CHALMERS
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Risk Assessment of Transport of Dangerous Goods with GIS

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

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Master's Thesis ACEX30-19-45

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Cover:
Visualization of societal risk (up right figure) and individual risk (down left figure). Figures is taken from case study of Mariestad, chapter 4.5.1 and 4.5.2

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ABSTRACT

In urban densification there is an increased need to exploit, for example, areas close to transportation links with transport of dangerous goods. Before it is possible to exploit such areas, a risk assessment is necessary to ensure people's health and safety. Different tools are used to assess the risk, two of them are RBM II used in the Netherlands and self-developed calculation models by consulting firms. An example of a self-developed calculation model is a spreadsheet calculation that has been developed by Norconsult. The spreadsheet calculation is a translation of RBM II with adaption to Swedish conditions and regulations, but with the limitation that all the calculations are made in a spreadsheet software. Thus, this thesis aims to examine the potential to use GIS as a tool to assess the risk of transport of dangerous goods. A first version of such a GIS-model was developed in the GIS-software QGIS. The first version was divided into two models, one with impact areas copied from the spreadsheet calculation and one with impact areas more similar to RMB II. Both GIS-models were validated against RBM II and the spreadsheet calculation. The validation was made on an imaginary case with a rectangular area and a road perpendicular to the area. The GIS-models were also compared with the spreadsheet calculation on a real case scenario where the risk already has been assessed by Norconsult.

The result from the validation showed that the risk from the GIS-models is in accordance with both RBM II and the spreadsheet calculation regarding the total risk assessment. However, the exact number of fatalities and frequency did not match just as good. This could be explained by several factors including simplification of weather categories, distribution of population and different shapes of impact areas. There are some drawbacks with the created GIS-models that advantageously can be developed further. However, the case study showed several features in GIS that provides the possibility for making a more correct risk assessment. Thus, the overall conclusion was that a GIS-based approach can be used to assess the risk in transportation of dangerous goods.

Key words: Risk, risk assessment, dangerous goods, transport, geographic information system, GIS, QGIS

Riskbedömning av transport av farligt gods med GIS

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SAMMANFATTNING

Vid förtätning av städer ökar behovet av att exploatera exempelvis nära transportleder där det transporteras farligt gods. Innan dessa områden kan exploateras krävs det en riskbedömning för att säkerställa människors hälsa och säkerhet. Det finns olika verktyg för att göra denna riskbedömning, två av dessa är RBM II som används i Nederländerna och konsulters egenutvecklade beräkningsmodeller. Ett exempel på en egenutvecklad beräkningsmodell är en kalkylberäkning som tagits fram av Norconsult. Kalkylberäkningen är en översättning av RBM II med anpassning till svenska villkor och regler, men med begränsningen att all beräkning görs i ett kalkylprogram. Syftet med detta examensarbete är att undersöka möjligheten att använda GIS som ett verktyg för att bedöma riskerna för transport av farligt gods. För att uppfylla syftet skapades en första version av en GIS-modell i GIS-programmet QGIS. Den första versionen är uppdelad i två modeller, en med effektområden kopierade från kalkylberäkningen och en med effektområden som mer liknar dem i RBM II. Båda GIS-modellerna validerades mot RBM II och kalkylberäkningen. Valideringen gjordes på ett påhittat fall med ett rektangulärt område och en väg vinkelrät mot området. GIS-modellerna jämfördes även med kalkylberäkningen i ett verkligt fall där riskerna redan har beräknats av Norconsult.

Resultatet från valideringen visade att risken från GIS-modellerna överensstämmer väl med RBM II och kalkylberäkningen med avseende på den totala riskbedömningen. Däremot överensstämde inte det exakta antalet dödsfall och frekvens lika bra. Detta kan förklaras av flera faktorer, bland annat förenkling av väderkategorier, fördelning av befolkning samt olika former av effektområden. Det finns några nackdelar med de skapade GIS-modellerna som med fördel kan utvecklas vidare. Det verkliga fallet visade dock att GIS har flera funktioner som skapar möjlighet för en mer korrekt riskbedömning. Därför var den generella slutsatsen att ett GIS-baserat tillvägagångssätt kan användas i en riskbedömning av transport av farligt gods.

Nyckelord: Risk, riskbedömning, farligt gods, transport, geografiskt informationssystem, GIS, QGIS

Contents

Preface

In this study, the future potential to use GIS as a risk assessment tool for transport of dangerous goods has been studied. The project was carried out during the spring 2019 at the consultancy firm Norconsult's office in Gothenburg, as well as under the department of Architecture and Civil Engineering at Chalmers University of Technology.

The project supervisor and examiner at Chalmers was Associate Professor Andreas Lindhe and the supervisor at Norconsult was Johan Hultman.

I would like to thank all the people at Norconsult for making me feel welcomed and included at their workplace. A special thanks to Johan Hultman for his help and guidance and Herman Heijmans, risk analyst at Norconsult, for his expertise and willingness to share his knowledge. Also, a special thanks to Andreas Lindhe for his helpful inputs to the project.

Gothenburg, June 2019

Robert Kallin

Abbreviations

ADR-S	European Agreement concerning the international carriage of Dangerous goods by Road. The S on the end means that it is the Swedish version
BLEVE	Boiling Liquid Expanding Vapor Explosion
Dp	Detail development plan
FN-diagram	Diagram showing cumulative Frequency of accident versus Number of fatalities
LFL	Lower Flammability Limit
TNT	Trinitrotoluene (Explosive material)

1 Introduction

In the world today, more than half of the population lives in cities. In Sweden, the share is greater with about 85% of the population living in urban areas (SCB, 2015). The trend is that the urbanisation will continue and to cope with an increasing population cities does not only have to expand but also to get denser (Boverket, 2012). In urban densification, the need to exploit areas near an exposed location increase. Still, the buildings should be on locations suitable for the purpose with regard to human health and safety and to the risk of accidents, flooding and erosion (SFS, 2010). Thus, in order to ensure health and safety, the need of risk assessment in urban planning is increasing. Risk assessment is needed both to identify locations with already acceptable risks but also to evaluate risk-reducing measures (Länsstyrelsen, 2007).

One type of the exposed locations is areas close to transportation links with transport of dangerous goods (Länsstyrelsen, 2016). Transport of dangerous goods is important for many industries. For example, it is important that petrol reach the petrol station and medicines the hospitals (Mårtensson, 2012). Other examples of dangerous goods are explosives, flammable gases and corrosive substances and at an accident these materials can cause injuries and fatalities on the individual as well as the society (MSB, 2017). By calculating the frequency and the consequences of an accident the risk of transportation of dangerous goods can be assessed.

