate the real environment, so the comparison of these models with real experiences is difficult. The models however are capable to make comparisons between different protection systems and solutions.

The OSLM aims to unite the advantages of both physical and stochastic models and provide a model structure which can be modified according to newer results. The current implementation of the OSLM uses similar mixed probabilistic approach by taking into account electric fields, various streamer leader models in both downward and upward leader propagation. Note however that the OSLM is not limited in this sense. Since its novelty lies in its modularity it may be implemented as a purely stochastic, or purely physical model. The choice of the mixed probabilistic approach for the current implementation was to combine the advantages of both model types.

6.2. The modular algorithm of the OSLM

The modularity of OSLM is in the algorithm of the simulation. The algorithm is practically applying the models of physical phenomena, and combines the result to calculate the progression of the lightning discharge (both the downward and upward leaders and the streamers).

The simulation algorithm consists of the following steps:

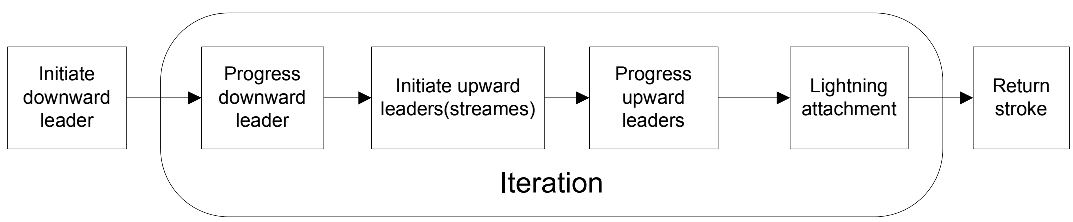

Figure 6.5.: The steps of the simulation [74]

The first step of the simulation is the random selection of the starting point of the discharge at the level of the cloud. The following iteration is basically the calculation of the steps of the leader, calculation of possible streamers and upward leaders, their path, and the possible attachment. Note that the return stroke models are currently not implemented (as the purpose of the current implementation was the simulation of lightning path only). There are several existing return stroke models, see [94-98]. Still the model structure is open for the implementation of such models.

The modular modelling structure of the OSLM means that in various parts of the simulations certain models applied in the calculation steps may be ‘exchanged’ if alternative models are available for certain physical processes (in the colour coded steps shown in Fig 6.6).

The iteration starts with the electric field calculations around the stepped leader, and the streamers, if there are any. This calculation is influenced by the following models and parameters: the cloud model, the ground conductivity, the leader charge model, and the streamer model. This shows the complexity of the OSLM and the influence of the various models.

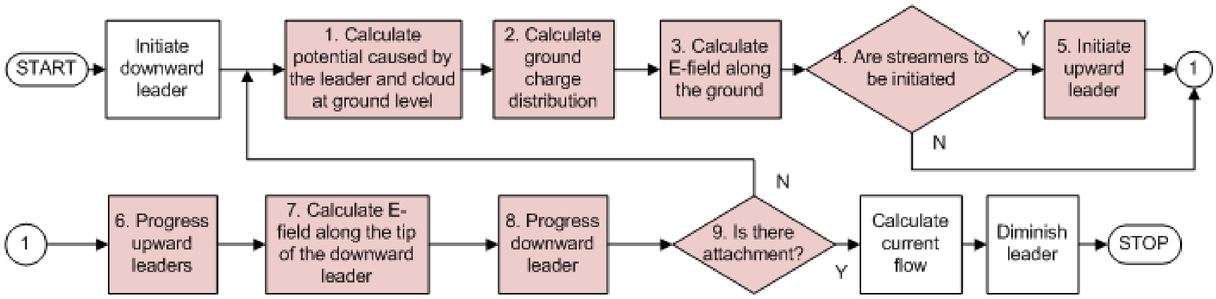

Figure 6.6.: Simulation steps in details (as implemented in the OSLM) [74]

As shown in Fig 6.6, the sequence of the calculation in a single simulation run follows the progression processes. First as the downward leader is initiated, the potential drop at the ground changes. This results in a change of the charge distribution as well and also in changes to the E-field. Each of these is calculated in this order to determine if the E-field exceeds the critical level for discharge formation. The streamers preceding the upward leaders are initiated and the progress of the upward leaders is calculated. This is followed by the progression of the downward leader and the determination of the attachment.

The applied models can’t be assigned to individual calculation steps, but influence multiple steps and also interact in some ways. There are 9 steps in total in Fig 6.6 (coloured), which are based on the applied models. As a short summary each of these steps is given in the following table in the modelling aspect.

Table 6.1.: The applied models in the simulation steps

	1	2	3	4	5	6	7	8	9
Cloud charge model	+		+	(+)			+	(+)	
Ground charge model		+	+	(+)			+	(+)	
Leader charge model	+		+	(+)		+	+	+	
Leader step model								+	+
Streamer initiation model				+					
Streamer charge model							+		
Upward leader step model					+	+			+

The ground potential calculation (the first step) is influenced by the applied cloud model and the applied leader model as well. The ground E-field and charge distribution (second and third steps) is influenced by both of these models, plus the applied ground model. In this sense the can be grouped into one model group. This shall be omitted though as the steps have unique parameters. For example the ground potential is calculated at numerous points, while the E-field is calculated at discrete locations (at the charges). In the modelling point of view this allows us to model complex ground topographic geometries with only a fixed number of charges.

The streamer initiation process (fourth and fifth step) may be separated from these models, however implicitly the E-field calculation includes the influence of the applied cloud, ground, and leader model (for the downward leader). If the streamer model handles the E-field as an input parameter or a boundary condition, then it may be handled as an independent calculation process from the ground, cloud and leader models[40].

The upward leader progression (sixth step) is described essentially by the same model as the downward leader, except for the amount of charges possibly contained in an upward leader. Upward leaders form only when the downward leader is close to the ground and as such their source is an external field. In case of a downward leader the formation is a completely different process. This difference also results in different propagation properties. Practically upward leaders progress towards the downward leader, as the source of the discharge is the downward leader itself (and the gap is considerably smaller than in the case of the downward leader and the ground).

Calculating E-Field at the tip of the downward leader (seventh step) requires the most calculations as the most charges are taken into account here (all charge models are included). The last two steps are generally about the step models – the direction of propagation and the step length. In the progression of the leader the charge configuration of the leader has to be changed according to the leader charge model (point charges, line charges, mixed). Finally the

[40] This enables the researchers to model the streamer micro processes separately.

attachment is currently described only through the step models of the upward and downward leader.

6.3. The structure of the OSLM – applied models

As mentioned before the uniqueness of the OSLM lies in its modularity. Also since this model is an "open source" model, it has to be modular in computing terms as well. It has to include parts which can be exchanged to include different approaches, different models. This modularity depends on the model structure and the input parameters.

The OSLM structure is based on the propagation of the discharge itself, so the main parts of the OSLM are the following:

- Input parameters: cloud level, structures and other objects on the ground, ground conductivity, lightning parameters.
- Applied models:
    - Cloud model: charge structure
    - Leader charge model: linear charge distribution, or point charges along the sections of the leader.
    - Leader step model: the direction the leader progresses after a given step, length of a step.
    - Streamer model: the formation and progression of streamers
    - Attachment model: the orientation point, and streamer "selection"

The input parameters are always exogenous; those are the starting conditions for the simulations. These parameters may differ in each simulation, as there may be multiple geometries and structure configurations to be examined.

Applied models on the other hand are integral parts of the OSLM. These models are assumptions and propositions of the different micro and macro processes of lightning propagation and charge configurations of the environment. Note, that an advantage of the OSLM is that it can be used not only as a whole, but also only parts of the model can be used to test theories.

So in certain simulation scenarios some applied models are practically 'boundary conditions' rather than actual models. For example when modelling the leader properties, simpler ground models may be adequate, but when modelling the attachment process, more complex ground models are to be applied.

The input parameters

The input parameters of the OSLM are the cloud height, the properties of the lightning (peak current, or transferred charge depending on the applied leader model), the ground structure configuration including the shielding system, and the ground conductivity.

An ideal approximation for ground conductivity in the model calculations (the effect of this is discussed at the given model) is the ideal conductor. This means that the ground resistivity is 0 and also implies that the charge transfer is instantaneous. When the charge configuration changes in the environment (the downward leader progresses), the charges on the ground change instantaneously.

The cloud height is the height the cloud is compared to the 0 point of the ground. 0 point does not mean sea level in this model, but the point where the ground structure has its lowest point. Usually the cloud level starts from 1000m depending on the actual geographical location.

The structure configuration on the ground includes the structures built and other objects. Also the terrain may play an important role, thus it is also to be included in a simulation. A practical representation – also used in the simulation – is the map of the ground surface showing the height at a given x_0,y_0 point.

Structures are also to be modelled electrically. The simplest model for the structures is the cube approximation, but special structures may be described only by using more complex charge configurations. It's possible to model the structures with ideal conductors resulting in less complicated calculations with the following boundary condition.

$$\varphi = 0 \qquad (6\text{-}1)$$

Even though this influences the calculations and as such shall be handled as an applied model, this is determined by the ground conductivity – a parameter which is given at the start of the simulation. The applied ground charge models are however mainly influenced by this input parameter.

Applied models – the cloud model

The first applied model of the model is the cloud model. Its function is to describe the electrical equivalent of a thunderstorm cloud. There are many types of cloud models: single charge models, bi- and tripolar cloud models, and also charge clouds are used to describe the structure of a thunderstorm cloud.Using different cloud models results in having different potential gradient and electric field in the air in front of the leader, and above the ground. According to the complexity of the cloud model, overall calculations take longer.

Multipolar cloud models mean that the cloud structure is described by using certain charges producing the same electric field below the cloud. Such models may describe the thunderstorm cloud as a dipole [99], tripole [100] or even with various charge layers [101]

Figure 6.1 shows the tripolar cloud model developed originally by Simpson and Robinson [102]. Using such a model is relatively easy, due to the low number of charges representing the cloud. A problem of this solution is that when modelling the progression of the discharge just below the cloud, the calculation error can be relatively high. In case of non-zero ground conductivity however the number of calculations is greatly reduced by using a tripolar cloud model. An advancement to this approach may be the use of charge clouds instead of point charges, as it was done in [103]. Using charge clouds means, that the 'area' of the thunderstorm cloud is taken into account, thus it's more accurate. It's drawback is that the number of calculation steps is huge.

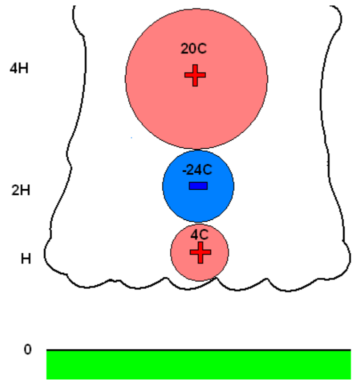

Figure 6.1.: The tripolar cloud model

Another possible solution to provide accurate resultant field also at the leader tip is the use of a distributed charge model, when calculating the electric field. The advantage of this model is that it reproduces the uniform electric field, when no discharge is present and also allows more accurate field calculations. It is realized again by using point charges, but for this case the point charges are distributed at cloud height through the whole cell. The charges are calculated to reproduce the electric fields at ground level.

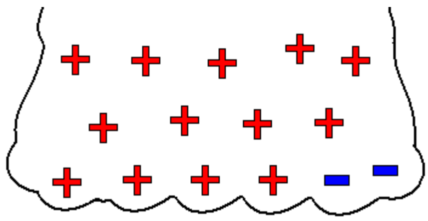

Figure 6.2.: The distributed charge cloud model

A further simplification is diverting from the charge models and using a constant E-field (produced by the charges in the cloud) as an offset in the E-field calculations. Note, that it decreases with the distance from the cloud. A somewhat similar approach was presented by Amoruso and Lattarulo [104], who introduced an 'electrostatic' cloud model consisting of multiple charge layers. For a further review on charge models see Rakov and Uman [105].

The choice of the cloud charge model also enables researchers to compare different theses concerning the physical phenomenon during the discharge formation. The amount of charges placed in the simulation highly influences not just the process of leader, but also the streamer formation and progression due to its influence on the E-field calculations.

The applied cloud model should not only include the charge configuration of the cloud, but also the charge movement in the cloud. During leader formation and attachment a certain amount of charges are transferred to the ground, thus the charge configuration of the cloud changes during lightning formation [106]. It's necessary to take these effects into account when modelling the diminishing of the thunderstorm, but when individual lightning paths, or micro processes are examined, a constant charge configuration is appropriate. Note though that incorporating charge movement during the discharge again introduces complexity which may not be necessary. Thus in the current implementation charge transfer in the clouds is entirely omitted. Referring to Fig. 6.6 the charge movement in the cloud could be included as an additional step after the progression of the downward leader (before checking attachment.)

Applied models – the ground objects

Ground objects represent a certain charge configuration in electrical terms. One of the input parameters – the ground conductivity – basically determines this charge configuration. In case of modelling the ground as an ideal conductor, the charge configuration is 'non-dynamic' in the sense that it only reacts to the changes in the cloud and leader charge configuration.

In non-ideal conductors the charge transfer is slowed down due to the resistance of the material, thus the charge equilibrium is not produced instantaneously. In other terms, during the progression of the downward leader, the change in the ground charge configuration 'follows' the changes in the leader and cloud charge configuration. In case of ideal conductors the charge transfer is instantaneous, so there's no 'dynamism' in charge transfer in this regards.

Also the charge supply of the ground is to be modelled. A simple assumption is the infinite supply. This is based on the assumption that the ground represented in a simulation is an infinitely small part of the earth and there are ample charges to make up for the increased charge demand. This assumption does not only hold when supposing an ideal conductor. When using a given ground conductivity, the supply of charges may be infinite, but the speed of charge transfer is not infinitely high.

Besides the ground conductivity and charge supply, the actual placement of charges is also important. The ground may be modelled as a set of surfaces having surface charges, or may be represented by point charges. When working with surface charges though, important points on the ground – especially the peaky structures, for example lightning rods! – are hard to be represented. Also both field and potential calculations with point charges are much simpler than with surface charges.

The ground and the cloud models in the OSLM are usually selected according to the purpose of the simulation. When simulating the leader progression process, the cloud plays an important role, as the changes in the cloud charges influence the steps of a leader, the channel size and also other factors. In this case a complex model is required to account for as many effects as possible. When the upward leader is modelled however, the ground model has to be chosen carefully.

However when the OSLM is used for statistical purposes only, the simplest cloud and ground models are adequate. The most important parts of the simulation are the upward and downward leader models.

Applied models – the leader model

The leader charge distribution model

When simulating the progression of a leader the presence of an ionized channel also has effect on the propagation due to the relatively high charge density along the channel. So the electrical behaviour of the leader channel has to be taken into account in the calculations. There are basically two types of models applied:

- Leader sections are substituted by point charges
- Leader sections are substituted by line charges (with constant or vertically decreasing charge densities)
- (Combined point-linear charge models for the simplification of calculations)

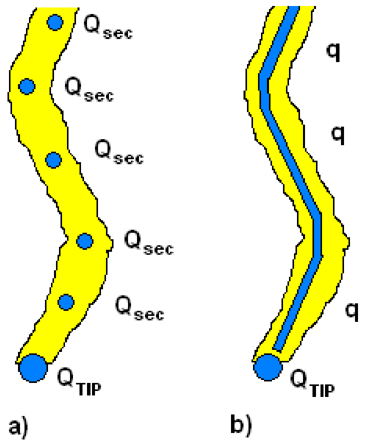

Figure 6.3.: Leader model using (a) point charges and (b) line charges

Also the tip of the discharge channel is usually modelled with a point charge, larger than any substituting charges. The type of leader model also determines the field strength in front of the discharge. The last few sections of the leader have the biggest influence on the field structure, so the simulation is very sensitive to the leader charge model [107]. Some leader charge distribution models are shown in appendix A4.

When using a point charge leader model, the E-field caused by the leader is calculated using the following approximation.

$$E = \frac{U_2 - U_1}{r_2 - r_1} = kQ\left(\frac{1}{r_2} - \frac{1}{r_1}\right)\frac{1}{r_2 - r_1} \tag{6-2}$$

In case of line charges, the following formula is used.

$$E = \frac{U_2 - U_1}{r_2 - r_1} = kq\left(\ln\frac{b + \sqrt{b^2 + d_2^{\,2}}}{-a + \sqrt{a^2 + d_2^{\,2}}} - \ln\frac{b + \sqrt{b^2 + d_1^{\,2}}}{-a + \sqrt{a^2 + d_1^{\,2}}}\right)\frac{1}{r_2 - r_1} \tag{6-3}$$

This expression was obtained using (6-2) using the geometry shown in Fig. 6.4. Note that this figure shows the potential calculation at a d_1 distance. To obtain the E-field, it has to be calculated at a further distance as well.

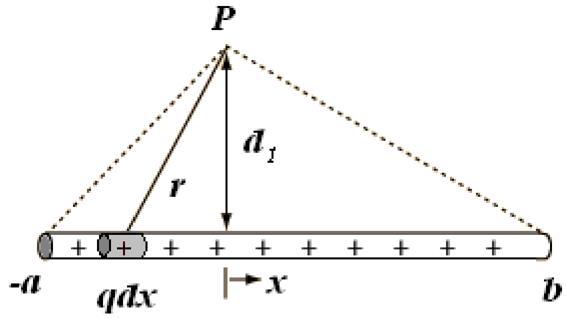

Figure 6.4.: Calculating the potential caused in point P by a finite line charge

Both of these formulae are derived from potential calculations, which have relatively low calculation needs. It is also practical, since the addition of the effects of numerous charges in the simulation space is quickest to be calculated using potential calculations.

Another parameter of the discharge channel is its conductivity, which is important when applying more complex physical models. This involves modelling the charge transfer through the downward leader not just a simple substitution with line charges, or point charges [106]. This model yields more complex calculations, but it's closer to reality. However depending on the purpose of simulation, such depth is not always required. For example when using it to determine strike points, or compare shielding systems, using very complex physical models for the leader channel may prove unnecessary.

The leader step model

The progression of the downward leader has two parameters. One parameter is the direction of the propagation and the second one is the distance the discharge progresses in one step. The step distance depends on the charges contained in the discharge. In a downward leader, huge quantities of charges are transferred, thus this discharge progresses in long leaps towards the ground.