When performing a risk assessment of transport of dangerous goods, many parameters must be considered and the calculations quickly become complex. Hence, a computer-based software is typically needed (MSB, 2017). In the Netherlands, the former Ministry of Traffic and Water management has developed a uniform tool to assess the risks called RBM II. In Sweden, there is no similar tool that is developed on behalf of the government. Instead, it is up to the one performing a risk assessment of transportation of dangerous goods (typically a consulting firm) to develop a suitable tool. The consulting firm Norconsult has developed an Excel spreadsheet to calculate the risk [here referred to as “spreadsheet calculation”]. The spreadsheet calculation is a translation of RBM II with adaption to Swedish conditions and regulations.

Both RBM II and the spreadsheet calculations have their drawbacks and limitations. RMB II is developed in Netherlands and thus needs to be adapted relevant conditions and prerequire if use elsewhere. For example, Sweden has a major mining industry which results in more transport of explosives. The spreadsheet calculation is, for example, limited by the shape of rectangles where both the impact areas and area of investigation needs to be simplified into rectangular shapes. With an increasing need for risk assessment in urban planning, the need of a more comprehensive tool design for Swedish conditions is desirable. One possible solution could be to use a GIS-based tool where information and attributes are connected with geographic information and can be analysed in different layers.

1.1 Aim and objectives

The aim of this project is to assess the potential of using GIS as a tool in risk assessment for transportation of dangerous goods and to develop a first version of such a model. The GIS-model will be compared with the spreadsheet calculation and the RBM II to validate the result and to assess the model's advantages and limitations. Specific objectives of the work are to:

- Investigate how the risk of transport of dangerous goods are calculated in RBM II and spreadsheet calculation. Assess the benefits and limitations with each of the tools.
- Assess if GIS can be used to address the limitations and retain the benefits of the risk assessment in RBM II and spreadsheet calculation.
- Assess the future potential to use GIS in risk assessment of dangerous goods and investigate if GIS can be used as the only tool.

1.2 Delimitations

Geographically, the study will focus on transportation of dangerous goods in Sweden and thus the GIS-model will be developed through Swedish conditions and regulations. The compared models will be delimited to consider two models: RBM II used in Netherlands and the spreadsheet calculation used at Norconsult. These two models are included since the thesis is written in collaboration with Norconsult and thus expertise about the spreadsheet calculation has been easily accessible. Moreover, since the spreadsheet calculation is a translation of RBM II it is important to include, and have a basic knowledge, of both these models. However, since the calculations in RBM II is not adapted to Swedish conditions and regulations the case study will only be a comparison between the developed GIS-model and the spreadsheet calculation.

Regarding the delimited number of compared models, the aim is to assess the potential of using GIS. Thus, the focus is to study the possibilities with GIS and not compare the model with all models used today.

The risk that will be analysed is limited to the risk connected to human health and safety and the unit for the analysis will be fatalities. These delimitations have been done to be able to compare the GIS-model with RBM II and spreadsheet calculation, which both present the result as risk of fatalities.

The GIS-model will be developed to assess the risk on roads and not on other transport modes such as railways and waterways. This delimitation has been made since it is likely that if a GIS-models can assess the risk for a road, the model can be modified to also assess the risk for other transport modes.

1.3 Thesis outline

The thesis is structed to first describe the method that is used to fulfil the aim, this is described in chapter 2. Following that, chapter 3 gives a theoretical background with subchapters about dangerous goods, risk assessment, RBM II and the spreadsheet calculation. The subchapter about dangerous goods give an initial understanding of what is included in the concept "dangerous goods". The subchapter about risk assessment firstly present an overview of the topic followed by a more specific description of regulations and guidelines linked to risk assessment of dangerous goods. The following two subchapters present the current risk assessment tools, RBM II and the spreadsheet calculation. These subchapters present an overview of the risk assessment tools, a more detailed description can be found in appendix A and B.

Following that, chapter 4 will present GIS and the models that were created. The chapter is divided to first present a brief introduction to GIS with some of its functions, then prerequires and desires on a GIS-model will be described followed by description of how societal and individual risk are calculated in GIS. Chapter 4 also contains a validation against RBM II and the spreadsheet calculation in an imaginary risk assessment case. Moreover, a case study where the risks are assessed by the GIS-models on a real case scenario will be presented in the end of chapter 4.

Lastly, chapter 5 present a discussion and conclusions about if GIS can be used as a future tool to assess the risk of transport of dangerous goods.

2 Method

The method used to fulfil the aim of this study was divided into the following steps:

1. Literature study
2. Analysis of the tools used today
3. Specifying the requirements and desires of a GIS-model
4. Development of a first version of a GIS-model
5. Validation against RBM II and spreadsheet calculation
6. Comparison with the spreadsheet calculation in a real case study.

The initial literature study was conducted to understand risk assessment of dangerous goods. The literature study developed an understanding of what kind of dangerous goods that are transported and what they potentially can cause. Moreover, the literature study included current approaches to risk assessment of dangerous goods and when a risk assessment is needed. Information for the literature study was collected via relevant library databases, including Scopus and Google Scholar. Keywords that were used as a starting point were risk assessment, transportation of dangerous goods, risk assessment of dangerous goods, GIS in risk assessment, and their synonyms.

The study also included an analysis of the tools used today: the spreadsheet calculation and RBM II. The goal of the analysis was to investigate the benefits and drawbacks of the two tools in order to know what to include and develop in a GIS-model. The analysis was based on continuous contact with Johan Hultman and Herman Heijmans, both working with risk assessment at Norconsult. Moreover, a meeting with these two was held on March 6th 2019 to specify the requirements and desires of a GIS-model. The result from the meeting and the continuous contact can be read in chapter 4.2.

A first version of a GIS-model was developed in QGIS. The development was carried out in different steps. Firstly, a GIS-model that was based on the same input as the spreadsheet calculations was developed, this model will later be referred to as "GIS-model 1". Later, this model was developed with impact areas that were more consistent with those in RBM II, this model will later be referred to as "GIS-model 2".

Both GIS-model 1 and 2 were validated against RBM II and the spreadsheet calculation. The validation against RBM II was conducted on the classes that are included both in Swedish and Dutch risk assessments (ADR-s class 2.1, 2.3 and 3). To validate the GIS-models a rectangular area with a straight line was set up in QGIS which the GIS-models were assessing the risks on. The area and line were rectangular and straight so that they could be copied into a risk assessment with RBM II and the spreadsheet calculation. Thus, with the same input values of number of dangerous goods, number of people, wind distribution etc. the result from the risk assessments could be validated against each other. The validation was carried out to find out if the GIS-model calculated the risk in accordance with RBM II and the spreadsheet calculation.

Lastly, the GIS-models were used on a real case scenario where the risk already has been assessed by Norconsult using the spreadsheet calculation. This was carried out in order to compare the developed GIS-models with the spreadsheet calculation to assess its potentials and drawbacks.

3 Theoretical background

This chapter provides a theoretical background to risk assessment of transportation of dangerous goods. The chapter starts with a general description of dangerous goods followed by risk assessment. Later, more specific information about the analysed risk assessment tools, RBM II and spreadsheet calculation, are described. Information about the two risk assessment tools are organized to contain a brief description about the tools and how they work. A more detailed description of the tools and their theoretical background can be found in Appendix A and B.

3.1 Dangerous goods

"Dangerous goods are substances and objects that due to its chemical or physical properties can cause damage on life, health, environment and property during transport" (Mårtensson, 2012, p.11). These substances and objects are classified as dangerous goods since they exhibit properties that are considered dangerous during transport (Mårtensson, 2012). For example, properties that are explosive, flammable or corrosive. Petrol, liquefied petroleum gas and fireworks can be mentioned as example of products that are considered as dangerous goods.

Many functions and activities in the society are dependent on dangerous goods and thus the transport of it. It is, for example, important that petrol reach the petrol stations and medicines reach the hospitals. Moreover, transport of dangerous goods is important in many industries, such as food, pharmaceutical and manufacturing industry (Mårtensson, 2012). The concept of transport of dangerous goods is including the transport from origin to destination by either vehicle, railway wagon, ship or aircraft. However, the concept also includes loading and unloading, as well as storage and handling of dangerous goods connected to transport. The concept does not include transport, storage and usage of dangerous goods within a production area (MSB, 2017). In this study, it is the transport of dangerous goods on the road that will be considered. Transport of dangerous goods on the roads and in terrains are regulated by ADR-S (MSB, 2019). Regulation regarding dangerous goods are further described in chapter 3.2.2.1.

In Sweden, dangerous goods should as much as possible be transported on the recommended links which are roads where dangerous goods are allowed for through traffic. If necessary, dangerous goods are allowed to be transported outside of the recommended links, but through traffic are not allowed on these roads. In some regions in Sweden the roads are called primary and secondary road, where primary roads correspond to the recommended links. Secondary roads are not allowed for through traffic, but often a smaller amount of dangerous goods is transported on these roads (Mårtensson, 2012).

3.1.1 Classifications

Dangerous goods on the roads and in terrain are classified according to ADR-S (MSB, 2019), see Table 1. There are nine classes and the classification are done according to type of dangerous goods. A substances or object can have several dangerous properties. If that is the case the classification will be made with a primary class, which indicates the dominant danger, and one or several secondary classes (MSB, 2019). All types of dangerous goods have also been given an UN-number which is a four-digit ID-number given by UN. This number is only for identification and does not specify the hazard (Mårtensson, 2012).

TABLE 1 - CLASSIFICATION OF DANGEROUS GOODS (ASP, 2019).

Class	Content	Example
1	Explosive substances and objects	Explosives, fireworks
2	Gases	Flammable gases (Liquified petroleum gas), toxic gases (ammonia, sulfur dioxide) and other pressurized gases (nitrogen, oxygen)
3	Flammable liquids	Petrol, fuel-oil
4.1	Flammable solids, self-reactive substances, polymerizing substances and solid insensitive explosives	Safety matches
4.2	Substances liable to spontaneous combustion	Aluminium alkyls, white phosphorus
4.3	Substances that emit flammable gas when in contact with water	Sodium, calcium
5.1	Oxidizing substances	Ammonium nitrate
5.2	Organic peroxides	Benzol peroxides
6.1	Toxic substances	Acids
6.2	Infectious substances	Medical/biomedical waste
7	Radioactive substances	Radioactive substances for hospitals
8	Corrosive substances	Different acids, lye
9	Other dangerous substances and objects	Asbestos

Mainly, it is class 1, 2, 3 and 5 that can give severe consequences regarding fatalities and is most relevant in a quantitative risk assessment (Davidsson & Thorwaldsdotter, 2011). However, according to Alvarsson & Jansson (2016) some county administration boards and consultants also includes class 4, 6 and 8 in their risk assessment. Nevertheless, Davidsson & Thorwaldsdotter (2011) states that these classes only give limited consequences on short distances or consequences without fatalities. Alvarsson & Jansson (2016) also discuss this and concludes that the difference regarding risk identification in general gives small differences in the risk assessment since these mainly consist of choice of classes for which frequencies and consequences are relatively low.

Below is a short description of class 1, 2, 3 and 5 and what these classes potentially can cause. The information is gathered from Davidsson & Thorwaldsdotter (2011) if no other reference is stated. How the risks are treated in RBM II and the spreadsheet calculation are explained in chapters 3.3 and 3.4 respectively.

3.1.1.1 Class 1

At an accident with transport of class 1 there is a risk of explosion that can be caused by spontaneously reaction, external fire or motion energy that develops in shock. The risk of an explosion is minimised by the way these substances and objects are packed and transported. The maximum allowed weight to transport in Sweden is 16 tones, but these transports are rare.

It is mainly mass explosive substances that can cause injuries on people in an accident. An explosive will lead to high pressure in the surroundings which will decrease with the distances. Fatalities can be caused either as a direct consequence of the pressure wave or through collapse of buildings, or from splits and flying materials. Humans withstand the increase of pressure better than buildings. Fatalities caused by the direct pressure wave can occur up to 75 meters at an accident with a transport of 16 tons explosives. Buildings can collapse at distances of a few hundred meters from the place of accident.