The upward leader on the other hand carries smaller amounts of charges. Usually a given fixed velocity ratio is used between 0.5 and 4 [108]. Using a fixed ratio for velocities results in leap lengths easily calculated.

The leaps of the stepped leader can be modelled as a fixed value using the electrogeometrical model [91], or by using corona models [81], [109]. The electrogeometrical model may only be used as an approximation as it models the striking distance rather than the leader step. It is based on empirical considerations and is described by the following expression [64].

$$\frac{r}{r_m} = \left(\frac{I}{I_m}\right)^p \qquad r = \alpha * I^\beta \qquad (6\text{-}4)$$

These expressions describe the connection between the striking distance (the distance of the point of the strike and the orientation point) and the peak current transferred by the lightning. The former expression uses the median values versus the actual values, while the latter expression is a simplification to that (mathematically). Both of them are empirical models and proved to be efficient in both theory and planning [110]. The parameters α and β in (6-4) have been determined using available data and experiments, resulting in $\alpha=10$ and $\beta=0.65$ [64].

According to other simulation results the parameters in the latter expression are $\alpha=3.947$ and $\beta=0.7851$ [111]. This is a major difference as for example at $I_p=100\ kA$ (a quite common peak current value) the striking distance is ~200m, while with the newer values result in ~140m.

The striking distance – or critical distance as it has been referred to by Horváth [112] – can be described in a probabilistic way. The density function of the critical distance includes the median striking distance (calculated using (6-4) assuming a median peak current of 35kA) and two other parameters, *k* and *p*. The resulting distribution is practically defined along the striking distance 'ratio' (compared to the median striking distance determined by the peak current). The parameters were defined by sever authors. *K* was usually assumed to be 1, while *p* ranges from 1.25 to 2. (For a complete review on this model see Horváth [112]).

$$\frac{dw}{dr} = \frac{kp}{r\sqrt{2\pi}} e^{\left[\frac{k^2 p^2}{2}\left(\ln\frac{r}{r_m}\right)^2\right]^p} \qquad (6\text{-}5)$$

This model implies that the 'peak' of the striking distance is always a bit below the median distance calculated using (6-4) depending on the peak current. Also note that different *p* values result in different distributions, but all of them are positively skewed normal distributions.

The direction of leader propagation is also an important point of the simulation. There are various models describing propagation direction starting from simple probabilistic models to complex physical models (mentioned before). Each of these approaches may be implemented in the OSLM, but it's important to keep in mind that due to the current focus of the OSLM (omitting micro processes) the stochastic approaches are more appealing for the implementation. Stochastic models range from purely probabilistic models [91] to mixed-probabilistic models [92], [113]. The former model assumed that the propagation direction is described by a simple probabilistic distribution, while the latter models assumed that the propagation direction is related to the local electric field – still retaining that it is random.

The streamer model

The streamers in a lightning strike appear at ground level when the discharge is relatively close to the ground. In this case the E-field along the ground – and the structures – becomes so high, that corona discharges turn into a streamer and then to upward leaders. This also means quite high charge concentration at that point[41].

As the charge concentration increases due to the presence of the downward leader and the electric field caused by the cloud charges, the E-field also increases along this point at the ground resulting in E-fields higher than a critical value of the breakdown of air (1MV/cm calculated 35 cm from a given point – the value of 5-10kV/cm at 70 cm was used in [113]). This initiates a streamer, which also changes the E-field along the ground. As the downward leader progresses, it also produces larger E-fields enhancing the streamer to an upward leader of the opposite charge, which then progresses towards the downward leader. This method is similar to the one proposed in [64].

Note that other criterion depending on the height of the building/lightning rod exist for example given by Rizk [116] or by Lalande [117]. Such criteria are quite practical as it gives the critical E field for a structure with a given height. Unfortunately in case of more complex structures this criterion was not investigated, so they are not used in the OSLM, but of course they may be implemented.

The attachment model

The attachment model incorporates the attachment processes of the upward and downward leader. Depending on the simulation purpose this may only be an 'attachment, non-attachment' type of check, or a thorough model of corona formation and charge transfer in air.

The attachment process is one of the most complicated processes of lightning, as it involves the interaction of two discharges – the upward and downward leaders. A very simple assumption for attachment is a simple distance criterion, which means that an attachment occurs, if the downward and upward leaders are close enough (in the range of their leap distance). Note however that this is a very simple model and shall be used only in the cases when the purpose of the simulation does absolutely not involve the modelling of the attachment process (this concept is in use since the earliest simulations [64], [76]).

A much more complex criterion was used by Borghetti et al. in their model [88]. In their model the 'final jump' of the stepped leader (the attachment to the upward leader) was made when the voltage gradient exceeded 500kV/m in a path crossing the space between these two leaders. In their model they evaluated this criterion for each E streamline connecting the leaders through their whole length.

For a deep review on the literature and a proposed model of attachment see [81] . Such models are quite complex and the current implementation of the OSLM does not aim to take the attachment process into account in this depth.

6.4. The current implementation of the OSLM

When implementing the various models in the OSLM, the purpose of the simulation has to be chosen first. In this thesis the OSLM is used to approximate exposedness of a certain areas of a building to aid the planning of preventive lightning protection. As written in the earlier

[41] Streamer progression was modelled by Arevalo et al. [114] and Agoris [115].

sections the OSLM is capable of modelling physical phenomenon at a much more thorough level, but since this thesis is centred on the topic of preventive lightning protection, only simple results of the OSLM is presented.

Here the implementation is discussed first from a theoretical aspect then from a practical aspect (including the numerical values corresponding to the current implementation). After the description of the current implementation it is compared with some existing methods in small sample tests (<1000 runs), and also simulation results for real building arrangements are shown.[42]

6.4.1. The theoretical approaches currently implemented

The implemented cloud model

An important point of this implementation was to reproduce the quasi-constant E-field between the ground and the cloud [104]. For the sake of simplicity a charge matrix was used as a model for the cloud charges. The dimensions of the charge matrix should be the same as the dimensions of the examined ground surface (widths). The number of point charges in the charge matrix should represent the effect of the charges contained in the cloud.

A good starting point to calculate the charges with the set of existing simple cloud charge models, the bi- and tripolar models. Using a few point charges only (bi/tripolar model) may be inaccurate at levels close to the ground, as the E-field produced by point charges far away diminishes, and is highly modified by the field of the leader. Using a charge matrix at cloud level producing the equivalent potential (and thus charge) distribution in the ground as a bi- or tripolar model would lead to more accurate charge distribution calculations along the ground even when the leader is closer to the ground.

Of course multiple charge configurations may be implemented. The easiest assumption is the charges in the cloud charge matrix are equal and their value is constant in time. This is an appropriate assumption if reproducing the E-field between the cloud and the ground is the purpose of the simulation. However, when charge transfer is modelled [106], this may be inappropriate, but it is not in the scope of the current implementation. When the charge amount varies in time, then there is an interaction between the cloud model and the leader model (and with the other applied models upon the return stroke calculation) to be taken into account.

The implemented ground model

Just as in the case of the cloud model, a simple approach is currently implemented. At the ground level and buildings, a simple charge matrix is implemented. Much lower charge density is applied at ground level than on the buildings.

This is due to that the E-field is mostly influenced by the charge concentration on the edges of buildings. The charge values change according to the leader progression.

[42] Simulation results for the model of the Ostankino Tower are found in Appendix A4.

The charges at the ground are placed 0.3m below ground level because potential points are placed at the ground surface. The boundary condition used in the model is described in (6-1) – the ground is modelled with an ideal conductor. Let's suppose that the leader and the cloud charges produce the potential distribution of $\underline{\varphi}$. The charge distribution at the ground and buildings counter this potential to satisfy the boundary condition of $\varphi=0$. The ground charges may be calculated then with the following formula.

$$\underline{D} * \underline{Q_g} = -\underline{\psi} \tag{6-6}$$

The D matrix in (6-6) contains the distance between the ground charges (also the building charges) and the potential produced by the downward leader (which is countered to satisfy (6-1)). The matrix inversion has a calculation requirement of n^3, so it is very difficult to realize real-time. This would result in very long simulation times. The calculation is a bit simpler, as the matrix is a symmetric matrix (since it contains distances only).

$$\underline{D} = \begin{bmatrix} d & d_{11} & d_{12} & \dots & d_{1,n-1} & d_{1,n} \\ d_{11} & d & d_{23} & \dots & d_{2,n-1} & d_{2,n} \\ d_{12} & d_{23} & d & \dots & d_{3,n-1} & d_{3,n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ d_{1,n-1} & d_{2,n-1} & d_{3,n-1} & \dots & d & d_{n-1,n} \\ d_{1,n} & d_{2,n} & d_{3,n} & \dots & d_{n-1,n} & d \end{bmatrix} \tag{6-7}$$

Also since the charge configuration does not change, the matrix D is unique for each configuration, thus it is to be calculated only once. Then if stored, then only (6-7) is to be calculated – a matrix multiplication and the potential calculation. A further simplification to calculating (6-6) is using the Cholesky decomposition of (6-7)[118]. It is also required as it is at least one order quicker than ordinary matrix inversion methods, and it is included in the current implementation.

When Q_g has been calculated, then the E-field along the ground is to be calculated. To simplify the simulation, it's possible to avoid E-field calculations, when the downward leader is far from the ground and buildings. In these cases the E-field is not high enough to produce streamers and upward leaders. The E-field is calculated using potential calculations as described in (6-2, 6-3).

The majority of calculations in the current implementation are related to the implemented ground model. The results of the calculations serve as the starting conditions for the further model calculations.

The implemented leader model

The leaders are implemented currently as point charges at the sections progressing towards the ground, each section resulting in a new point charge (with the leader tip having a considerably higher point charge). The E-field in front of the discharges influences the progression of the leader and the streamers. The progression direction is determined randomly using a probability distribution function based on earlier results [92].

An improvement to this result in the current implementation OSLM is that a non-flat (normal) distribution of start electrons was taken into account when determining progression. The presence of start electrons and the strength of the E-field both influence the propagation direction. Thus the probability distribution function is calculated the following way.

$$p(\sigma,\delta) = p(\bar{E},\sigma_e,\delta_e) \sim E(\sigma,\delta) * n_e(\sigma,\delta) \tag{6-8}$$

The expression above shows that the probability distribution of the progression direction is proportional to the convolution of the E-field values and the start electron distribution. The angles in the expression represent the angles, when the distance from the tip of the discharge is described in polar coordinates. The number of start electrons is currently modelled with a normal distribution having a standard deviation of 20° and the final propagation distribution is formulated by centring this normal distribution to the direction of the highest E-field value.

The step length is calculated using the distribution defined in (6-5) with $p=1.85$ as suggested by Horváth. Step values may change, if a different expression is used. Besides the length of the leaps, the existence of branches is characteristic to a downward leader. In the current implementation however the branching effect is omitted due to the purposes of the implementation[43].

The upward leader is modelled differently, as multiple steps may be made by the upward leaders before the attachment. Each new upward leader section is represented with a point charge at the tip of the upward leader sections, which decreases the chance of the initiation of a new leader decreasing the E-field. The charge carried by the upward leader was set using the results of Ait-Amar and Berger [108].

The upward leaders progress towards the downward leader tip or the closest point of the leader, if the downward leader tip propagates in another direction. Hence there may be aborted upward leaders as well [119]. The steps taken by the upward leader are modelled using the suggestion of Ait-Amar and Berger as well, by using the velocity ratio of the downward and upward leader. They suggest values between 0.5 and 4.

The implemented streamer model

In the current implementation the streamer model is used in the first step of modelling the upward leader. The critical E-field criterion is 10kV/cm for negative downward leaders and 5 kV/cm for positive downward leaders calculated 70 cm from the possible point of initiation based on [113]. The upward leaders are initiated only from the points of the point charges to simplify calculations. Also buildings constructed by numerous point charges are taken into account in more details with more sources of upward leader initiation.

The criterion is first evaluated at the point of the maximal E-field. Then a distance criterion is applied. A critical radius where no other upward leader may be produced when one is already initiated is given. Since a perfect conducting ground is assumed with infinite charge

[43] Regarding modelling branching and general models see [111].

resources, the effect of an existing upward leader in the formation of other upward leaders may not be taken into account. At these locations the E-field is evaluated and new leaders are initiated further applying these criterions. This may lead to oversimplification, but since usually the maximal E-field is closest to the downward leader tip, it yields adequate results.

The implemented attachment model

The attachment process is not modelled physically in the current implementation. The criterion of the attachment is purely a practical one. Since the upward leaders progress towards the downward leader, they get closer to the tip with each step. The criterion for the attachment is the distance between the downward leader tip and the upward leader tips. Once an upward leader tip is closer than one step of the downward leader (determined probabilistically using (6-5)), the attachment occurs. In case of multiple upward leaders in that range, the closest one is selected.

Due to the purpose of the current implementation the return stroke process is not modelled at all, nor are multiple attachments taken into consideration.

6.4.2. The practical implementation

The current implementation of the OSLM is capable of handling charge configurations of around ~5000 ground charges. This limitation is of course only practical, as this size requires a huge number of calculations at each step. Due to the available memory of current computers, the OSLM is capable of handling much more than 5000 charges, but the calculation times are not reasonable at such high numbers. Note that even though the OSLM is intended to be used for lightning calculations, its modularity makes it capable of handling various geometries. The OSLM is implemented in 3D using up-to-date computing techniques.

Figure 6.7 shows a starting point of a simulation. A simple geometry is used and the cloud height is 2000m.

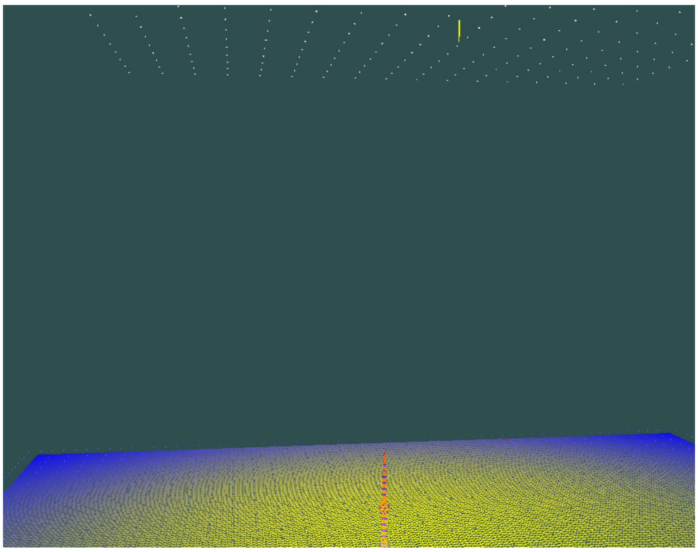

Figure 6.7.: The start of the simulation

At the top of the screen the cloud is represented by point charges. The leader is assumed to be starting from the centre of the simulation space, at cloud height. The ground objects are coloured according to the potential drop at the given point in this figure. The resolution of the ground for potential drawing is 1 point per 20 m (user defined). The point charges are represented by red, white or blue diamonds (depending on their charges). The charges density on the ground is 1/100 m (user defined) in each axis, but in case of buildings, the density is higher. See the appendix on further implementation details.

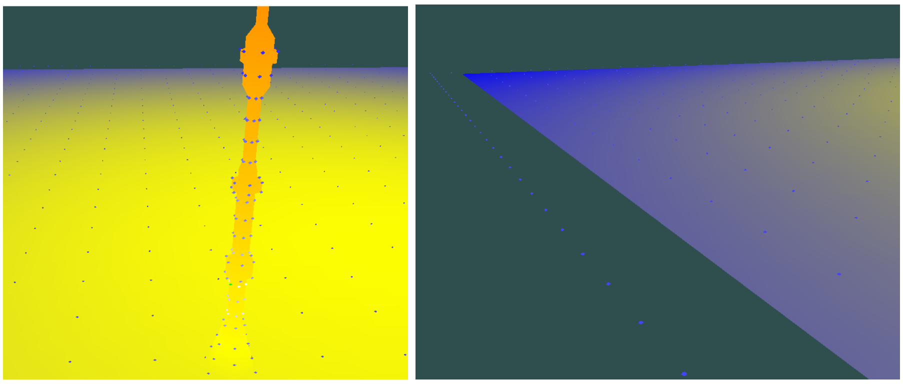

Figure 6.8: the charge resolution at the buildings (left), boundary charges (right)

As seen in Fig. 6.8 the potential drop is higher at the edges of the building, as is the charge density. The ground surface is usually a rectangle shaped terrain, so the outmost charges are calculated to be much higher than the others on the ground. The reason for this is that the size of the ground plane "opposite" the cloud is determined by the dimensions of the charge matrix. Thus a ground plane does not represent an "infinite" surface. To compensate for this effect a charge ring is defined around the ground plane (as seen in fig 6.8 right). As a result of the calculations these charges are usually higher, than the other charges. For better symmetry a cylindrical structure may be applied.

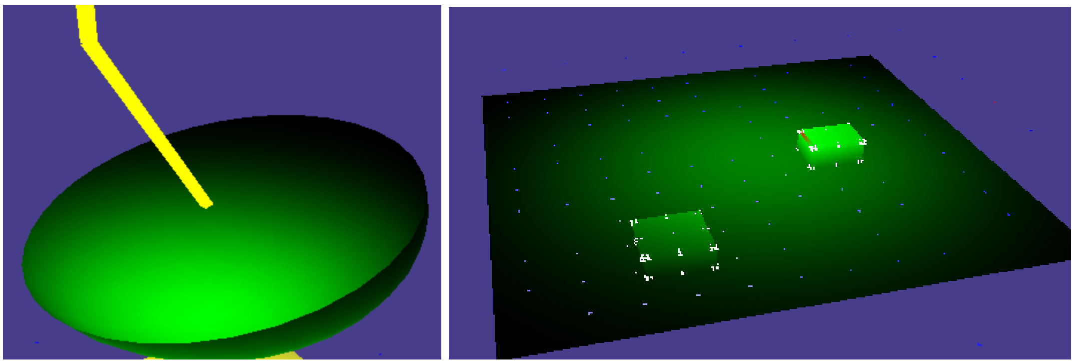

Figure 6.9: E-field around the leader tip (left) and at the ground (right) in case of a simple geometry

The resulting charges – the cloud, leader, ground, and boundary ground charges result in a strong E-field in front of the downward leader (fig 6.9 left), and at ground level (fig 6.9 right). The voltage gradient in front of the leader is calculated at 0.3-0.35m. According to the E-field distribution (convolved with a normal distribution, see (6-8)) then leader progresses randomly.