3.1.1.2 Class 2

If flammable gas is leaking out through a small hole and is ignited immediately, a jet flame will appear. Fatalities caused by a jet flame can be caused on distances to about 50 meters from the accident. If the gas is not ignited immediately a flammable vapor cloud will appear. Depending on when the vapor cloud is ignited either a flash fire or vapor cloud explosion will appear. If the vapor cloud is ignited at an early stage the risk of an explosion is small, and thus it is likely with a flash fire. A rarer scenario is boiling liquid expanding vapour explosion (BLEVE). BLEVE can happen if a tank with fused flammable gas is exposed to external fire so that the pressure in the tank increase until an explosion. The tank must be greatly heated which could happen by a fire in a tank close by. The sequence of a BLEVE happens with a certain delay which can give time to evacuate the area.

Regarding accidents with toxic gases the causes depends heavily on number of factors such as which gas, the size of the emission, weather conditions etc. In general, the probability of fatalities is greater closer to the accident and is reduced by distance. Also, the gases are spreading in the wind direction which means that the fatalities are dependent on ground conditions and number of peoples in the area where the gas cloud emerges.

3.1.1.3 Class 3

An accident with flammable liquids, class 3, can lead to burning liquid on the ground, a so-called pool fire. The extent of the pool fire depends on the area around the accident, the spreading can for example be limited by ditches. One other prerequisite for the liquid to ignite is the flashpoint. For example, petrol has a flashpoint under 21°C and can be ignited in regular outdoor conditions, while diesel has a higher flashpoint and is not expected to ignite at temperatures below 55°C. Around 40% of the transports in class 3 are liquids with low flashpoints.

3.1.1.4 Class 5

Pure emissions of substances from class 5 are normally not causing any fatalities or injuries. It is when the substances get enough energy to start reacting spontaneously as they can cause fire or in worse case an explosion. The substances can get enough energy either through heating, contact with organic substances (petrol and fuel-oil) or in case of very strong shocks. The risk of explosion exists if the substances are mixed with fuel, which can happen if, for example, the fuel tank is damaged in the accident or if another vehicle is involved. The consequences of an explosion can have the same extent as class 1.

3.1.2 Statistics

Knowledge about how and where dangerous goods are transported is important in order to assess the risks in urban planning. Statistics on the quantities of dangerous goods transported and which transport routes that are used is an important tool (MSB, 2015). The latest mapping of dangerous goods in Sweden was carried out by SCB during September 2006. The result can be seen in Table 2. It is important to clarify that the result from the report only shows tendencies of how the transports take place. The results are also based on several assumptions and important uncertainties exist. For example, not all companies that transport dangerous goods took part in the survey and the survey gives only a picture of the transport flows for one month (SRV, 2006).

TABLE 2 - LATEST MAPPING OF DANGEROUS GOODS BY SCB, CARRIED OUT SEPTEMBER 2006 (SRV, 2006).

Class	Weight [ton]	Share
1	1100*	0.1
2.1	25047	1.8
2.2	80736	5.9
2.3	166	0.0
3	959953	69.6
4.1	3630	0.3
4.2	429	0.0
4.3	753	0.1
5.1	8820	0.6
5.2	46	0.0
6.1	1694	0.1
6.2	1819	0.1
7	..**	..
8	172767	12.5
9	123163	8.9
Total	**1380124**	**100**

* Net wight

** Only presentated in the maps

The result from SRV (2006) can be compared with statistics from Trafikanalys that analyses and reports official statistics of transports and communications in Sweden. The total weight of dangerous goods in 2006 and 2017 can be seen in Figure 1. The numbers from 2006 can be compared with Table 2 to see the difference between September (Table 2) and whole 2006 (Figure 1). The numbers from 2017 can be used to see the difference between dangerous goods transportations between 2006 and 2017. The trend in tonne-kilometres performed in the classes that can give severe consequences can also be seen in Figure 2.

Trafikanalys has also made a pre-study on the possibility of an extended mapping of dangerous goods flow in Sweden. The conclusion was that it is possible to identify main routes for dangerous goods with information of origin and destination, but with a lack of geographical resolution. Moreover, there must be a clear assignment and finance of a new collection if the need of a mapping exists. The mapping must also consider that an extend report obligations from the goods owners and fright distributors are needed (Trafikanalys, 2015).

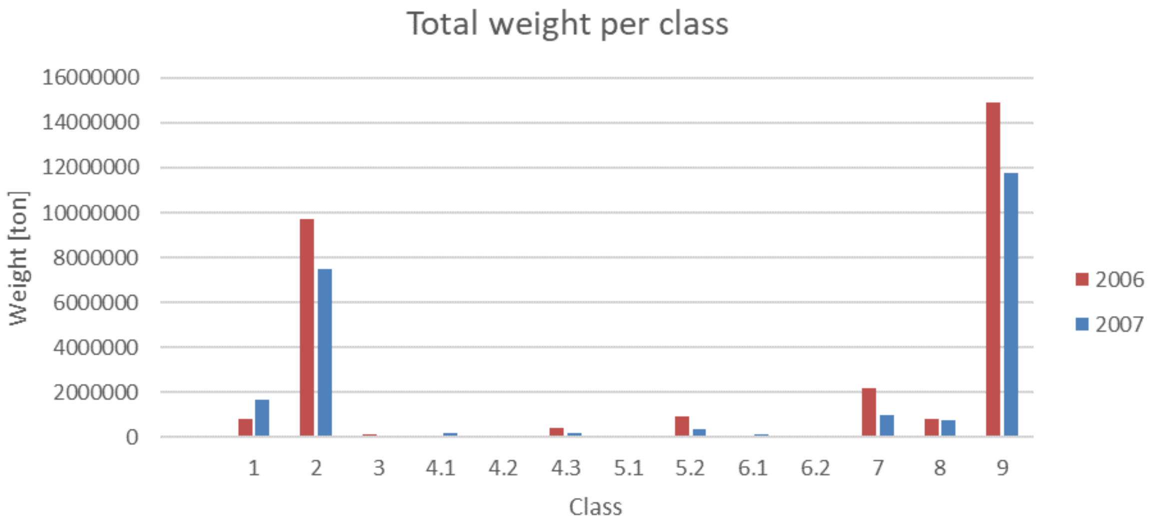

FIGURE 1 - TRANSPORTED DANGEROUS GOODS BY WEIGHT IN 2006 AND 2017. DATA GATHERED FROM TRAFIKANALYS (2019).