When the downward leader approaches the ground, the streamer initiation is evaluated according to the criterion given in the applied streamer model. If the criteria are fulfilled (in the current implementation it is an E-field criterion and a distance criterion), then a new upward leader is formed as show in fig. 6.10 (left) with very simple building models. It progresses towards the downward leader.

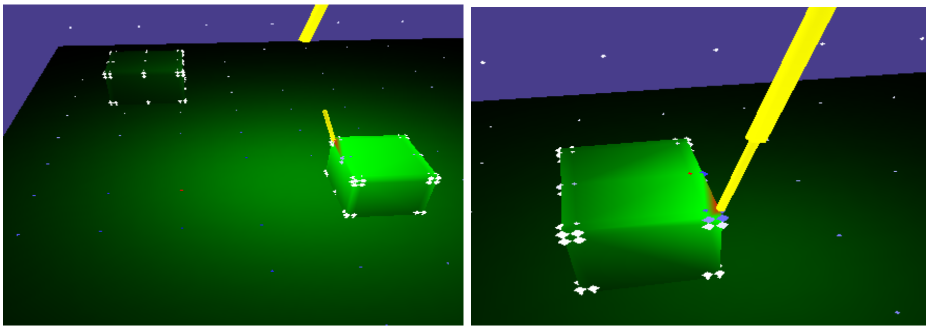

Figure 6.10: Initiation of an upward leaders (left) and the attachment (right)

In the next steps the upward leader progresses towards the downward leader until it gets near enough (closer than a step of the downward leader). At the next step the downward leader progresses toward the upward leader, then the attachment occurs (fig. 6.10 right).

The current implementation does not include the return stroke, so no current calculation is done. Instead – as per the purpose of the model – the location of the strike is saved. After the attachment all leaders are diminishes and the simulation starts again. As noted above currently the upward leaders are initiated only from point charges at the ground, so the 'distribution of strike points at the ground' is discrete. For the current implementation this resolution is adequate.

6.4.3. Comparison of the current implementation of the OSLM with other models

Lateral protection distance

To test the OSLM models a simple implementation (discussed earlier in details) was realised and a small sample test was conducted to provide comparison with other existing models. Here a short comparison is given with two other models. Both of them are numerical models and they do not apply stochastic methods, but are similar to the current implementation of the OSLM in many background assumptions.

A very recent article of Borghetti et al. described the numerical solution of a complex downward and upward leader progression model (LPM) proposed earlier by Dellera and Garbagnatti [88]. In their paper they have analyzed the lateral distance of strikes from a 30m tall rod. Their model used the finite element method (FEM) in their calculations.

The results of their simulations (numerical) showed the non-linear relationship between lightning peak current and the lateral distance, which is especially emphasized in case of higher lightning peak currents. The current implementation of the OSLM may be compared to the results of this model. Just as in case of the simulation of Borghetti et al., a non-linear relationship was found.

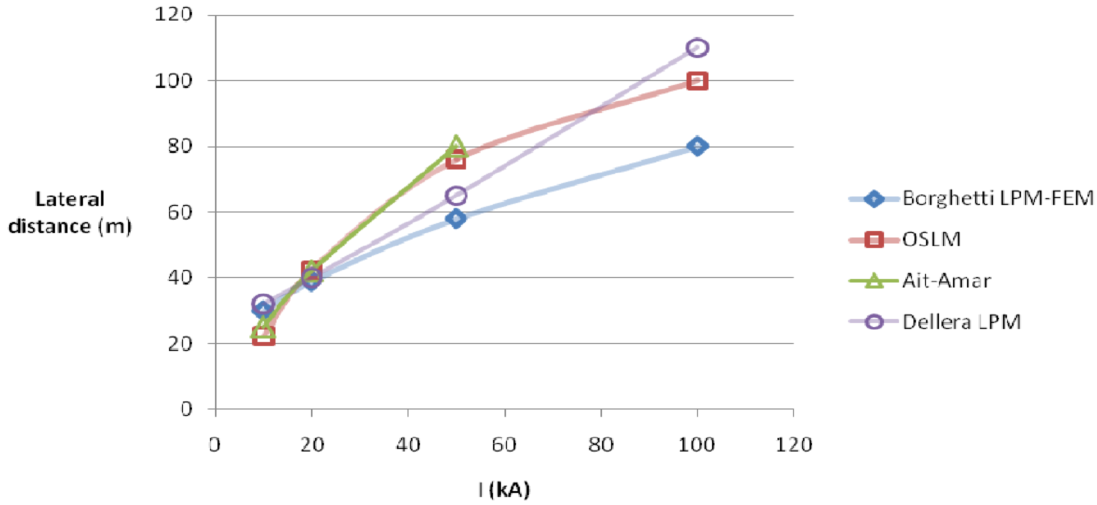

Figure 6.11.: Comparing the results of Ait-Amar and Berger, Borghetti et al. and Dellera and Garbagnatti (the latter values taken from Borghetti et al.)

The results obtained by the current implementation of the OSLM are in-line with those of Borghetti et al. The minor differences are to be addressed though. In the solution by Borghetti et al. a vertically propagating stepped leader was assumed, while in the OSLM a competition of upward leaders was allowed. There progression of the stepped leader was assumed where no upward leaders were initiated yet (the E-field criterion was not yet fulfilled). The starting point of the leader was 50-200m away from the rod, in the height of 200-800m. This, combined with the randomness of the leader progression (and much longer steps than used by Borghetti et al.) results in strikes to the 30m tall rod in most of the cases.

In the solution of Borghetti et al. the authors assumed a vertical lightning channel which changes its propagation direction once the effect of the upward leader is strong enough. The ground charges or the charge accumulated previously (and the E-field generated by that charge in front of the leader tip) is not taken into account, while in case of the OSLM these charges contribute the most to the E-field when the upward leader is non-existent, or is far from the stepped leader.

There were 200 simulations ran for each lightning current and most of the simulation runs resulted in a strike to the rod with only a few strikes to the ground. Also note that the step length of the downward and upward leader had a ratio of 4 (as it was suggested by Ait-Amar and Berger), while the LPM does not suggest such a constant ratio. As it was shown in their results, this ratio is usually higher resulting in a less significant effect of the upward leader.

Also note that while the numerical solution of the LPM results in one solution, the results obtained from the OSLM model are to be interpreted differently. In Figure 6.11 the solution of the LPM represents an individual numerical solution, while in case of the OSLM they show the worst case lateral distances – practically the closest ground strikes to the tall rod. The choice fell for the worst case data because the lateral distance means the distance where no ground strike may be observed and the worst case data in the simulations represents this.

A similar comparison may be made with the results of Ait-Amar and Berger [108], with some constraints. This model is also a numerical model, but unlike the LPM it takes into account the effects of the ground (assuming an ideal conductor) using the image of the stepped leader. In their model the leader always propagates towards the maximal E-field, which is a huge difference compared to the randomness assumed by the current implementation of the OSLM. Note though that the model of Ait-Amar and Berger may be realised per se with the OSLM for more sophisticated arrangements.

There are important differences in the models of Borghetti et al. (LPM) and Ait-Amar and Berger. First of all, the former model models stepped leader propagation based on leader propagation processes, while the latter takes into account the effect of the ground as well, but lacks the sophisticated description of leader propagation. Due to that the current implementation of the OSLM is closer to the model of Ait-Amar. As Fig 6.11 shows the OSLM results are somewhere “between” the two models with lower peak current values being closer to the results of Ait-Amar (in their paper they have results for 30m tall rods with peak currents of 10kA and 50kA only), and higher being closer to Borghetti et al. An explanation for this may be that the leader propagation ratio was higher than the one used in the results of Ait-Amar, but lower than the one resulted in the calculations of Borghetti et al.

As this brief comparison shows, the parameters and the propagation model included in the current implementation of the OSLM aims to have keep the advantages of both approaches presented here. In the development and the tests of the OSLM several remarks have to be made regarding model parameters and the applications. These remarks are found in the appendix.

Exposedness – comparison with the study of Becerra et al.

The current implementation of the OSLM may be used to investigate building exposedness in a similar way as it was done by Becerra et al. [85], [109]. In their study they investigated the exposedness of several buildings in Kuala Lumpur. Here the results of the ‘Faber Building’ are shown and results of the simulation with a similar building arrangement are introduced.

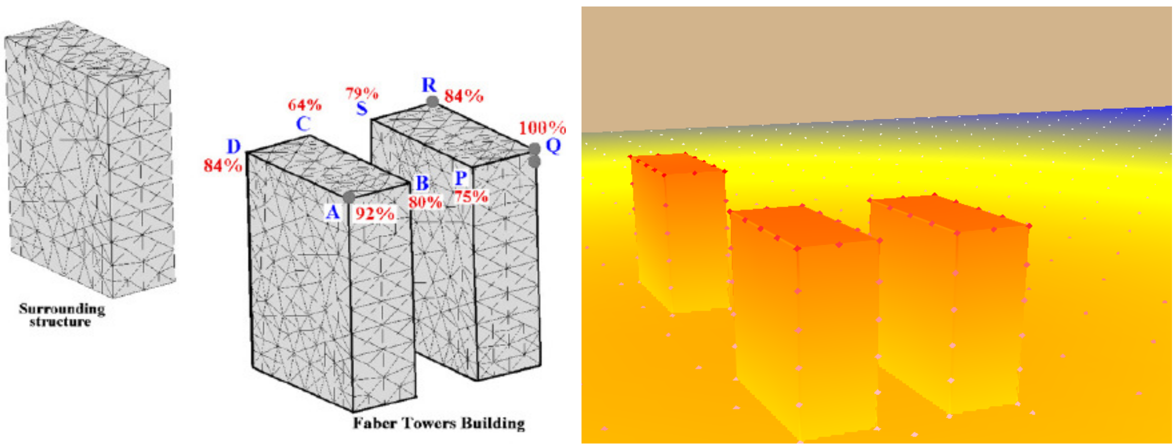

Figure 6.12.: Left: The simulated structures of the Faber Towers building with the points of interest marked in Becerra et al. [85] (Fig. 6. pp 569.); Right: implementation in the OSLM

In their study Becerra et al. investigated the corners of the Faber Towers building (marked); calculated the leader inception likelihood (marked with %) and compared their results with actual strike locations. There were only a few strikes to the corners of the building, so their comparison is qualitative in this sense. In a more recent study they also modeled the orientation (striking) distances to the different points on the buildings.

The Faber Towers Building consists of 2 buildings (H=90m, W=30m, L=70m) 30 m apart from each other, with a third similar structure 100 m away, just as it's shown in Fig 6.12. (in Becerra et al.).The building arrangement in the OSLM was placed on a 2000m x 2000m ground with a ground charge density of 1/40m, and a charge density of 1/20m on the building. The low number of charges on the ground, but this did not degrade performance, as the ground charges affected the E-field at the leader tip (the leader did not strike the ground at all). There were 250 runs in total in this simulation using stepped leaders from 5 starting locations 500m above the Faber Buildings (with the cloud height of 1000m).

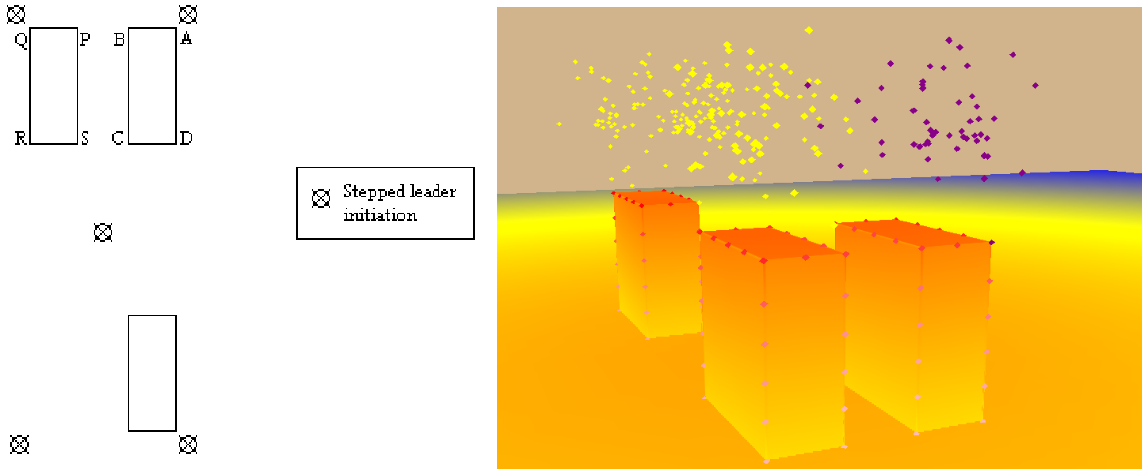

Figure 6.13.: Left: Simulation setup with stepped leader initiation locations and points of interest on the building (marked) Right: implementation in the OSLM with striking points

Fig. 6.13 (left) shows the arrangement of the simulation which corresponds to the original arrangement. The leaders were initiated at five locations to provide symmetry – the central initiation point was set to increase the likelihood of strikes to points S and C. During the simulation the striking points (the location of the leader tip before the step of the attachment) were collected and saved. A peak current of I=15kA was used, similarly to the study of Becerra et al.

The results of the simulation contradict the conclusions of Becerra et al on some points. There were no strikes to point P, S, and C (inner corners) at all, and only a few to point R, B, and D. The study of Becerra et al. has concluded that the ratio inception likelihood factors, which are in line with the results presented here. Mostly the corners of the buildings were struck, namely point Q and A (and the other building's outmost corners), and there were a very few strikes to the edges as well.

Table 6.2.: The results of a 250 strike simulation session

Point	Strikes	Orientation Distance		
		Average	Min	Max
Q	50	65.19	44.71	100.24
P	0			
R	4	64.67	30.05	87.53
S	0			
B	1	24	24	24
A	51	64.63	31.96	92.53
C	0			
D	1	57.22	57.22	57.22
Other	143	67.52	19.76	105.68
Sum	250	66.27	19.76	105.68

Table 6.1 shows the exact strikes with the orientation distances. It's interesting to see that the orientation distances are also in line with the strike inception likelihood calculated by Becerra et al., with Q being the highest and A coming second. Also note that calculating the orientation distances, the difference to the electro-geometrical model is low (66.27m compared to 58.14m given by the EGM).

These comparisons show that the current implementation of the OSLM is a good starting point for the further development. Of course it has weak points, centered mainly on the leader charge models and the ground models, as it is shown in the appendix. Also besides these comparisons the current implementation of the OSLM was tested with the model of the Ostankino tower as well. The results of those tests are found in the appendix.

6.5.Summary on the OSLM

The Open Source Lightning Model (OSLM) is a novel realization of lightning modelling in the sense that its purpose is to describe the lightning phenomenon with a complex modular model Modularity means that the different applied models in the OSLM may be exchanged, thus their background assumptions may be compared.

The current implementation of the OSLM is a mixed stochastic physical model assuming a stochastic leader progression influenced by the E-field; and physical models describing other parameters (charge configurations and the upward leader behaviour).

As this section showed the OSLM model structure is capable of incorporating many approaches in lightning modelling including cloud charge configurations [99-101], stepped leader models [92], [93], [113], [120], lightning attachment and upward leader models [81] and return stroke models [94-98] (not included in the current implementation) as well. I have shown that the algorithm introduced may easily be implemented using up-to-date technologies.

Also as other implementations show (see Appendix A4) the application of different models yields quite different results. Thus different models may be compared using the OSLM. The micro processes are not modelled in the current implementation, but the OSLM is capable of including micro models as well. To demonstrate this, a relatively complex leader charge model was applied in the small sample tests.

The implementation shown in this section served the purpose of modelling building exposedness. Several test runs were run with a simple building arrangement and boundary conditions to demonstrate the operation of the OSLM. The test runs' results indicated that leader distance and peak currents have spectacular effects on the strike locations.

Various other approaches are used nowadays in lightning modelling [82], [86], [87], [121], [122] each having different purposes. Each of these models may be described in the OSLM structure introduced in this section. Implementing multiple models into the same model structure allows comparison to be done between the different models. As it is shown with the OSLM different models produce significantly different behaviour (for the comparison see Appendix A4).

The current implementation has some disadvantages though. It contains simple assumptions and generally simple models. As discussed and introduced here there are much more complex models which are capable of describing the stepped leader propagation in depth. Also the applied models have some drawbacks (see remarks in Appendix A4), which are yet to be corrected.

We have to add that the current implementation of the OSLM is not a complete implementation. It does not include for example the return stroke models, so it's not able to execute electromagnetic calculations at various locations. Also the capabilities of the OSLM depend on model complexity and computing capability. Theoretically there's no upper bound for the OSLM but complex arrangements including numerous point charges result in large computation times. Also some optimization is included in the OSLM, but there are other ways to further improve the calculations which were not in the scope of this thesis.

Yet as it is an 'open source' model the implementation of advanced calculation algorithms and models not accounted for (return stroke or any other micro or macro process) is possible. Hence the OSLM can be used as both a scientific and practical tool for researchers and lightning experts for future research.

7. Thesis summary

The purpose of this thesis is to give a theoretical description on a novel method in lightning protection, the *preventive lightning protection* method. This method is new in the sense that the forecasting of the thunderstorm hazard is used in conjunction with specific preventive actions. Lightning hazard forecasting is used since the last decade with the development of nowadays' lightning detection networks, but it was not planned nor applied according to the 'reaction' to the presence of the lightning hazard. Lightning data 'nowcasting' is accessible thanks to the networks but their proper use in lightning protection – the preventive actions – has not been described theoretically before.

This thesis takes a step in this direction discussing different features of preventive lightning protection to provide a scientific framework for the use of this method. I discussed the use of forecasting in preventive lightning protection and proposed two possible methods to realize preventive lightning protection. I described methods to approximate the efficiency and costs of this method and developed a complete theoretical framework; the event space approach describing the operation of preventive lightning protection.