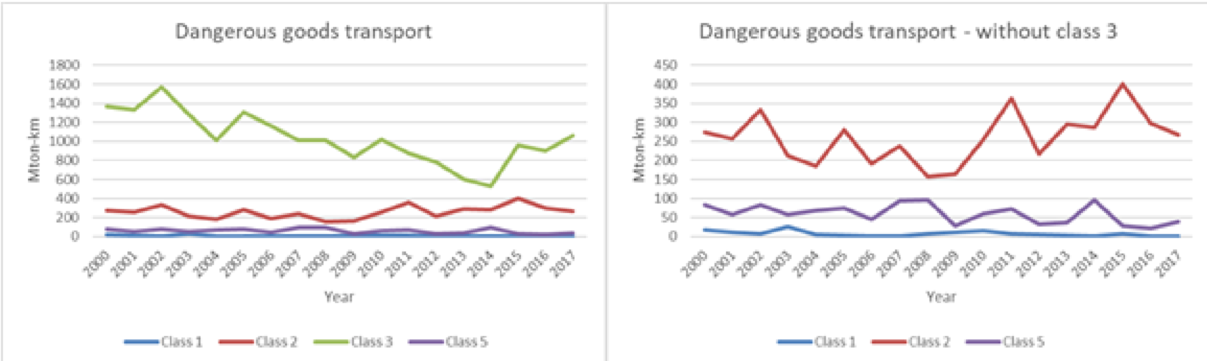

FIGURE 2 - TREND IN TONNE-KILOMETRES PERFORMED IN CLASSES 1,2,3 AND 5. DATA GATHERED FROM TRAFIKANALYS (2019).

3.1.2.1 Accident statistics

In Sweden, there are generally few accidents of dangerous goods (Mårtensson, 2012). However, every year there occurs many accidents with heavy vehicles where trucks could have had dangerous goods. Due to the similarities in type of vehicles and risk reduction measures between dangerous goods transport and heavy vehicles, the accident in these two categories are connected. Hence, from a traffic perspective it is interesting to investigate accident with heavy vehicles in general and not only focus on dangerous goods (Mårtensson, 2012).

To get an overview of what kind of accidents that occurs with heavy vehicles, data have been extracted from the Swedish accident database STRADA. The extract has been made during the period 2008-01-01 until 2018-12-31 and contains all accidents which involve the traffic category “trucks”. The trend in total accidents, containing all severity of injuries, can be seen in Figure 3. According to Mårtensson (2012), it is the severity type *fatalities* and *severely injured* that are interesting in a dangerous goods perspective. These two types for severity are interesting since they generally include greater collision impact and hence a bigger risk of damages on the freight of the truck. How these accidents are distributed in type of accident can be seen in Figure 4. However, it is important to point out that the statistics extracted from STRADA contains all accidents were trucks are included which means that the fatality or severely injured can be in another type of vehicle. For example, it is likely that the fatality or severely injured is not in the truck in the accident type bike/scooter and pedestrians in Figure 4, and thus they will not create damages on the truck's goods.

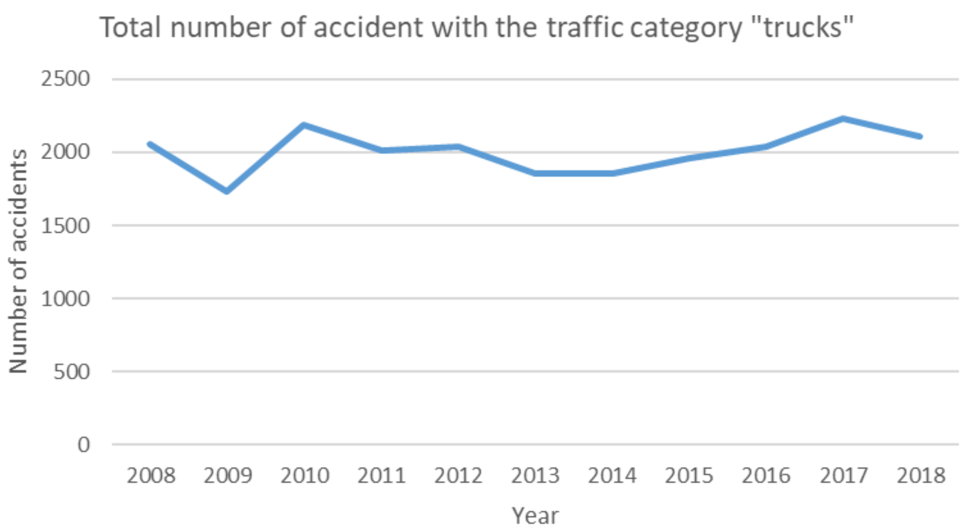

FIGURE 3 - TREND IN TOTAL ACCIDENTS WITH THE TRAFFIC CATEGORY "TRUCKS". DATA EXTRACT FROM STRADA (2019).

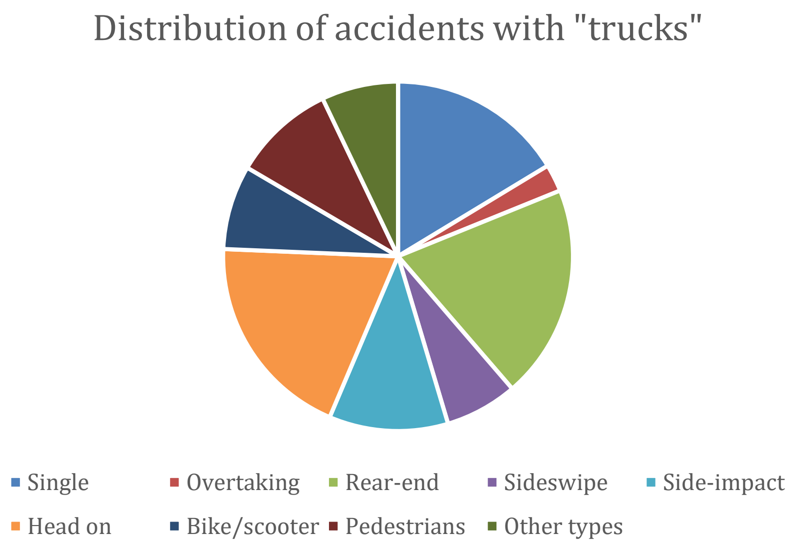

FIGURE 4 - DISTRIBUTION OF TYPE OF ACCIDENTS WITH TRUCKS. DATA EXTRACT FROM STRADA (2019).