Also to provide a compatibility with the standards I proposed a method of risk calculation to preventive lightning protection. I used the proposed method in the annual cost approximations as well. By approximating risks and costs the feasibility of preventive lightning protection can be evaluated and with the proposed algorithm the optimal solutions can be planned. The assessment of other costs was not in the scope of my research.

In the approximation of the risks I also introduced these methods into the SCOUT system, a novel method of evaluating electrostatic hazard. With the proposed method the dynamic protection methods can be handled in the SCOUT system as well. Also the methods of the SCOUT system – the pre- and postaudit – can be used in preventive lightning protection to provide a more reliable solution.

Finally I created a modular lightning model, the OSLM. The model can be used for many purposes starting from examining building exposedness of certain building arrangements to investigating micro processes. The model can be used in planning preventive lightning protection as well to assess exposedness. In this thesis I demonstrated the capabilities of the OSLM model by investigating strike frequencies in case of a simple building geometry.

Lightning protection has gone through a huge development in the past decades with the development of newer planning methods and the rapid advancement of devices for secondary protection. The protection of human life however is still realized with the tools of primary lightning protection, but in some cases this protection method is not feasible.

Preventive lightning protection offers a method of protection for these cases and the comprehensive framework I introduced in this thesis defines the methods to plan and apply this solution. The theories in this thesis enable preventive lightning protection to be planned according to the international standards making it an effective addition to currently applied methods in lightning protection.

8. Acknowledgement

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Finally I couldn't have written my thesis without the patience and support of my family, Emese, my love who forgave me for working through several evenings and weekends, my father and step mother who provided me a safe home and an inspiriting environment for my work.

9. References

[1] A. B. Cook, *Zeus: a study in ancient religion*, vol. 2, 3 vols. New York: Bibilo & Tannen, 1964.

[2] G. Dumézil, *Gods of the Ancient Northmen*. University of California Press, 1973.

[3] B. F. J. Schonland, “The work of Benjamin Franklin on thunderstorms and the development of the lightning rod,” *Journal of the Franklin Institute*, vol. 253, no. 5, pp. 375-392, 1952.

[4] I. B. Cohen, “Prejudice against the introduction of lightning rods,” *Journal of the Franklin Institute*, vol. 253, no. 5, pp. 393-440, 1952.

[5] H. Prinz, “Lightning in history,” in *Physics of lightning*, Academic Press, 1997.

[6] P. Hasse, J. Wiesinger, and W. Zischank, *Handbuch für Blitzschutz und Erdung*, 5th ed. Pflaum, 2005.

[7] T. Horváth, “Ein 75 jähriges Blitzzähler,” in *13th International Conference on Lightning Protection*, Venice, Italy, 1976.

[8] C. T. R. Wilson, “A theory of thunderstorm electricity,” *Proceedings of the Royal Meteorological Society of London:*, vol. 236(32D), p. 297, 1956.

[9] E. Philip Krider, R. Carl Noggle, and Martin A. Uman, “A Gated, Wideband Magnetic Direction Finder for Lightning Return Strokes,” *Journal of Applied Meteorology*, no. 15, pp. 301-306, Mar. 1976.

[10] Richard E. Orville, “Development of the National Lightning Detection Network,” *Bulletin of the American Meteorological Society*, no. 89, pp. 180-190, Feb. 2008.

[11] IEC, “IEC-62305: Protection against lightning.” 01-Jan-2006.

[12] A. Gulyás, B. Németh, S. Szonda, and I. Berta, “Application of preventive measures in lightning protection,” presented at the 28th International Conference on Lightning Protection ICLP, Kanazawa, Japan, 2006, pp. 8-1.

[13] A. Gulyás, B. Németh, I. Kiss, and I. Berta, “Planning and evaluation of preventive lightning protection,” presented at the 17th Conference on Electromagnetic Disturbances, Bialystok, Poland, 2007.

[14] D. Aranguren, J. Montanya, G. Solá, V. March, D. Romero, and H. Torres, “On the lightning hazard warning using electrostatic field: Analysis of summer thunderstorms in Spain,” *Journal of Electrostatics*, vol. 67, no. 2-3, pp. 507-512, 2009.

[15] W. H. Beasley, L. G. Byerley, J. A. Swenson, A. L. Hinckley, and I. G. Bogoev, “Development and applications of a new, low-power, low-maintenance electric-field meter for research and hazard-warning decision support,” presented at the 13th International Conference on Athmospheric Electricity, Beijing, China, 2007.

[16] A. Gulyás, J. S. Mäkelä, B. Németh, V. Cooray, I. Kiss, and I. Berta, “Local detectors in preventive lightning protection,” in *30th International Conference on Lightning Protection*, Cagliari, Italy, 2010, p. 1105.

[17] M. Murphy and R. L. Holle, “Warnings of cloud-to-ground lightning hazard basedon combinations of lightning detection and radar information,” presented at the International Lightning Detection Conference, USA, Tucson AZ, 2006.

[18] A. Gulyás and I. Kiss, “High reliability preventive lightning protection,” in *20th International Lightning Detection Conference*, USA, Tucson AZ, 2008, p. 13.

[19] J. S. Mäkelä et al., “Single-station narrowband ranging of active storm cells without lightning-type discrimination,” *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 71, no. 8-9, pp. 911-922, 2009.

[20] R. Gunn, “The Electric Field Intensity and Its Systematic Changes Under an Active

Thunderstorm," *Journal of the Atmospheric Sciences*, vol. 22, no. 5, pp. 498-504, Sep. 1965.
[21] J. Y. Lojou, M. J. Murphy, N. W. S. Demetriades, and K. L. Cummins, "Assessment of thunderstorm lifecycle using total lightning systems," presented at the 13th International Conference on Athmospheric Electricity, Beijing, China, 2007, pp. os8-6.
[22] J. Y. Lojou and K. L. Cummins, "Total Lightning Mapping using both VHF Interferometry and Time of Arrival Technique," presented at the International Conference on Lightning Protection, Kanazawa, Japan, 2006, pp. 391-396.
[23] A. Gulyás, B. Németh, I. Kiss, and I. Berta, "The theoretical framework of preventive lightning protection," presented at the 29th International Conference on Lightning Protection ICLP, Uppsala, Sweden, 2008, pp. 8-6-1.
[24] A. Gulyás, B. Németh, I. Kiss, and I. Berta, "Comparison of forecasting methods in preventive lightning protection – a case study," in *21th International Lightning Detection Conference*, Tucson, Arizona, USA, 2010.
[25] B. Németh, A. Gulyás, I. Kiss, and I. Berta, "Efficiency of Lightning Detection Systems in Preventive Lightning Protection," presented at the International Youth Conference on Energetics 2007, Budapest, 2007.
[26] A. Gulyás, B. Németh, and I. Kiss, "Importance of Forecasting in Preventive Lightning Protection," presented at the 13th International Conference on Athmospheric Electricity, Beijing, China, 2007.
[27] A. Gulyás, "Preventív Villámvédelem (Preventive Lightning Protection)," presented at the Tavaszi Szél 2007, Budapest, 2007, p. 132.
[28] A. Gulyás, "A preventív villámvédelem alapjai (Basics of Preventive Lightning Protection)," presented at the Tavaszi Szél 2005, Debrecen, 2005, pp. 132-135.
[29] A. Gulyás, "A villámdetektálás alapjai (Basics of lightning detection)," presented at the Tavaszi Szél 2006, Kaposvár, 2006.
[30] B. Németh, "Új - preventív - villámvédelemi rendszer a villamos hálózatokon végzett korszerű munkavégzés biztonságának növelésére ('New – preventive – lightning protection system to increase power line maintenance safety')," Ph.D. thesis, Budapest University of Technology and Economics, 2010.
[31] B. Németh and I. Kiss, "Application of fuzzy logic based expert system in preventive lightning protection," *Journal of Electrostatics*, vol. 67, no. 2-3, pp. 477-481, May. 2009.
[32] B. Nemeth, A. Gulyás, and I. Kiss, "Lightning protection of open air mass performances," presented at the 29th International Conference on Lightning Protection ICLP, Uppsala, Sweden, 2008, pp. 8-9-1.
[33] J. Montanya, J. Bergas, and B. Hermoso, "Electric field measurements at ground level as a basis of lightning hazard warning," presented at the 26th ICLP, Krakow, 2002, p. 8b3.
[34] J. Mendes and M. O. Domingues, "Lightning path simulation based on the stepped leader: Electrical conductivity effects," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 67, no. 14, pp. 1287-1297, 2005.
[35] *NASA facts: Lightning and the space program*. USA, FL: NASA, 2006.
[36] H. Solomon, *Geometric Probability*. Society for Industrial Mathematics, 1987.
[37] B. Németh, A. Gulyás, and I. Berta, "Increasing Safety in Live Line Maintenance Applying Preventive Lightning Protection," presented at the 13th International Conference on Athmospheric Electricity, Beijing, China, 2007.
[38] B. Németh, A. Gulyás, I. Kiss, and I. Berta, "Practical Uses of Preventive Lightning Protection," presented at the 15th International Symposium on High Voltage Engineering, Ljubljana, Slovenia, 2007, pp. T2-735.
[39] B. Németh and A. Gulyás, "How to Use Lightning Detection in the Examination of Power Line Faults?," presented at the Elektroenergetika 2005, 2005.
[40] A. Gulyás, B. Németh, I. Kiss, and I. Berta, "Introducing dynamic protection methods

into the SCOUT system," presented at the International Youth Conference on Energetics 2009, Budapest, 2009, p. 5B1.
[41] L. G. Byerley, A. E. Pifer, and K. L. Cummins, "An electro-optical,lightning detection, classification and ranging sensor forautomatic lightning protection and human warning," presented at the 22th International Conference on Lightning Protection, Germany, Berlin, 1992.
[42] L. G. Byerley and L. M. Shumaker, "Novel approaches to powercontinuity using thunderstorm sensing and preventativeresponses," presented at the PCIM/Power Quality, USA, Irvine CA, 1993.
[43] R. L. Holle, R. E. Lopez, and C. Zimmermann, "Updated recommendations for lightning safety—1998," *Bulletin of the American Meteorological Society*, vol. 80, no. 10, pp. 2035–2041, 1999.
[44] M. Murphy, N. W. S. Demetriades, and K. Cummins, "The value of cloud lightningin probabilistic thunderstorm warning," presented at the 16th Conference on Probability and Statistics in the Atmospheric Sciences, USA, Orlando FL, 2002, pp. 134–139.
[45] M. Murphy, N. W. S. Demetriades, and K. L. Cummins, "Probabilistic early warning of cloud-to-ground lightning at an airport," presented at the 16th Conference on Probability and Statistics in the Atmospheric Sciences, USA, Orlando FL, 2002, pp. 126–131.
[46] A. Soulage, N. Demetriades, M. Murphy, K. Hufnagel, M. Dunn, and K. Cummins, "On the Use of Thunderstorm Warning in Active Lightning Protection.," presented at the 27th International Conference on Lightning Protection, Avignon, 2004, p. 2a.4.
[47] M. Murphy, R. L. Holle, and N. W. S. Demetriades, "Cloud-to-ground lightningwarnings using total lightning mapping and electric field mill observations," presented at the International Lightning Detection Conference, USA, Tucson AZ, 2008.
[48] R. L. Graham, B. D. Lubachevsky, K. J. Nurmela, and P. R. J. Östergård, "Dense packings of congruent circles in a circle," *Discrete Mathematics*, vol. 181, no. 1-3, pp. 139-154, Feb. 1998.
[49] J. A. George, J. M. George, and B. W. Lamar, "Packing different-sized circles into a rectangular container," *European Journal of Operational Research*, vol. 84, no. 3, pp. 693-712, Aug. 1995.
[50] P. L. Bowers and K. Stephenson, "Circle packings in surfaces of finite type: an in situ approach with applications to moduli," *Topology*, vol. 32, no. 1, pp. 157-183, Jan. 1993.
[51] A. B. Moore, "The circle tree - a hierarchical structure for efficient storage, access and multi-scale representation of spatial data," presented at the 14th Annual Colloquium of the Spatial Information Research Centre, Wellingon, New Zealand, 2002, pp. 149-156.
[52] K. L. Cummins, M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, "A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network," *Journal of Geophysical Research*, vol. 103, no. 8, pp. 9035-9044, 1998.
[53] K. L. Cummins, M. J. Murphy, N. W. S. Demetriades, B. Pifer, A. Pessi, and S. Businger, "Modeling and calibration of Vaisala's operational long range lightning detection network," in *20th International Lightning Detection Conference*, USA, Tucson AZ, 2008.
[54] B. Németh, A. Gulyás, and I. Berta, "New Preventive Methods in the Lightning Protection of Power Lines and Systems," presented at the PSC2005, Timisoara, Romania, 2005.
[55] "Information about the Lucas Oil Stadium." [Online]. Available: http://www.lucasoilstadium.com/About/Trivia/.
[56] V. Cooray, *Lightning Protection*. London, UK: The Institution of Engineering and Technology, 2010.
[57] "Lightning-Warning Systems for Use by Airports - ACRP (Airport Cooperative Research Program)." Transportation Research Board of the National Academies, 2008.

[58] S. F. Jablonsky, “A cost-effectiveness approach to planning and control for the nonprofit organization--a university example,” *Socio-Economic Planning Sciences*, vol. 12, no. 1, pp. 7-15, 1978.
[59] H. Zabronsky, “A mathematical theory of cost-effectiveness,” *Socio-Economic Planning Sciences*, vol. 1, no. 1, pp. 3-18, 1967.
[60] J. Froomkin, “Cost/effectiveness and cost/benefit analyses of educational programs,” *Socio-Economic Planning Sciences*, vol. 2, no. 2-4, pp. 381-387, prilis. 1969.
[61] O. Igra, “Cost-effectiveness of the vortex-augmented wind turbine,” *Energy*, vol. 4, no. 1, pp. 119-130, Feb. 1979.
[62] R. C. Carlos, J. M. Scheiman, H. K. Hussain, J. H. Song, I. R. Francis, and A. M. Fendrick, “Making Cost-Effectiveness Analyses Clinically Relevant: The Effect of Provider Expertise and Biliary Disease Prevalence on the Economic Comparison of Alternative Diagnostic Strategies,” *Academic Radiology*, vol. 10, no. 6, pp. 620-630, 2003.
[63] I. Kiss, B. Németh, N. Szedenik, A. Gulyás, and I. Berta, “Advanced risk analysis of systems endangered by ESD,” *JOURNAL OF PHYSICS-CONFERENCE SERIES*, vol. 142, no. 4, pp. 1-4, 2008.
[64] T. Horváth, *Computation of Lightning Protection*. Research Studies Press, 1991.
[65] T. Horváth, “Evaluation of the Risk of Lightning Protection Systems,” presented at the ICLP 1988, Graz, Austria, 1988.
[66] A. Rousseau, M. Guthrie, J. Struck, and J. Covino, “Application of risk analysis for temporary events,” presented at the 30 international Conference on Lightning Protection, Cagliari, Italy, 2010.
[67] I. Berta, “Use of soft computing methods in risk assessment of electrostatic fire and explosion hazards in industries,” *Journal of Electrostatics*, vol. 67, no. 2-3, pp. 235-241, May. 2009.
[68] I. Berta, “Static control: Modelling and application,” *Journal of Electrostatics*, vol. 30, pp. 365-379, May. 1993.
[69] E. Balog, “Elektrosztatikus eredetű veszélyek kezelése, értékelése (The evaluation and handlig of electrostatic hazards),” Budapest University of Technology and Economics, 2004.
[70] W. Schultz and K. Cummins, “A method to determine relative stroke detection efficienciesfrom multiplicity distributions,” in *20th International Lightning Detection Conference*, USA, Tucson AZ, 2008, p. 13.
[71] A. Nagh et al., “NLDN responses to rocket-triggered lightning at Camp Blanding, Florida in 2004-2009,” in *30th International Conference on Lightning Protection*, Cagliari, Italy, 2010, p. 1336.
[72] T. Horváth, *Understanding Lightning and Lightning Protection: A Multimedia Teaching Guide*. Wiley, 2006.
[73] B. N. Gorin, I. P. Kuzhekin, K. I. Sokolov, and A. V. Simkin, “System of a thunderstorm warning on the Ostankino TV-Tower,” presented at the 26th International Conference on Lightning Protection, Krakow, 2002, p. 9b.1.
[74] A. Gulyás and N. Szedenik, “3D simulation of the lightning path using a mixed physical-probabilistic model – The open source lightning model,” *Journal of Electrostatics*, vol. 67, no. 2-3, pp. 518-523, May. 2009.
[75] R. Klingbeil and D. Tidman, “Theory and computer model of the lightning stepped leader,” *Journal of Geophysical Research*, vol. 79, no. 6, 1974.
[76] M. Darveniza, F. Popolansky, and E. R. Whitehead, “Lightning protection of UHV transmission lines,” *Electra*, vol. 41, 1975.
[77] A. Bondiou and I. Gallimberti, “Theoretical modelling of the development of the positive spark in long gaps,” *Journal of Physics D: Applied Physics*, vol. 27, no. 6, pp. 1252-

1266, 1994.
[78] A. Beroual, A.- Bedja, I. Fofana, and P. Auriol, "Modelling attempt of negative discharge in long air gaps using equivalent electrical networks," presented at the 27th International Conference on Lightning Protection ICLP, Avignon, France, 2004, p. Ib-8.
[79] L. Arevalo, V. Cooray, and R. Montano, "Numerical simulation of long laboratory sparks generated by positive switching impulses," *Journal of Electrostatics*, vol. 67, no. 2-3, pp. 228-234, 2009.
[80] I. Gallimberti, G. Bacchiega, A. Bondiou-Clergerie, and P. Lalande, "Fundamental processes in long air gap discharges," *Comptes Rendus Physique*, vol. 3, no. 10, pp. 1335-1359, Dec. 2002.
[81] M. Becerra and V. Cooray, "Dynamic Modeling of the Lightning Upward Connecting Leader Inception," presented at the 28th ICLP, 2006, p. IV-3.
[82] P. Lalande, A. Bondiou-Clergerie, G. Bacchiega, and I. Gallimberti, "Observations and modeling of lightning leaders," *Comptes Rendus Physique*, vol. 3, no. 10, pp. 1375-1392, Dec. 2002.
[83] S. Grzybowski and G. Gao, "Laboratory study of Franklin rod height impact on striking distance," in *ICLP 2000*, Rhodes, Greece, 2000.
[84] S. F. Madsen and H. V. Erichsen, "Improvement of numerical models to determine lightning attachment points on wind turbines," in *ICLP 2008*, Uppsala, Sweden, 2008, pp. 9c-6-1.
[85] M. Becerra, V. Cooray, and Z. A. Hartono, "Identification of lightning vulnerability points on complex grounded structures," *Journal of Electrostatics*, vol. 65, no. 9, pp. 562-570, Aug. 2007.
[86] L. Dellera and E. Garbagnati, "Lightning stroke simulation by means of the leader progression model. I. Description of the model and evaluation of exposure of free-standing structures," *Power Delivery, IEEE Transactions on*, vol. 5, no. 4, pp. 2009-2022, 1990.
[87] L. Dellera and E. Garbagnati, "Lightning stroke simulation by means of the leader progression model. II. Exposure and shielding failure evaluation of overhead lines with assessment of application graphs," *Power Delivery, IEEE Transactions on*, vol. 5, no. 4, pp. 2023-2029, 1990.
[88] A. Borghetti, F. Napolitano, C. A. Nucci, M. Paolone, and M. Bernardi, "Numerical solution of the leader progression model by means of the finite element method," in *30th International Conference on Lightning Protection*, 2010, p. 1498.
[89] V. Cooray and M. Becerra, "Attractive radius and the volume of protection of vertical and horizontal conductors evaluated using a self-consistent leader inception and propagation model - SLIM," in *ICLP 2010*, Cagliari, Italy, 2010, p. 1062.
[90] R. Iwashita, Y. Shimosako, N. J. Vasa, and S. Yokoyama, "Protection Efficiency of Lightning Rods Based on Monte-Carlo Method," in *ICLP 2006*, 2006, p. IV-13.
[91] S. Vujevic, P. Sarajcev, and I. Sarajcev, "Stochastic assessment of external LPS of structures," presented at the 29th International Conference on Lightning Protection ICLP, Uppsala, Sweden, 2008, pp. 8-11.
[92] L. Niemeyer, L. Pietronero, and H. J. Wiesmann, "Fractal Dimension of Dielectric Breakdown," *Physical Review Letters*, vol. 52, no. 12, pp. 1033-1036, 1984.
[93] L. Pietronero and H. J. Wiesmann, "From physical dielectric breakdown to the stochastic fractal model," *Zeitschrift für Physik B Condensed Matter*, vol. 70, no. 1, pp. 87-93, 1988.
[94] Y. Baba and V. Rakov, "Evaluation of lightning return stroke electromagnetic models," presented at the 29th International Conference on Lightning Protection ICLP, Uppsala, Sweden, 2008, p. Ia-1.
[95] C. E. Baum and L. Baker, "Analytic Return-Stroke Transmission-Line Model,"

Electromagnetics, vol. 7, no. 3, p. 205, 1987.
[96] V. Cooray, "A novel procedure to represent lightning return strokes – current dissipation return stroke models," presented at the 29th International Conference on Lightning Protection ICLP, Uppsala, Sweden, 2008, p. Ia-2.
[97] V. Cooray, V. Rakov, and N. Theethayi, "The relationship between the leader charge and the return stroke current – Berger's data revisited," presented at the 27th International Conference on Lightning Protection ICLP, Avignon, France, 2004.
[98] D. Pavanello, F. Rachidi, V. A. Rakov, C. A. Nucci, and J. L. Bermudez, "Return Stroke Current Profiles and Electromagnetic Fields Associated with Lightning Strikes to Tall Towers:Comparison of Engineering Models," in *27th ICLP*, Avignon, France, 2004, p. 1b7.
[99] W. M. Farrell and M. D. Desch, "Cloud-to-stratosphere lightning discharges: A radio emission model," *Geophysical Research Letters*, vol. 19, no. 7, pp. 665-668, 1992.
[100] E. R. Williams, "The tripolar structure of thunderstorms," *Journal of Geophysical Research*, no. 94, pp. 13151-13167, 1989.
[101] T. C. Marshall and W. D. Rust, "Two Types of Vertical Electrical Structures in Stratiform Precipitation Regions of Mesoscale Convective Systems," *Bulletin of the American Meteorological Society*, vol. 74, no. 11, pp. 2159-2170, Nov. 1993.
[102] G. Simpson and G. D. Robinson, "The Distribution of Electricity in Thunderclouds, II," *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, vol. 177, no. 970, pp. 281 -329, Feb. 1941.
[103] J. R. Hermoso, J. Montanya, V. March, D. Romero, G. Solá, and O. van der Velde, "A propagative model for simulations of electric fields produced by downward leaders," in *ICLP 2010*, Cagliari, Italy, 2010, pp. 1324-1.
[104] V. Amoruso and F. Lattarulo, "Thundercloud pre-stroke electrostatic modeling," *Journal of Electrostatics*, vol. 56, no. 2, pp. 255-276, 2002.
[105] V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects*. Cambridge University Press, 2007.
[106] S. Tao, Y. Tan, B. Zhu, M. Ma, and W. Lu, "Fine-resolution simulation of cloud-to-ground lightning and thundercloud charge transfer," *Atmospheric Research*, vol. 91, no. 2-4, pp. 360-370, Feb. 2009.
[107] N. L. Aleksandrov, E. M. Bazelyan, and Y. P. Raizer, "Initiation and development of first lightning leader: The effects of coronae and position of lightning origin," *Atmospheric Research*, vol. 76, no. 1-4, pp. 307-329, Jul. 2005.
[108] S. Ait-Amar and G. Berger, "A 3-D Numerical Model of Negative Lightning Leader Interception. Applications to the Collection Volume Construction.," in *ICLP 2004*, 2004, p. 4a.1.
[109] M. Becerra, V. Cooray, and F. Roman, "Striking distance of vulnerable points to bestruck by lightning in complex structures," presented at the 28th ICLP, 2006, p. IV-15.
[110] T. Horváth, "Interception efficiency of lightning air termination systems constructed with rolling sphere method," presented at the 28th International Conference on Lightning Protection ICLP, Kanazawa, Japan, 2006, p. IV-5.
[111] M. Vargas, V. Cooray, M. Becerra, and H. Torres, "Lightning Leader Channel Modeling," presented at the 28th ICLP, Kanazawa, Japan, 2006, p. I-22.
[112] T. Horváth, "Villámcsapások valószínűségének meghatározása elméleti úton (Determining lightning strike probabilities based on theory)," Budapest University of Technology and Economics, 1972.
[113] N. I. Petrov, G. N. Petrova, and F. D'Alessandro, "Quantification of the probability of lightning strikes to structures using a fractal approach," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 10, no. 4, pp. 641-654, 2003.
[114] L. Arevalo, M. Becerra, and F. Roman, "Understanding the point discharge DC

current produced by corona needles," in *28th ICLP*, Kanazawa, Japan, 2006, p. IX-13.
[115] D. P. Agoris, V. P. Charalambakos, E. C. Pyrgioti, and S. Grzybowski, "Estimation of the protetction zone of a Franklin Rod using a stochastic model," in *ICLP 2002*, Krakow, Poland, 2002, p. 4b1.
[116] F. A. M. Rizk, "Switching impulse strength of air insulation: Leader inception criterion," *IEEE Transactions on Power Delivery*, vol. 4, no. 4, pp. 2187-2195, 1989.
[117] A. Bonamy, A. Bondiou-Clergerie, P. Lalande, P. Laroche, and I. Gallimberti, "The stabilization field□: a physical concept for the description of the lightning connection on grounded structures," in *Lightning and Mountain*, 1997.
[118] J. C. Nash, *Compact Numerical Methods for Computers: Linear Algebra and Function Minimisation*, 2nd ed. Taylor & Francis, 1990.
[119] L. Gaopeng and W. Walden-Newman, "Analysis of the Video Recordings of an Aborted Upward Leader at Daytime from a 'Bolt-from-the-Blue' Discharge," *Journal of Lightning Research*, no. 1, pp. 22-27, 2009.
[120] J. J. Lowke, "Formation, structure and development of the stepped leader," presented at the 29th International Conference on Lightning Protection ICLP, Uppsala, Sweden, 2008, p. Ia-3.
[121] V. P. Charalambakos, D. P. Agoris, E. C. Pyrgioti, and C. P. Stamatelatos, "Computer Simulation of Lightning Strokes," presented at the 28th ICLP, 2006, p. I-23.
[122] A. Dul'zon, V. Lopatin, M. Noskov, and O. Pleshkov, "Modeling the development of the stepped leader of a lightning discharge," *Technical Physics*, vol. 44, no. 4, pp. 394-398, prilis. 1999.
[123] B. Németh, I. Kiss, and I. Berta, "Preventive lightning protection for live line workers," presented at the IEEE ISEI 2008, Vancouver, 2008.
[124] B. Németh, I. Kiss, and I. Berta, "The cost effective lightning protection for live line workers," presented at the 9th International Conference on Live Maintenance, Torun, 2008.
[125] R. H. Golde, "The frequency of occurrence and the distribution of lightningflashes to transmission lines," *AIEE Trans.*, vol. 64, pp. 902-910, 1945.
[126] G. Diendorfer, W. Schulz, H. Umprecht, and H. Pichler, "Effect of tower initiated lightning on the ground stroke density in the vicinity of the tower," in *ILDC 2010*, 2010.
[127] T. Horváth, "Ermittlung der Wahrscheinlichkeiten von Nahe- und Seiteneinschlaege bei Fernsehturm Moskau durch Modellversuche," presented at the 13. Blitzschutzkonferenz, Gdansk, Polen, 1978.
[128] A. M. Hussein, S. Jan, V. Todorovski, M. Milewski, K. L. Cummins, and W. Janischewskyj, "Influence of the CN Tower on the lightning environment in its vicinity," in *2010 ILDC*, Orlando, Florida, 2010.

A1. ZPLP – Calculations of the event space

A1.1. Calculations in circular arrangements

For the first example I assume a circular DZ, and WZ, and the thunderstorm is also approximated with a circle (with a radius of r_S). I assume that the thunderstorm touches the WZ at a specific point. The heading of the thunderstorm is described with the angle α relative to the straight line connecting the centre of the thunderstorm, and the object to be protected. When calculating other shapes this is an incorrect way of defining this angle, but since the circle is a symmetric shape, this definition is correct in this case.

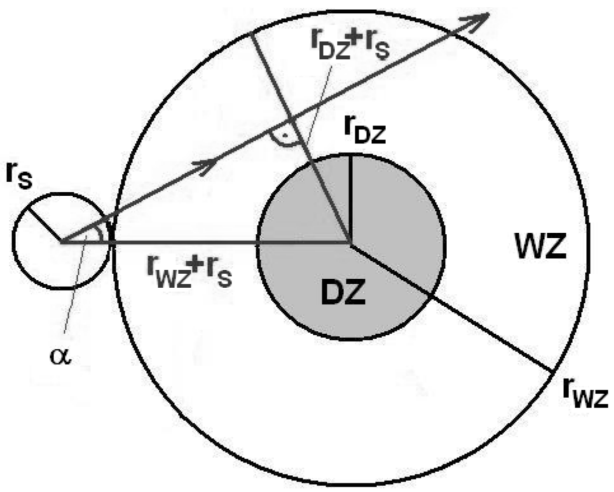

Figure A1.1.: Geometrical calculation of the probability of accurate alarm

The probability of the accurate alarm equals the probability of that the propagation angle is smaller than $\alpha_{\lim}$, the angle when the thunderstorm cloud touches the DZ.

The angle $\alpha_{\lim}$ depends only on the structure of the zonal protection.

$$\alpha_{\lim} = \arcsin\left(\frac{r_{DZ}+r_S}{r_{WZ}+r_S}\right) \quad \text{(A1-1)}$$

This shows, that the bigger the radius of the DZ, the bigger $\alpha_{\lim}$ gets. Thus p_{aa} increases with the increase of the DZ as it was shown earlier. However it is important to note that the boundary criterion that the thunderstorm cloud enters the WZ is to be fulfilled. This also gives an upper limit to α, since the alarm is given only in these situations – the thunderstorm cloud propagates into the WZ, not away from it. I denote this upper limit to α as α'. In case of a circle α'=90º. Note however that when discussing different shapes of DZs the calculation is more complicated.

Finally the probability of accurate alarms can be described with the following expression.

$$p_{aa} = \frac{\alpha_{\lim}}{\alpha'} = \frac{\arcsin\left(\frac{r_{DZ} + r_S}{r_{WZ} + r_S}\right)}{90} \qquad \text{(A1-2)}$$

When calculating this value, the probability of late alarms, p_{la} was absolutely neglected. This was done due to the fact that in this case I assumed that the thunderstorm cloud touched the WZ, and thus an alarm was given, and the preventive action was executed. When putting these probabilities into the event space model, p_{la} has to be taken into account and these probabilities have to be normalized to the criterion: $p_{ua} + p_{aa} = 1 - p_{la} - p_{na}$.

A1.2. Calculations objects modeled with a single line section – analytic solution

The calculations of the probability of accurate alarms are much more complicated thanks to the geometry of the solution. The object to be protected is a approximated with a simple line, and in this example the protection of only a straight section is introduced.

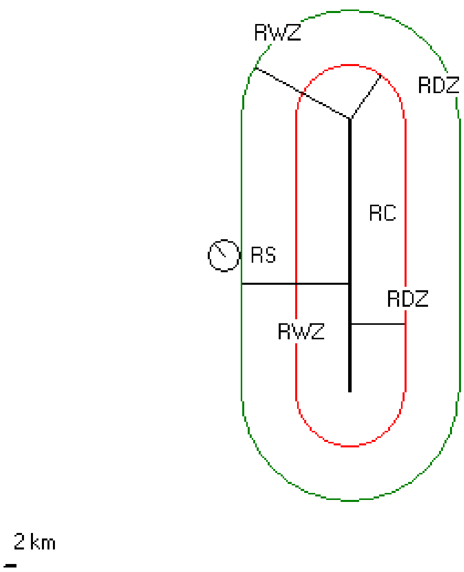

Figure A1.2.: Zonal protection of an object modelled with a single line section

In Fig. A1.2 a 50kms long object with a 10kms DZ, and 20kms WZ is drawn. With approximating the thunderstorm cell velocity to 120 km/h a 20km WZ is appropriate. The size of the DZ is specified following the principles described in section 3.2.1.

The calculation of the probability of accurate (and unnecessary) alarms is quite different from the calculations of the circular geometry. This shape is also symmetric, but the calculations require the division of this shape into two parts – further on in the calculations I denote these parts as 'sectors'.

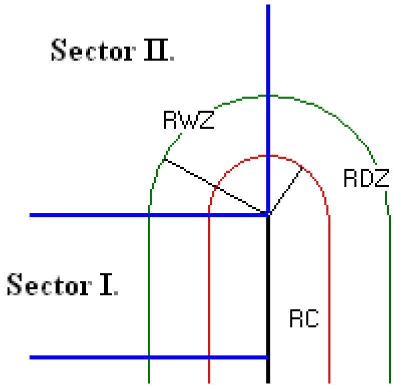

Figure A1.3.: Division into sectors

In Fig. A1.3 the two sectors defined for the calculations are shown. Sector I. is defined along the line – starting from the middle of the object and ending at its end – and sector II is along the circular part of the WZ. These sectors fully describe the solution, so the calculations are to be done for these two sectors only – along the border of the WZ, denoted as *z* in the expressions. To get one probability value, the average of the calculations is to be taken.

The probabilities are still calculated using (3-12), so practically the α_{lim} values are to be calculated, since the α' values are 180°in these cases. The calculation for the different sectors is as follows.

In Sector I α_{lim} may be divided into four parts as denoted in Fig. A1.4. Each of these angles corresponds to a triangle. A new parameter is introduced in this figure as well. The *d* parameter is the ratio of the distance from the end of the line versus the total line length.

In Sector I:

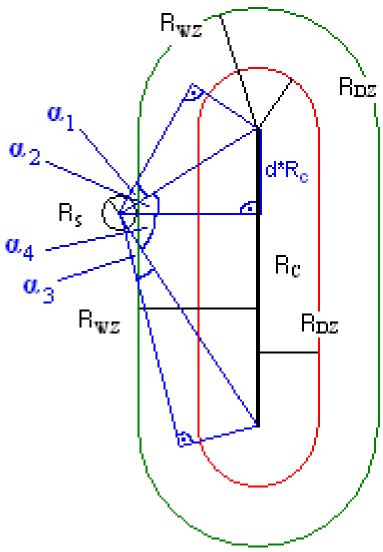

Figure A1.4: Angles composing α_{lim} in Sector I.

The angles shown in Fig. A1.4 are calculated in (A1-3). The same calculation method is to be followed in these calculations regardless of shape. Mostly $\alpha_{\lim}$ is to be calculated defining rectangular triangles, and calculating an angle in the triangle, summing them up in the end.

$$\begin{aligned}
\alpha_1 &= \arcsin\left(\frac{r_{DZ}+r_S}{\sqrt{(r_{WZ}+r_S)^2+d^2R_C^2}}\right)\\
\alpha_2 &= \arctan\left(\frac{dR_C}{r_{WZ}+r_S}\right)\\
\alpha_3 &= \arctan\left(\frac{(1-d)R_C}{r_{WZ}+r_S}\right)\\
\alpha_4 &= \arcsin\left(\frac{r_{DZ}+r_S}{\sqrt{(r_{WZ}+r_S)^2+(1-d)^2R_C^2}}\right)\\
\alpha_{\lim} &= \alpha_1+\alpha_2+\alpha_3+\alpha_4
\end{aligned} \tag{A1-3}$$

In calculating α_{lim} for Sector II. the same method is used but in this case instead of parameter d a new parameter is introduced in this calculation, namely parameter γ. This parameter shows the angle of the given line section and the line connecting the endpoint of the object (line) and the thunderstorm cell.