3.2 Risk assessment

Risk assessment is conducted to make decisions about uncertainties in unwanted future events (Burgman, 2010). The risk assessment can be addressed to evaluate risks to species, natural communities or ecosystem processes. Whatever the focus, the risk assessment should evaluate and communicate the nature and extent of uncertainties (Burgman, 2010). According to ISO31000:2009 risk assessment is defined as the "overall process of risk identification, risk analysis and risk evaluation". Moreover, in ISO31000:2009 the term risk is defined as the "effect of uncertainty on objectives" and is often expressed as a combination of the consequences of an event and the associated likelihood. The definition of risk applied in this thesis is the consequences of an event multiplied by the associated likelihood, see equation 1.

$$RISK = LIKELIHOOD \ X \ CONSEQUENCE \qquad (1)$$

Risks can be divided into different groups depending on starting point (Davidsson, Haeffler, Ljudman, & Frantzich, 2003). According to Schyllander (1998), a simple division can be conducted based on the character or origin of the risk such as technological, natural or social risks. Schyllander (1998) also suggest a division according to damage incident or protection object, for example individual, work related, financial, environmental or collective risks. However, many of the definitions used for the concept risk are connected to the degree of randomness or uncertainties (Davidsson et al., 2003). Thus, Thedéen et al. (2010) divides risks into the following groups:

Deterministic risks are based on the law of large numbers which implies that if many observations (accidents) are observed the average number will be stable in the long run. For example, number of fatalities due to traffic accidents on a national level is rather constant.

Risks with relatively large random variations. In this category the variations are larger than in deterministic risks. One example is number of fatalities due to traffic accidents in a small region. Here, the number of observations (accidents) are much smaller than on a national level and thus the risk is not deterministic.

Catastrophes are events that are concentrated in time and space. In general, catastrophes mean low probability and high negative consequences. For catastrophes it may be possible to calculate the negative consequences, but the probability is often very difficult to estimate. If a risk is facing the opposite situation, where the probability is possible to estimate but the consequences are difficult to estimate, the risk can be classified as **uncertainty**.

Individual and societal risk are two commonly used measures of risks. Both these measures can be calculated in a risk assessment. Individual risk specifies the likelihood of a fatality and could be explained by the risk for an individual to be killed if that person is outdoors 24 hours a day, all year around, and does not move even though the danger is perceived. Individual risk does not consider how many people there is in the analysed area and are independent if there are anyone in the area or not. Moreover, individual risk is often declining with the distance to the risk source such as a road (Mårtensson, 2012). The result is often presented as a negative number with the power of 10, for example $1*10^{-6}$. These numbers can be interpreted as how often an event occurs. For example, $1*10^{-6}$ means that if one million people are exposed to the risk during a year the expectancy is that one of them will be effected (Mårtensson, 2012).

Societal risk describes the risk for the society as a whole and includes risks for all people that are exposed for a risk even if they are just exposed once (Davidsson, Lindgren, & Mett, 1997; Mårtensson, 2012). The purpose with a societal risk criterium is to delimit the risk for a certain area, for example a specific residential area. Societal risk can be defined as the connection between frequency of a potential accident and the consequences that will arise. Normally, frequency is stated with number of accidents per year and the consequences as number of deaths per accident. Societal risks are usual presented in a FN-curve which shows the cumulative **F**requency of accident versus **N**umbers of deaths, see Figure 5. With a FN-curve it is possible to evaluate if the risks are within the acceptable limits (Davidsson et al., 1997).

3.2.1 Risk limits

All risks cannot be prevented and in order to know if the risk is acceptable or not the risk needs to be evaluated and compared with set limits. For individual risk the limit is often set as a specific number of the maximum probability of a fatality during a year. For societal the limit can be set with a FN-curve not only to evaluate the average number of fatalities, but also the risk connected to accident where many people are affected (Davidsson et al., 1997). For both individual and societal risk Davidsson et al. (1997) suggest two different grades of limits, giving three different levels of risks:

Unacceptable risks, in this level the risks are not acceptable for new constructions and for existing situations a more flexible application is proposed. Actions to reduce the risk should be taken and an action plan should be drawn up.

ALARP, the region between acceptable and unacceptable is often referred to as “ALARP” which stand for As Low As Reasonably Practicable. This means that the risk can be acceptable if all reasonable measures have been taken. In practice, this means that the risk can be tolerated if risk reduction is not practicable or if costs are totally disproportionate.

Acceptable risks, in this level the risk is considered to be acceptable. However, it is still necessary to show that the risks are maintained at this low level.

There are different methods for valuing the risk and place them in one of the mentioned level of risks. The main methods are deterministic, probabilistic, risk comparison, protection area, rules and norms, subjective risk valuation (Mårtensson, 2012). If a probabilistic valuation is used the limits below are suggested by Davidsson et al. (1997). Since there are no national stated limits in Sweden, it is often the limits set by Davidsson et al. (1997) that are used in risk assessments.

Individual risk: Upper limit of 10^{-5} and lower limit of 10^{-7}, see Figure 5. This suggestion is for individual persons with an average sensitivity against the risk that is continuously present and is located outside. The criterium applies for the public, not the employees in the business creating the risk.

Societal risk: The criteria are suggested in a FN-curve with a likelihood (frequency [F]) that is declining with an increased number of fatalities [N], see equation 2 and 3 and Figure 5.

$$F = {10^{-4}}/{N} \qquad (2)$$

$$F = {10^{-6}}/{N} \qquad (3)$$

These limits are suggested for all societal risks and can be applied for transport risks. For transport risks the criteria are based on a road distance of 1km and should be rescaled if another distance is analysed, for example if 0.5 km is analysed the criterium should be halved. Moreover, the risk criteria are set for a total risk of the road which implies that if the area of investigation is located on one side of the road the criterium should be halved.

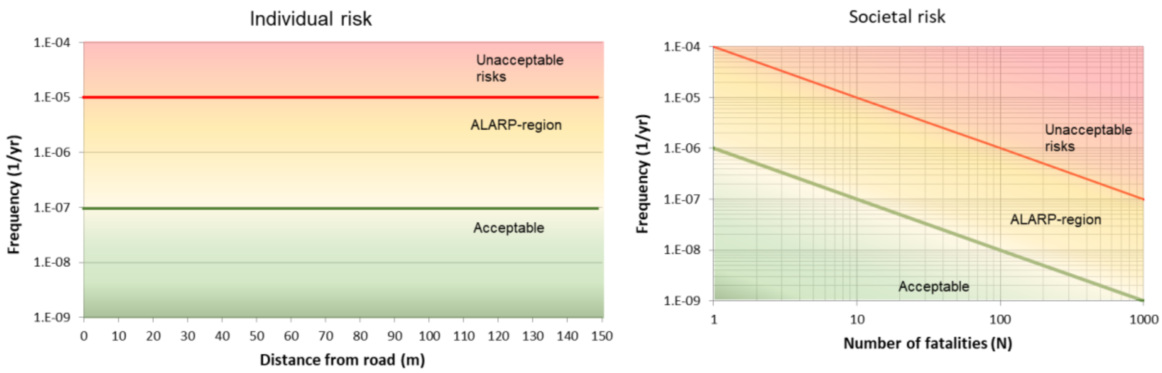

FIGURE 5 - SUGGESTED LIMITS FOR INDIVIDUAL RISK TO THE LEFT AND FOR SOCIETAL RISK TO THE RIGHT.

3.2.2 Need of risk assessment of transport of dangerous goods

In Sweden, there is no national guideline about when and how risks in transportation of dangerous goods should be assessed in urban planning (Mårtensson, 2012). However, risk assessment is connected to the urban planning through Sweden's Planning and Building act [PBL] and the Swedish Environmental Code [MB] where it is stated that risks for people health and security should be considered (Länsstyrelserna, 2006). Regarding when risk assessment is needed, there are guidelines that county administrations and municipalities usually refer to. Some of these guidelines are Risk policy, RIKTSAM, Comprehensive plan for Gothenburg, Risk assessment in Hallands county and Risk assessment in Stockholm county. To understand when and how risk assessment of transportation of dangerous goods should be assessed this sub-chapter gives a brief description of the above mentioned laws and guidelines.

3.2.2.1 Regulations

It is mainly PBL and MB that regulates risks in urban planning and risk assessments (Stenberg, 2007). The purpose of both these laws is to promote a good and long-term sustainable living environment in today's and tomorrow's society. PBL emphasize that constructions should be on land that is suitable for the purpose and that risk against accidents are considered (SFS, 2010). Also, PBL requires that questions concerning security and safety should be decided in connection with planning. To meet this requirement, it is important that the work with risks are starting at earliest possible stage in urban planning and are continuously worked through the process (Stenberg, 2007).

One of the things described in MB is the Environmental Impact Assessment [MKB] which should be developed in connection to a comprehensive plan. Also, when establishing a detailed developing plan, an assessment must be made of whether the plan's implementation can be assumed to have significant environmental impact. If that is the case, an MKB should also be developed in connection to a detailed developing plan. The purpose of an MKB is to be able to do an overall assessment of the planed construction's effects on human health and environment (SFS 1998:808).

The overall description should consist of a risk assessment which should be an in-depth study of the security and should be integrated in the other work with the MKB (Stenberg, 2007).

Other laws that deals with risk includes the law of protection against accidents (SFS 2003:778) which for example regulates the emergency services. Also, there are other laws that affect the transport of dangerous goods, but not the work with risk connected to urban planning. Transport of dangerous goods are regulated by law 2006:263 and ordinance 2006:311 of transport of dangerous goods. The law and ordinance are connected to several regulations which describe how the goods should be labelled, which education the different actors should have and how the documents should be structured (Walsh, 2017).

3.2.2.2 Risk assessment guideline "Risk policy"

The county administration boards of Skåne, Stockholm and Västra Götaland have created a guideline called "Risk policy" to present how land use, distance and risk assessment are connected to detail planning close to transport links with dangerous goods. The risk policy that they present implies that risk assessment should be considered in detail plans closer than 150 meters from a road with transport of dangerous goods, see Figure 6.

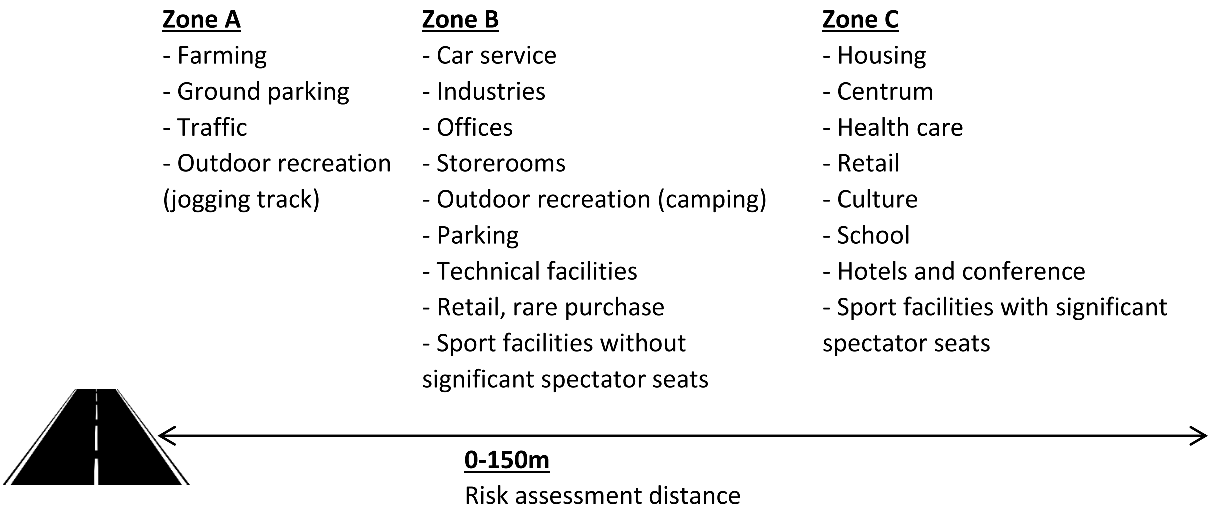

FIGURE 6 - ZONING FOR THE RISK ASSESSMENT DISTANCE FOR THE RISK POLICY (BASED ON LÄNSSTYRELSERNA, 2006).

The zoning in Figure 6 is only handling development districts. The zones are representing possible land use in relationship to the distance to the transport link. However, the zones do not have any distinguish boundaries since the risks for the different developing areas are crucial for the placement of the land use. Factors that can affect the level of risk in the different areas are for example density of inhabitants, grade of exploitation, age of the inhabitants, reduced mobility, language difficulties etc. Regarding public space, the area closest to the transport link should be constructed to reduce the visiting time (Länsstyrelserna, 2006).