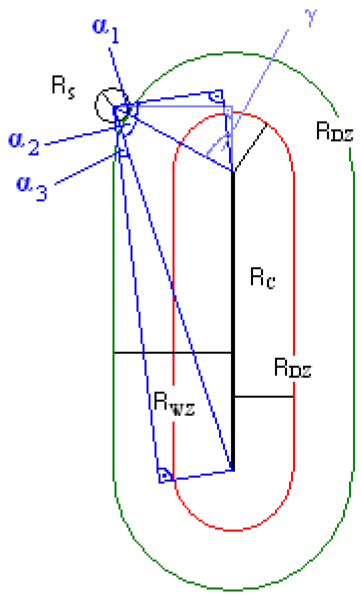

Figure A1.5: Angles composing $\alpha_{\lim}$ in Sector II.

$$\alpha_1 = \arcsin\left(\frac{r_{DZ} + r_S}{r_{WZ} + r_S}\right)$$
$$\alpha_2 = \arctan\left(\frac{(r_{WZ} + r_S)\cos\gamma + r_C}{(r_{WZ} + r_S)\sin\gamma}\right) + \gamma - 90 \qquad \text{(A1-4)}$$
$$\alpha_3 = \arcsin\left(\frac{r_{DZ} + r_S}{\sqrt{(r_{WZ} + r_S)^2 \sin^2\gamma + ((r_{WZ} + r_S)\cos\gamma + r_C)^2}}\right)$$
$$\alpha_{\lim} = \alpha_1 + \alpha_2 + \alpha_3$$

Expression (A1-4) shows that at this point the calculation gets rather complicated thanks to the change in the point of the calculation. Going further to the end of section II the angle α_{lim} reaches a point, when $90 - \gamma = \arcsin\left(\frac{r_{DZ} + r_S}{r_{WZ} + r_S}\right)$. After reaching this point, $\alpha_{\lim} = 2 * \alpha_1$, as the rest of the section is similar to a circular shape in the sense of the angle α_{lim}.

A1.3. Calculations for a objects modeled with lines consisting of two and three sectors – numerical methods

As it was shown the calculations of α_{lim} for complex shapes yield complicated calculations. However in practice (for example in line maintenance [37], [123], [124]) more complex DZ and WZ shapes are used.

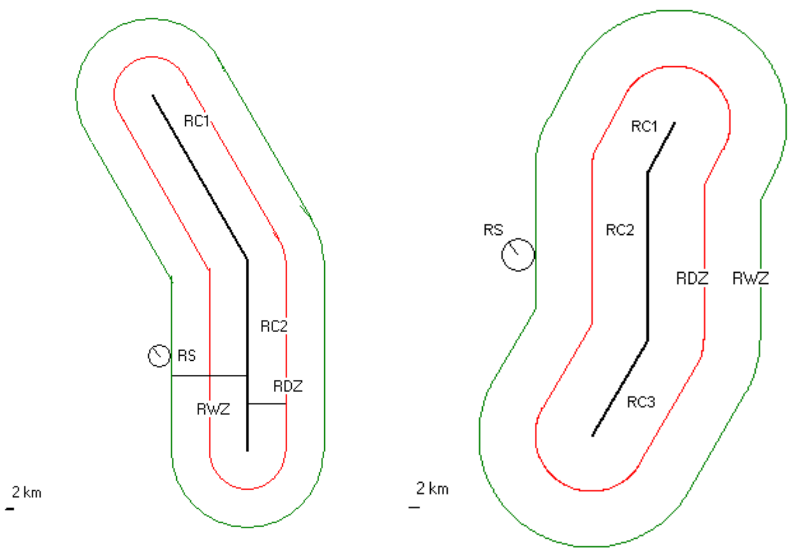

Figure A1.6: More complex geometries

Figure A1.6 is an example of a shorter object, modelled with two straight sections of lines and a longer one modelled with three straight sections.

The calculation method introduced above does apply to more complex shapes as well, but the numerical calculation of (3-11) is simpler, yet yields adequate results. In the numerical solution requires simulations to be run. The purpose of the simulation is to determine α_{lim} (and thus the probability of an accurate alarm, see (3-12)) along the edge of the WZ. Then it may be weighted according to (3-18) to take the propagation direction distribution into account as well.

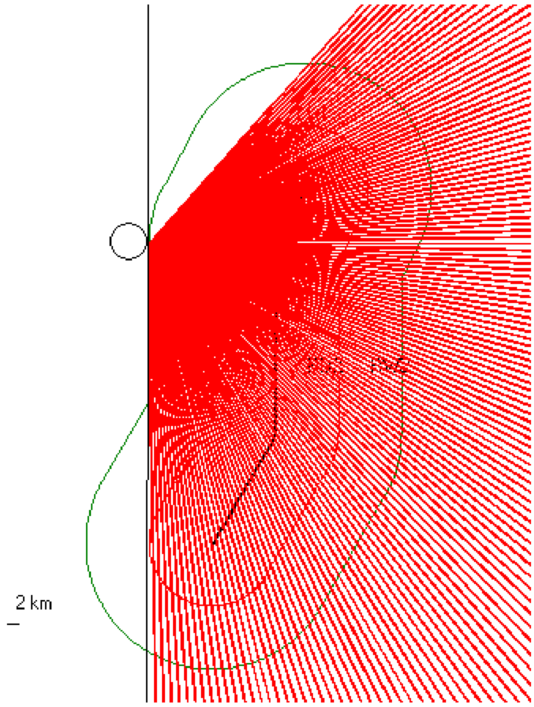

Figure A1.7: Simulation of p_{aa} on an object modelled with 3 sections

Results of simulations

Using the simulation technique described in this section the effect of the WZ size can be investigated. The following results were obtained using the arrangement seen in Fig. A1.6 (left) assuming a flat propagation direction distribution:

RS\RWZ	5	6	7	8	9	10	11	12	13	14	15
1	0.640	0.606	0.574	0.546	0.521	0.497	0.477	0.456	0.438	0.423	0.408
2	0.649	0.613	0.583	0.555	0.529	0.507	0.485	0.466	0.448	0.431	0.416
3	0.654	0.621	0.590	0.562	0.538	0.514	0.493	0.474	0.457	0.440	0.425
4	0.661	0.628	0.597	0.570	0.545	0.522	0.502	0.482	0.465	0.449	0.433
5	0.667	0.634	0.605	0.577	0.552	0.530	0.509	0.490	0.472	0.457	0.442
Mean	0.654	0.620	0.590	0.562	0.537	0.514	0.493	0.474	0.456	0.440	0.425

Table A1.1.: The probability of accurate alarms depending on WZ radius (km) and cell size (km)

The results are worst case approximations, since no propagation direction distribution was given. Also note that a DZ of 10 km was assumed in these simulations, so technically very long horizontal lightning paths are considered. It's clearly seen that the probability of the accurate alarms decreases with the WZ size, but increases with the increase of cell size – even though its influence is nearly negligible. Note however that here the 'accurate alarms' refer to the cases when the hazard indeed occurs after the alarm, so late alarms are also included!

When a propagation direction distribution is assumed with a straight propagation direction as the mean, we get much better results. For the sake of simplicity a normal distribution was assumed at each point of the WZ. In reality though, this distribution shall be different at each point of the WZ depending on wind parameters.

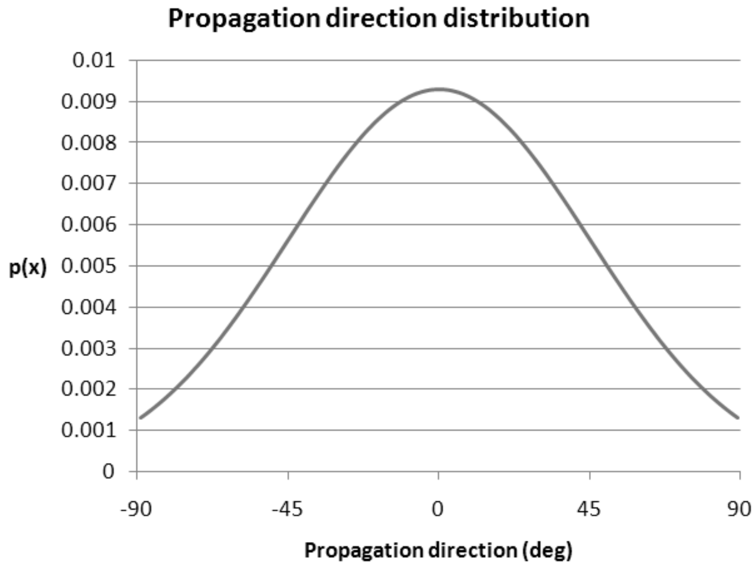

Figure A1.8: Assumed propagation direction distribution

Using the distribution shown in Fig. A1.8 the following results can be obtained.

RS\RWZ	5	6	7	8	9	10	11	12	13	14	15
1	0.813	0.785	0.758	0.733	0.709	0.686	0.666	0.644	0.625	0.609	0.592
2	0.821	0.793	0.767	0.743	0.719	0.698	0.676	0.657	0.637	0.619	0.602
3	0.827	0.801	0.775	0.751	0.729	0.707	0.686	0.667	0.650	0.631	0.614
4	0.833	0.808	0.783	0.759	0.737	0.716	0.697	0.677	0.659	0.643	0.625
5	0.838	0.814	0.791	0.767	0.745	0.725	0.705	0.686	0.668	0.652	0.636
Mean	0.827	0.800	0.775	0.751	0.728	0.706	0.686	0.666	0.648	0.631	0.614

Table A1.2.: The probability of accurate alarms depending on WZ radius (km) and cell size (km)

According to these results in case of a preventive action with low execution times, the probability of unnecessary alarms is quite low, even as low as 20% percent. In case of larger WZ-s this increases up to 40% in this simulation. The actual accuracies always depend on the exact application, as the WZ size is chosen according to the preventive action time requirement and the average thunderstorm propagation.

A2. HRPLP – Simulations and a theoretical case study

A2.1. Inaccuracies due to system parameters – simulation results

In Section 3.3 the calculation of p_{ua} included the inaccuracies due to system parameters – along with the inaccuracies due to the cloud model used. The system parameters in this case mean that the position and the shape of the thunderstorm cell is not detected adequately.

The suppliers of a lightning detection network usually give certain approximations on the detection accuracy. This information can be used to approximate how accurately a cloud is detected. In this section only the inaccuracies in case of a circular cloud model - approximation of a thunderstorm cell with circles – are discussed.

Both the simulation method and result is shown in this section. The inaccuracy of a lightning detection network means that the location of a certain discharge (IC, CC, CG) is mislocated due to the electromagnetic wave propagation parameters. Such system may have a median error of 500m [37].

Based on this data and accepting the circular cloud model – as it fits to the calculation method – it's possible to give an approximation based on a probabilistic approach on the average error of the radius, and the centre point of the circular cloud. Thus one can calculate the effect of mislocations in the calculation of the event space parameters in the sampling period.

The simulation method is the following:

- a circular cloud with a fixed radius is created using a fixed number of strikes randomly distributed in its area
- another circular cloud is created using the strike points of the previously created circular cloud, but the strikes are deviated randomly from the original strikes using the claimed accuracy of a system

The result of the first step is a circle with a random centre point (should be 0, but it's not since the finite number of random strikes), but with a radius given. The circle drawn in the second step of course has different centre point and radius parameters. The difference shown below is the difference between these centre points, and the difference between the radii.

The input parameters of a simulation are the radius of the circular cloud, and the claimed accuracy of the system. In the following the results of a simulation like that are shown. The simulation is done 50 times for each input parameter set, and the results can be summed easily giving a good 'rule' for the planning of HRPLP.

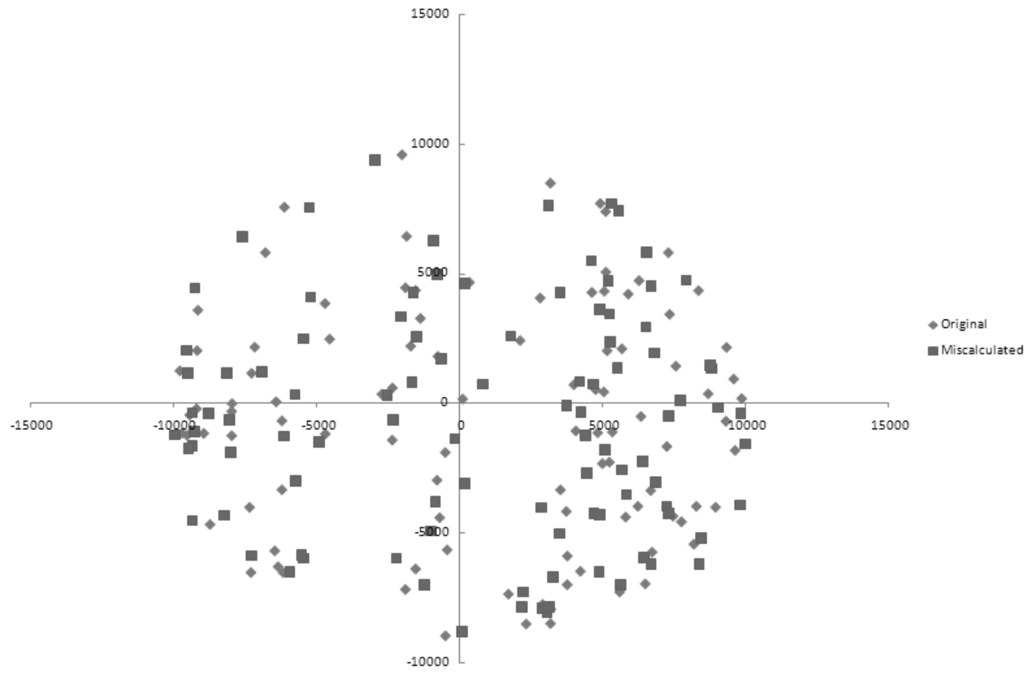

Figure A2.1.: Simulation of the mislocation of a thunderstorm cloud using a circular cloud model

In Fig A2.1 a simplified simulation result is shown with only 100 discharges. The simulations are done with 1000 discharges to give a more accurate result. The results for different sizes and claimed detection accuracies are shown below.

	Accuracy	CenrErrorRel [%]	RadErrorRel [%]
R=10000	50	2.79	357.14
	100	2.82	266.95
	200	2.81	153.00
	300	2.47	125.30
	400	2.45	116.00
	500	2.31	117.17
	600	2.86	112.70
	700	2.79	103.91
	800	2.63	101.11
	900	2.62	102.06
	1000	2.94	99.58

	Accuracy	CenrErrorRel [%]	RadErrorRel [%]
R=5000	50	2.52	212.69
	100	2.51	151.16
	200	2.70	117.26
	300	2.34	106.21
	400	2.52	102.14
	500	2.59	99.82
	600	2.63	100.64
	700	2.15	98.61
	800	2.61	97.59
	900	2.45	98.67
	1000	2.69	97.50

Table A2.1.: Simulation results

Table A2.1 shows the centre location error compared to the cell radius and the radius error compared to the cell radius in percentages. For example if the thunderstorm cloud has a 5000m radius and the system accuracy is 50m, then the radius error is 106m (212,69%) according to the simulation.

This data shows that the centre point location is around 3% of the accuracy, while the error in the radius of the circular cloud is in the interval of the accuracy itself. A system having an accuracy of 500m may give a cloud with a radius error of 500m – note that this is a worst case approximation. Of course this holds, when the distribution of the error in locating a discharge has flat distribution. A similar simulation is possible using normal or exponential distribution when creating the miscalculated second circle. The accuracy in this case means the distribution, which describes a deviation from the original strike points. The results shall differ depending on the distribution itself, it is not in the scope of this thesis.

The event space parameters in HRPLP calculated at each sampling period depend highly on the accuracy of the centre point and radius determination. On one hand it depends on the accuracy of the lightning detection network, while on the other hand it also depends on the circular cloud model. Since there are many possible models for one thunderstorm cell, the different circles' may result in different alarming decisions.

The simulations show a slight deviation of the center point only, if we take into account the inaccuracies of the lightning detection networks only. The difference in the radius means that in the calculations the critical distance may be bigger than planned. This may yield in increased probability of unnecessary alarms to preserve protection efficiency.

The next section describes a theoretical case study to give a brief overview of a practical solution. It also gives a short comparison between ZPLP and HRPLP.

A2.2. A theoretical case study

In this section a short theoretical case study is shown, along which the operation of HRPLP can easily be demonstrated. The first step in this case study is the description of the object to be protected. The case study deals with an existing object, the Lexington airport. On an airport preventive lightning protection is easily realized to provide protection during refueling operations.

Usually the airports have real-time meteorological data, so HRPLP can be realized by only installing an upgrade to the monitoring terminal and an appropriate alarming system.

Figure A2.2.: Lexington airport, the object to be protected

In the theoretical case study a severe thunderstorm is analyzed, which in the end does not endanger the airport. A simplified version of the circular cloud model is used in the study. All the circles have a radius of 5 km. This simplification is acceptable, as seen in the case study later on.

The progression of the thunderstorm is quite rapid, which makes forecasting quite difficult. The cells change their heading rapidly, so a constant monitoring is required.

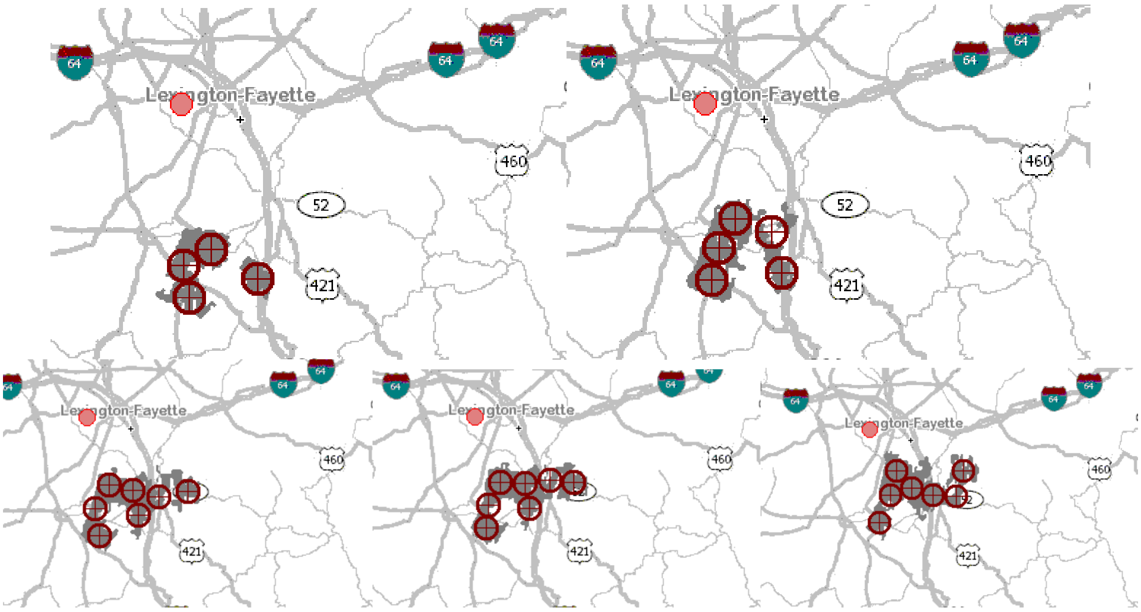

Figure A2.3.: Lexington airport, the object to be protected

The progression of the thunderstorm cell is shown in fig A2.3 with a sampling period of 5 minutes. The southmost thunderstorm cell is being analyzed in this case study. Lexington airport and the according DZ is denoted by the red circle in the middle of the pictures. The circular cloud model consists of 4-7 circles having a radius of 5 km each. Also the DZ has a radius of 5 km[44]. The cell progression is also quite rapid, a part of the cell moves quickly, while other parts remain where they were.

The sampling time is 5 minutes between these pictures. The circles are analyzed one by one, and the decision is made according to the behaviour of the thunderstorm cell based on the motion of the individual circles.

As a part of the protection, a preventive action shall also be selected accordingly. In this case I assume an action which takes less than 10 minutes.

This case study is also a good opportunity to compare preventive lightning protection and HRPLP. For this purpose of course a WZ has to be designated. Since the refueling operation requires 5 minutes the only parameter to choose is the speed up to which the protection prepares for. In this case study the airport operators prepare for thunderstorm cells up to 150 km/h. This results in a WZ having a radius of 30 km – this also includes the 5 km radius of the DZ.

[44] A warning is given at 3 miles per the NAVEDTRA 12390, Air Traffic Controller. See: http://www.militarynewbie.com/pubs/NAVEDTRA%2014342%20-%20Air%20Traffic%20Controller.pdf, so the DZ shall be smaller.

The following table shows the motion of the 5 circles in the sampling periods, their speed, and the distance to the object to be protected. Using the distance data it's easy to determine when a preventive protection method was used.

As a start for this analysis a simple calculation is done both for preventive lightning protection and for HRPLP supposing fully accurate data. In the case of HRPLP, it's only required to see if the direction and the distance condition is fulfilled.

Circles	Param	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0 min	veloc																								
	dist	66	55	51	65																				
5 min	veloc	72	87	126	24																				
	dist	60	49	40	63	49																			
10 min	veloc	78	85	96	153	121																			
	dist	55	42	33	51	40	50	58																	
15 min	veloc	42	35	22	40	47	92	49																	
	dist	51	41	32	49	39	45	55																	
20 min	veloc	66	113	121	140	43	105	120																	
	dist	46	34	24	45	35	54	51																	
25 min	veloc	0	30	54	99	54	175	195																	
	dist		31	21	41	32	44	55	53																
30 min	veloc		157	148	139	99	204	38	144																
	dist		39	26	39	36	47	51	64	52															
35 min	veloc		150	42	52	132	78	52	30	116															
	dist		31	25	41	38	40	47	67	52	55														
40 min	veloc		44	49	67	22	70	70	34	85	46														
	dist		28	24	37	36	38	46	64	45	51	56	47												
45 min	veloc		25	30	38	52	62	43	52	13	97	73	135												
	dist		28	26	37	35	40	46	67	46	57	57	49												
50 min	veloc		40	42	114	46	102	38			8	84	17												
	dist		26	23	36	32	37	43			57	50	47	27	44										
55min	veloc				17		60	133			12	8	36	118											
	dist				35		40	38			58	50	49	37		56									
60 min	veloc				102		90	48				42	46	48		47									
	dist				35		35	37				53	49	40		59									
65 min	veloc				285		191	137				67	0	136		70									
	dist				19		19	25				55	0	39		64	40	26	42	29	26	38	30		
70 min	veloc				13		48					60	0	57		57	32	51	60	80	90	48	34		
	dist				20		20					59	0	41		68	38	23	44	34	30	36	27	48	48

Table A2.2.: The distance and speed of the thunderstorm cloud (v [kmph]; d [km]) in the rest of the sampling periods

The red cells in Table A2.2 indicate that if ZPLP is applied using the parameters given above, then an alarm would've been given, while the orange cells denote when the alarms would've been given by HRPLP as well. Note though, that in the 70th minute HRPLP would not trigger an alarm, the direction condition would be fulfilled in this sampling period as well.

This means that the thunderstorm cell is still closing on the object to be protected, but also as it's seen in the table the speed of the thunderstorm cell decreased.

Although this is not a part of the analysis, the thunderstorm cell does not endanger the airport in the end, but heads northwards. This simple analysis yields in an alarm from the monitoring system after 65 minutes from the start. At this time no part of the thunderstorm cell is in the DZ. The minimum distance is 19.1kms. In this case if the thunderstorm cloud heads straight towards the airport with a velocity larger than 54.6 km/h may endanger the refueling operation.

So in this case study, an alarm would've been given, but it would've been an unnecessary alarm. When using HRPLP the time of alarm would've been 65 minutes from the sighting, but with ZPLP this time would be 45 minutes earlier. It also would've been an unnecessary alarm, but it would've resulted in much higher costs.

A3. HRPLP – Calculation of the event space parameters

In HRPLP the event space parameters shall be calculated at each sampling period. This information shall be used in the alarming decisions. Ideally only the distance and direction criterion shall be evaluated, but since the center of the cloud is determined inaccurately, it also has to be taken into account.

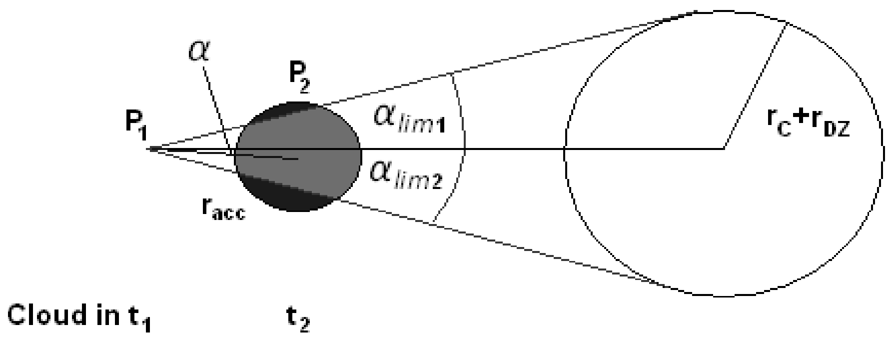

Figure A3.1.: Miscalculation of the direction criterion due to inaccuracy [18]

Figure A3.1 (equivalent to Fig 3.24) shows the effect of the inaccuracy. Here it is assumed that the point gotten in the previous sampling period was determined accurately. The figure shows that the trajectory of the thunderstorm cell is determine using the center points obtained in two sampling periods, t_1 and t_2. The point in t_2 is determined inaccurately its possible location being inside the circle with the radius of r_{acc}. Thus the vector describing the trajectory of the thunderstorm cell is distorted by this inaccuracy.

The probability that the alarm is given unnecessarily (assuming that the distance criterion would be fulfilled), is the ratio of the area which has been 'cut' out from the circle representing the inaccuracy by the limiting angles (the brown area),[45] and the area of the circle. These areas are calculated using simple geometric expressions, and the result is the following.

[45] These angles denote the limit of directions, when the direction criterion is fulfilled.

$$p_{ua} = \frac{T_{c1} + T_{c2}}{r_{acc}^2 \pi} \quad \text{(A3-1)}$$

In this expression T_{c1} and T_{c2} represent the area of the individual slices, which are calculated using the following expressions.

$$T_{c1} = r_{acc}^2 \pi \cos^{-1}\left(\frac{|v|\sin(\alpha_{\lim 1} - \alpha)}{r_{acc}}\right) - \sqrt{r_{acc}^2 - (|v|\sin(\alpha_{\lim 1} - \alpha))^2} \, * \\ *\left(r + \sqrt{r_{acc}^2 - (|v|\sin(\alpha_{\lim 1} - \alpha))^2}\right) \quad \text{(A3-2)}$$

$$T_{c2} = r_{acc}^2 \pi \cos^{-1} \frac{|v|\cos(\alpha_{\lim 2} - \alpha)\tan\alpha_{\lim 2}}{r_{acc}} - \sqrt{r_{acc}^2 - (|v|\cos(\alpha_{\lim 2} - \alpha)\tan\alpha_{\lim 2})^2} \, * \\ *\left(r + \sqrt{r_{acc}^2 - (|v|\cos(\alpha_{\lim 2} - \alpha)\tan\alpha_{\lim 2})^2}\right) \quad \text{(A3-3)}$$

There are several remarks to these kinds of calculations. First of all, HRPLP is even less ‘static’ than preventive lightning protection. This also makes calculations, and also the concept of ‘efficiency’ even harder to describe and to calculate using theories only. So the efficiency is to be approximated using the available empirical data, calculating the relative frequencies of each event.

In practice it is necessary to calculate these expressions in every sampling period, and this requires real time computing for which the complete calculation (depending on the sampling period of course) would take a lot of computing time. Also clouds are only rarely circular. Thus it is very hard to give a clear expression to the probability of unnecessary alarms which is easy to calculate. The expressions mentioned above are only guidelines to make the framework clear.

As noted before in this calculation I assumed that the starting point of v (P_1) has been accurately calculated. It is possible to account for this oversimplification in the calculations, but the price in calculation time is quite high.

Abandoning this criterion I assume that there’s also a circle around P_1 with the radius of r_{acc} meaning the area where the starting point of v could have really been.

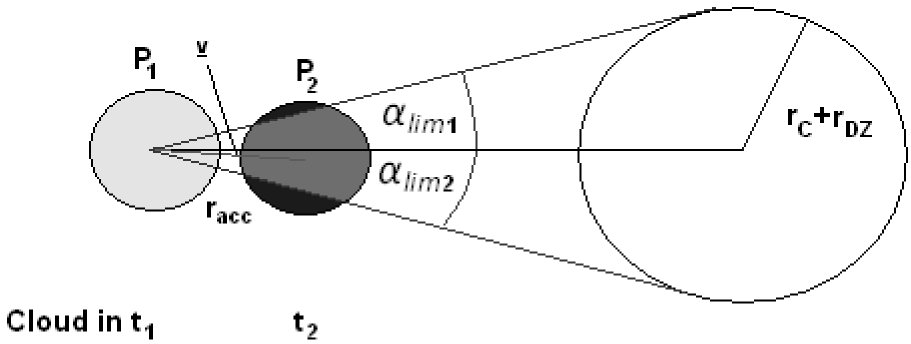

Figure A3.2.: Miscalculation of the direction criterion due to inaccuracy

Using the circular cloud model again, the calculation for that case could be done with the following expression.

$$p_{ua} = \frac{1}{r_{acc}^2 \pi} \int \left(T_{c1}(P_1) + T_{c2}(P_1) \right) dP_1 \qquad \text{(A3-4)}$$

The boundary of the integral in this case is the circle around P_1 representing the inaccuracy at the calculation of P_1. The numerical solution can be obtained, but this will give a picture only of the probability of unnecessary alarm to an individual thunderstorm cloud, above an individual area. Of course in these calculations a worst case approximation is made to p_{ua}, but this means that the worst case protection efficiency is kept in mind during the calculations.

Since both T_{c1} and T_{c2} depend on the location of P_1, expressions (A3-2) and (A3-3) do not apply when calculating (A3-4), but has to be recalculated during the integration. Of course numerical methods are much simpler than analytical calculations.

Besides the direction criterion, the distance criterion is also distorted by the inaccuracies, since difference in the trajectory vector length means a difference in the calculated speed of the thunderstorm cell. Thus not only the probability of accurate and unnecessary alarms can be approximated, but also the probability of late alarm. Also if the distribution of the inaccuracy is known (A3-4) shall be extended with the distribution as a weighting factor.

To demonstrate the results of these calculations, suppose the following data was obtained by lightning hazard forecasting of the progression of a thunderstorm cell with a 1 km radius (for the example shown in Section 5.1):

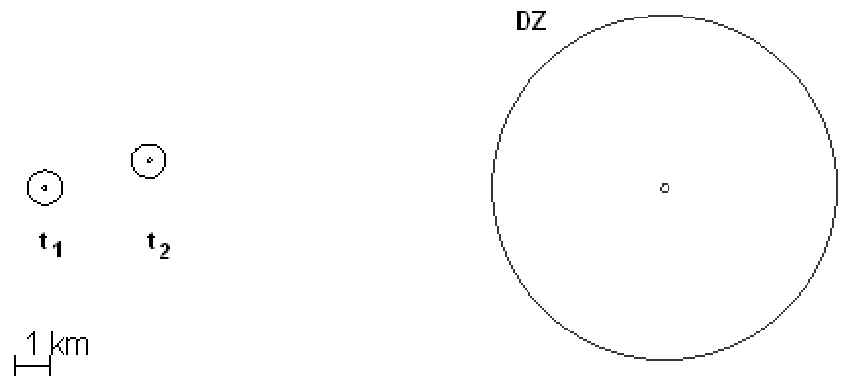

Figure A3.3.: Calculation example for HRPLP

The parameters of this example were the following: $t_{sampling}=3\ min$, $t_{action\ execution}=9\ min$, $d_{t1}=20\ km$, $d_{t2}=17\ km$, $r_{DZ}=10\ km$, $r_{acc}= 500m$, $r_{cell}=1\ km$. In this case the numerical calculation of (A3-4) and also including the evaluation of the distance criterion as well yields the following event space:

	Alarm was given in time	Alarm wasn't given in time
Hazard develops	p_{aa} =0.613	p_{la} =0.218
Hazard does not develop	p_{ua} =0.169	-

Table A3.1: The event space calculated using (A3-4) (and other deducted expressions) for A3.3

This means that if the alarm would be given at the current time (t_2) then it would have a 61% of being accurate, and 22% chance that it would be late. Also the distribution of time left to execute the preventive action may be important. In this example the following distribution was calculated.

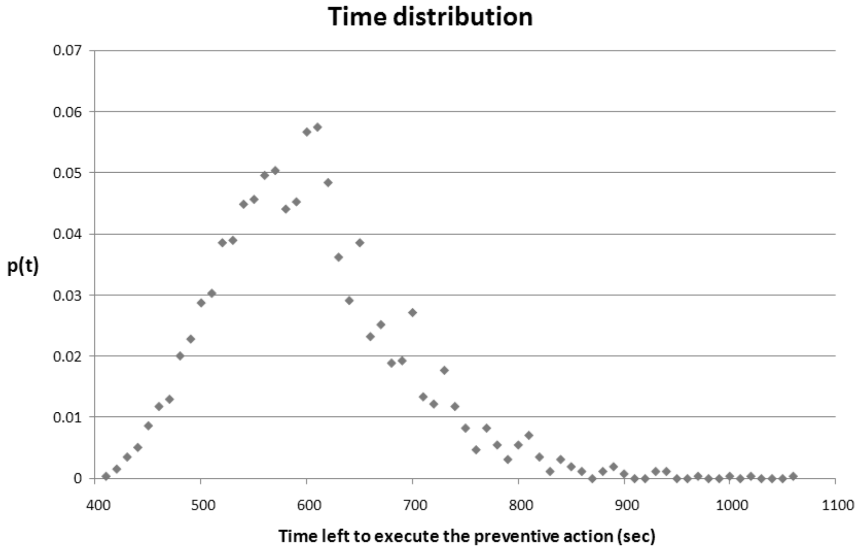

Figure A3.3.: Calculation example for HRPLP

The distribution is close to a normal distribution with a mean of 10.03 min. It means that the alarm in this case would be statistically 1 minute too early. This may not be adequate in terms of cost efficiency, but it is certainly not an object in terms of protection efficiency.

A4. OSLM – implementation details and further tests

A4.1. Special features of the OSLM implementation

The current implementation of the OSLM focuses on realizing a modular model structure. A key feature of a modular model is the modularity of the applied models. The OSLM uses a 'solution approach' to realize the experiments. Each experiment is defined by a 'solution' file with the following data therein (you may find an example solution file at the end of this section):

- Input parameters: the numerical input parameters (peak current, cloud model values, ground model values); applied models
- Experimental arrangement file paths: one file corresponds to the basic 'height map' of th area (in a coloured BMP format); another file describes the locations of the buildings in the arrangement; the third file contains the building models, and their locations in the arrangement.

The OSLM is capable of accepting custom buildings written in a special file format ('.cx') developed specifically for the OSLM. In this format the vertices of the building model may be entered and the charge locations may be designated as well. Note that also the indices (used in DirectX drawing) for the building are necessarily included in the file.

The OSLM also supports the '.x' extension 3D models drawn with advanced CAD software. In those models materials and textures shall be omitted (they're not implemented, as they're not necessary for the simulation), only colours shall be used with red denoting the charge locations.

The applied models are given explicitly in the solution file. The applied models defined therein are the cloud, ground, upward and downward leader models. Currently there is only one model implemented for the cloud and the ground (charge matrix for the cloud, and point charges for the ground), but more for the leader charges, and the E-field calculation in front of the leader.

A4.2. Implemented models

The models have been described in section 6 of this thesis so here the emphasis is on their realization (in details). In this section the theoretical background is described (where necessary) and some numerical values are given. The exact implementation in case of the small sample test with the Ostankino model is shown in section 4.3. Note that there are multiple test results in that section not found in section 6.4.

The cloud charge model is generally constructed to provide the 'background E-field' during the thunderstorm. The best data for the background E-field was provided by Amoruso and Lattarulo [104]. They described the distribution of the E-field under the thunderstorm cloud and found maximums at around ~20-25 kV/m under the centre of the cloud. Note that they did not concentrate on the lightning phenomena, only the pre-thunderstorm electric field. Thus their values shouldn't be used per se – it is assumed to be changing during the storm –, but these values may be used as guidelines for setting the OSLM's input parameters (defining the cloud charges without the presence of the leader). Also they've used an 'electrostatic model' which differs from the models described herein.

The ground may be described as an ideal or a non-ideal conductor. Besides that it's vital to emphasize the importance of the discrete (mesh) charge distribution on the ground. This is a major difference from reality, as the charge distribution is continuous and depends on soil conductivity as well. Yet in the current implementation the complex non-ideal conductor models are omitted. The distance between the point charges at ground level have been determined to influence the E-field at the leader. Their distance shouldn't be bigger than the distances of the cloud charges.

One of the most complex applied models in the OSLM is the leader charge model. It has the most options, and it has a big impact on the simulations. It was mentioned in Section 6 that there are point charge models and line charge models of clouds. According to the general theorem of the lightning channel (see a great review in [56]), it is best to be described by line charges with given charge densities along the leader channel.

According to various authors there is a definite connection between the total charge of a downward leader and the peak current of the succeeding return stroke. The earliest value was given by Golde [125], who assumed that $Q=0.05I_{peak}$ (C, I in kA). This was modified later, but for modelling purposes such a simple expression this is a good starting point. Golde also gave a very simple expression of the charge densities: an exponential decay of charges.

$$\rho_s = \rho_0 e^{-\frac{z}{\lambda}} \tag{A4-1}$$

In this expression ρ_0 is the charge density at the leader tip, and λ is a constant (with a value of 1000m). Values for ρ_0 were also given by several authors. Golde gave a very simple (linear) expression for it, depending on the peak current: $\rho_0 = 4.36\text{x}10^{-5} I_{peak}$. This result in relatively high charges, 43.6 μC/m for a strike with 1kA return stroke peak current. Another (more realistic, as it will be shown later) approximation was given by Wagner and Hileman (in Horváth [112]) to the charge distribution by assuming a minimal charge density and an exponential decay to that value. It is calculated by the following expression:

$$q_\infty = \frac{1.535}{c}\sqrt{I^2 + A*I}\,\left(\frac{I}{I_m}\right)^{0.54} \tag{A4-2}$$

Here c denotes the speed of light (m/s), $A=250kA$ thus the expression results in μC/m with these dimensions. Horváth also gave a review on the values suggested by other authors as well. The charge density at the leader tip is calculated by multiplying (A4-2) with 3.95. The resulting values are generally lower than the one suggested by Golde.

The leader step model determines the step length on a stochastic basis. In the current implementation a fixed step length (based on the orientation distance calculation) is used or randomized values are taken based on the following density function (described in Section 6.4).

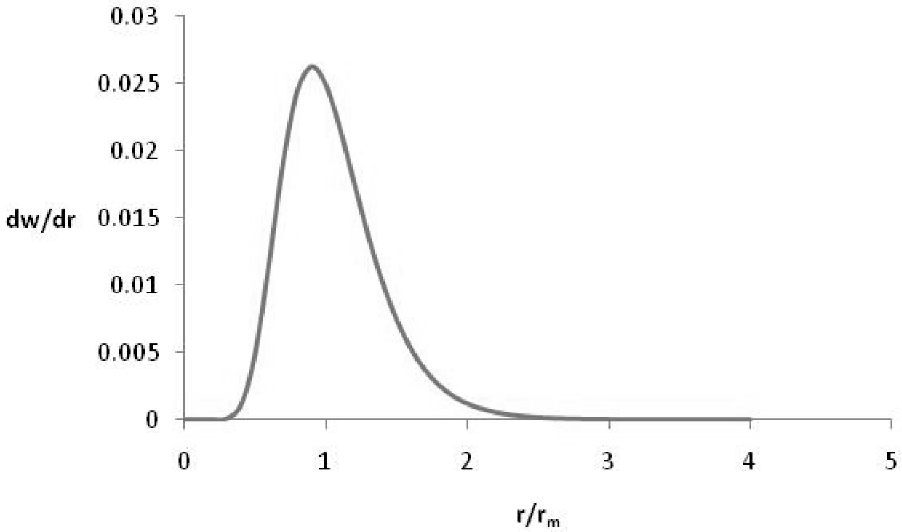

Figure A4.2: The density function of the striking distance

The same applies to the upward leader step model. The current implementation assumes a step length of 0.2 times the striking distance (fixed or random values). The streamer model and the upward leader charge model can also be determined using micro processes, but in the current implementation the charge from which an upward leader originates is 'transported' to the upward leader tip. This influences the E-field in front of the downward leader tip, thus the propagation distribution.

Streamer initiation was discussed by Dellera and Garbagnati in their 3D model as well [87]. As mentioned before they took E=10kV/cm for negative leaders and E=5kV/cm for positive leaders as critical field strengths 70 cm above ground level. A point charge of 54.4 μC produces similar fields in this distance (which is an interesting value compared to the 43.6 μC/m leader charge density mentioned by Golde for a 1kA strike). Thus in the simulations it is expected to have upward leaders above these point charge values.

A4.3. Remarks on the use of different applied models

During the tests of the OSLM and the comparisons with the other models, several interesting phenomena occurred when using different applied models and different charge configurations. Here a short review is given on these remarks explaining some of the observed phenomena.

The two most important applied models in this sense are the applied leader model and the ground (and obstacles on the ground) charge model. The leader step model is crucial in the sense that it basically determines the charges at ground level and influence leader propagation along with them.

The current implementation allows for a point charge model – and a linear charge model transformed to a point charge model. The E-field calculation in front of the leader is highly distorted by the single point charge at the tip of the discharge as it dominates the potential gradient compared to any other charges in the simulation space (due to its vicinity). In the simulations this point charge was omitted in the leader tip E-field calculations. The reason for this was the floating point calculation error of computation, which was in the range of the effect of the other charges. So the result of these calculations including the point charge at the leader tip was a highly distorted field. (It is possible to counter this effect by calculating the component only once and applying that at all points of the calculation.) Yet without the effect of this point charge the same distribution is obtained.

The leader step model is also a constraint, since the leaps of the leader – as it is modelled currently – constrain the movement of the leader and in the last step (when multiple upward leaders are competing for attachment) the determination of the attachment point is not sophisticated enough (nor does the model support multiple attachments!). Of course this can be countered by separately modelling the last step (with physical models mentioned in section 6.), but modelling the phenomenon to this depth is not in the scope of this thesis – yet it is an important extension for future research.

The same constraint applies to the upward leaders, which propagate with a constant ratio to the downward leader step (0.25 of the downward leader step). The result of using such simple step models is that the attachment point is partially determined by the starting point of the discharge (and thus when and where the upward leaders are initiated). Using multiple starting points for the discharges helps this problem, but increases computation needs.

The second important model is the ground model applied, which is currently an infinite conducting ground model with point charges. In ideal circumstances this approximation is useful to implement imaging in the calculations, but in complex arrangements (for which the OSLM was developed) it may not be used. Point charges are a practical way to solve this problem, but their placement largely influences the simulation.

First of all the upward leaders were assumed to start only from the location of the point charges, which is a practical assumption only. But since the point charges mainly determine the E-field at ground level, their accurate placement is crucial. If the charge matrix is not dense enough, the upward leader initiation starts very early, it may start even after the first few steps of the downward leader,

Secondly, if the ground plane is not big enough (and the boundary charges are too close) the highest E-field may be found at the edge of the ground plane (just as if it were a capacitor) and upward leaders may initiate from that location. That does not influence the simulation, but is inaccurate. This may be solved by using a large ground plane with a cloud of a smaller area, which yields another problem. A high number of ground charges results in increased computation times, but most of those charges will not play a significant role in the simulation (no upward leaders will be initiated from them).

This yields intuitively in the solution of placing the ground charges with different density, but that also introduces distortion. If there are differences in the charge density on the ground, than there will be differences in the ground E-field favouring regions having less point charges – resulting in higher calculated charges, higher E-fields and earlier upward leader initiation.

Summarizing these remarks: the choice of applied models largely influences the simulations. This is once a drawback (a few pointed out here already), once an advantage. The biggest advantage of the OSLM is explicitly the ability of making comparisons and the flexibility of the applied models. Based on these experiences future research should focus just as much on applied model selection as on the implementation of existing models.

A4.4. A small sample test of the OSLM, comparison of some implemented models

The OSLM has been tested using a simplified model of the Ostankino TV tower in a small sample tests. The height of the Ostankino is ~540m, a cloud height of 2000m was assumed. The building itself was modelled with 162 point charges, while the ground itself (4 km^2) was modelled with 1089 point charges. To improve calculation accuracy also 162 boundary charges were defined giving the total number of charges to 1419 resulting in relatively quick simulations (one strike was simulated in 1 minute).

The model of the tower was based on the original dimensions of the Ostankino tower. The most important feature was maintaining the height and width of the different sections. The number of point charges placed at the building provided adequate accuracy in the calculations.

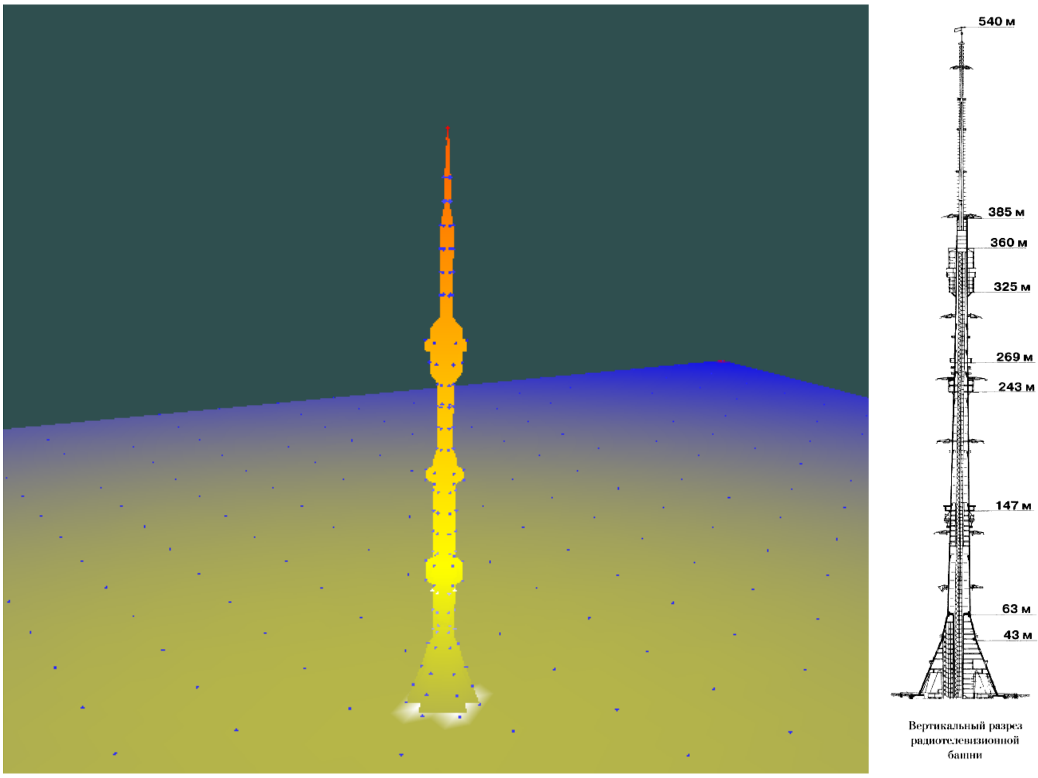

Figure A4.3: The model of the Ostankino TV tower (Moscow), and a schematic of the tower[46]

The cloud charge matrix consisted of 121 point charges with -240 μC charge each. These values were chosen to reproduce the peak electric field of -25kV/m underneath a thunderstorm cell calculated by Amoruso and Lattarulo [104]. Note that in a measurement at the Gaisberg Tower (Austria) the field strength close (170m) to the tower was much less than this value at the time of a strike [126]. The cloud area was 4km^2 (its height was not taken into account, since the cloud was modelled with one single charge layer).

[46] Downloaded from: http://www.tvtower.ru/56_HistoryMRC/eng/

A simple charge matrix model for the cloud was used and an E (>10^6 kV/m at 70 cm from the ground) criterion were used for the upward leader initiation. The leader model was a point charge model with vertically decreasing charges (using the early approach of Golde [125] for vertically decreasing charge densities). The simulation was ran assuming a negative lightning with -15kA peak current resulting in a mean step (and striking distance) of 44.66. The choice for this low peak current fell because there are mostly upward strikes initiated from the tower with considerably higher peak currents. The only occasion when downward strikes may be observed is when the peak currents are low. So high current simulation sessions were entirely omitted in the case of the Ostankino.

The Ostankino model was also placed in the middle and the stepped leader was moved from the axis of the tower further away (up to 800m in 100m steps and also 50m away from the tower) to take into account the various starting points of the lightning discharge to some extent. The total number of runs was 1000 (100 strikes for each location).

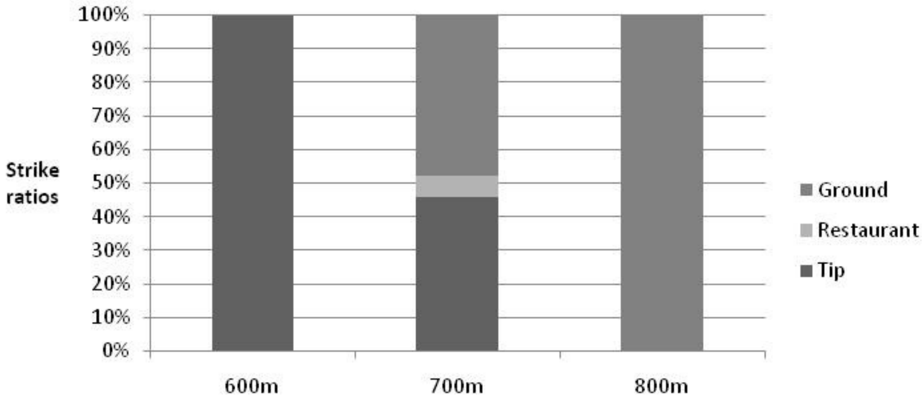

Figure A4.4: Strike locations vs. the distance of the Ostankino from the discharge

Fig. A4.4 shows only three values (600-800m), because all other values (0-600m) resulted in strikes only to the tip of the tower itself. In case of a distance of 700m however some simulated discharges struck the restaurant area of the Ostankino as well. This is a very important result, as in practice generally these two locations are struck [127]. Also note that real world observations also support this result. In case of the CN tower (of similar height) the stroke density decreases rapidly when getting closer to the tower [128].

Results at other distances are deterministic because they are mostly influenced by the first initiated upward leader. If the discharge is close enough, then it develops at the tip of the tower, while in other cases, it starts from the ground. The results at 700m distance show, that it's possible to have an upward leader initiate from the restaurant level as well.

The results shown here are brief, using simplified models only. Their purpose is to demonstrate the capabilities of the OSLM, their in depth analysis is not in the scope of this thesis. We have to emphasize though that the small sample test (1000 runs) results are basically in line with observations (and the other models as noted before). Hence running the OSLM with a wider array of initial conditions for various enables a more detailed analysis.

A4.5. Sample files used in the OSLM

The ‘solution’ file used in the simulation of the Ostankino follows (the explanations on the different parts are written in Italic):

‘[Terrain Path]
TerrainHeightFile=C:\Projects\C#\OSLM3D\Simulations\Ostankino\bigflat.bmp
BuildingLocationFile=C:\Projects\C#\OSLM3D\Simulations\Ostankino\bigflat.bmp
BuildingHeightFile=C:\Projects\C#\OSLM3D\Simulations\Ostankino\Ostankino.hgt
InitLeaderFile=C:\Projects\C#\OSLM3D\Simulations\Ostankino\Simp.inl’

These paths show where the different files for the height map of the ground, the building arrangement and the initial stepped leader are found.

‘[IsCompiled?]
Compiled=true’

Shows that the solution was ‘compiled’, the distance matrices created, the cloud potential calculated.

‘[PotValue resolution]
GroundPotDist=20’

The resolution of the ground. Currently this value shows that one point where the potential is calculated is placed in 20m.

‘[CloudHeight]
CloudHeight=2000
CloudLocX=500
CloudLocY=500
CloudWidth1=1000
CloudWidth2=1000’

Cloud placement and size. The data is taken in meters.

‘[MatrixInverse]
MatInvCalculated=false’

Again for compilation, the inverse of the distance matrix has been already calculated, no need to recalculate it.

‘[Charge parameters]
CloudType=Matrix
CloudQ=-0.00024
LeaderType=Point
LeaderSecQ=-0.0008
LeaderTipQ=-0.008
IPeak=10’

The initial charge configuration of the cloud and the leader. All charge data are Coulombs. The peak current (IPeak) is measured in kA. The possible leader types are Point or Line (in case line the models are selected in the code currently).

'[Charge distances]
GroundChgModel=Normal
CentralDensity=300
ChargeDistanceGnd=50
ChargeDistanceBldg=10
ChargeDistanceCloud=100
ChargeDistanceBound=50
BoundChargeRingDistance=50'

Placement of the point charges on the ground. The numbers represent the frequency of the point charges on the ground, cloud and boundary ring. The GroundChgModel may be Normal, Radial or CentralDense. Normal means flat distribution, Radial means a radial symmetry in the placement and CentralDense means that in the center (in circle with a radius of CentralDensity from the middle) the charge placement frequency is 10m.

'[Applied models]
LeaderNearDistance=10
UpLeaderStepModel=UseRatio
UpLeaderCalcDistance=5000
LeaderChargeModel=Golde
LeaderTipEFieldModel=LTipEFieldNoDL'

The applied models. LeaderNearDistance means the distance criterion for upward leader calculation, the UpLeaderStepModel may be UseRatio, or StepFixed. The former uses the ratio of 4 – as mentioned in Ait-Amar and Berger [108]- *and the latter is a Fixed step length found in the code.*