3.2.2.3 Risk assessment guideline "RIKTSAM"

The county administration board of Skåne have published the document nemaed "RIKTSAM", which is a guideline for risk assessment in urban planning (Stenberg, 2007). The guidelines are split up in three parts. Together, the three parts constitute a system that shall ensure that satisfactory and comparable safety is obtained in all cases. The guideline should be used on detailed development plans closer than 200 m from a recommended link for transport of dangerous goods. The guidelines are dependent on type of land use and distance to transport link, important distances are 30, 70 and 150 m, see Figure 7.

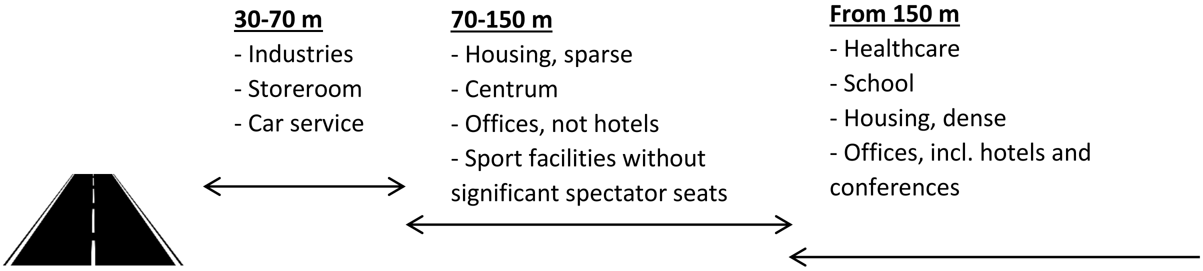

FIGURE 7 - ZONING FOR RISK ASSESSMENT IN RIKTSAM (BASED ON STENBERG, 2007).

The first part is based only on protection distance and requires that the land use in Figure 7 is applied. If not the land use in Figure 7 can be applied either part two or three should be used. The second part is based on deterministic criteriums which means that it is clearly stated that the consequences of "net addition" of unwanted events are eliminated by the condition on the development site. Net addition refers to the additional individual risk that are added when the protection distance cannot be fulfilled. The second part can be used when actions or conditions on the development site allows deviation to be appropriate. The third part is based on both deterministic and probabilistic criteriums regarding individual and societal risk. In the third part risks limits are evaluated in the same way as described in chapter 3.2.1 (Stenberg, 2007).

3.2.2.4 Risk assessment guideline "Comprehensive plan for Gothenburg"

In the comprehensive plan for Gothenburg ("Översiktsplan för Göteborg" in Swedish), guidelines for recommended distances between buildings and transport links with dangerous goods are presented. The following applies for a building close to a road (Palme & Lamnevik, 1997):

- A building free distance of 30 m on both sides of the road.
- Dense office buildings 50 m from roadside and dense residential buildings 100 m from roadside.

The above criteria are schematically presented in Figure 8. No further risk assessment is required if these criteria are fulfilled. A deterministic analysis is required if a developing site is planned outside of these land uses. The assessment must show that safety is fulfilled (Palme & Lamnevik, 1997).

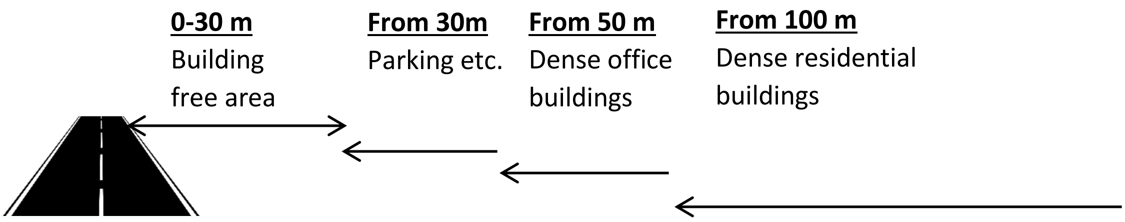

FIGURE 8 - CRITERIUM FOR LAND USE ACCORDING TO COMPREHENSIVE PLAN FOR GOTHENBURG (BASED ON PALME & LAMNEVIK, 1997).

3.2.2.5 Risk assessment guideline by Hallands county

In this report guidelines for urban planning along roads and railways with dangerous goods are established. The guidelines are based on a four zones division of the urban area along the transport links, see Figure 9.

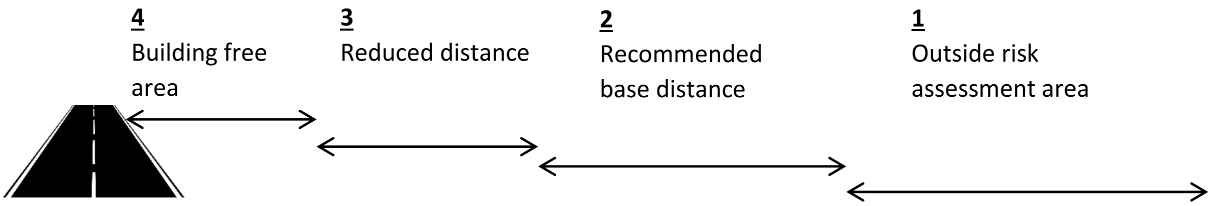

FIGURE 9 - CRITERIUM FOR LAND USE ACCORDING TO HALLANDS COUNTY (BASED ON DAVIDSSON & THORWALDSDOTTER (2011).

Zone 1 is the area outside of the risk area and is in the report set to distances further than 150 m from the transport links. In this zone all kinds of building can be established without specific concerns about risk with dangerous goods. Zone 2 is the recommended base distance and can variate between 30-100 m depending on transport link and land use. This area can be affected in an accident with dangerous goods, but the risk level is considered as acceptable without specific actions if some base requirements are fulfilled. In zone 3 the consequences at an accident with dangerous goods can be high. In order to build in this area specific risk reduced actions are required. Zone 4 is the building free area which is the minimum distance between buildings and transport links. The distance can variate between 15-30 m depending on transport link and land use.

The goal with the guideline is that the requirements can be used for normally occurring construction plans. However, the requirements cannot be used for constructions which may involve specific risks such as hospitals and larger arenas (Davidsson & Thorwaldsdotter, 2011).

3.2.2.6 Risk assessment guideline by Stockholm county

The county administration board of Stockholm present in their report recommended security distances between transport links with dangerous goods and different types of land use, see Figure 10. The county administration board thinks that the municipality should located buildings according to these recommendations in order to get a good urban planning.

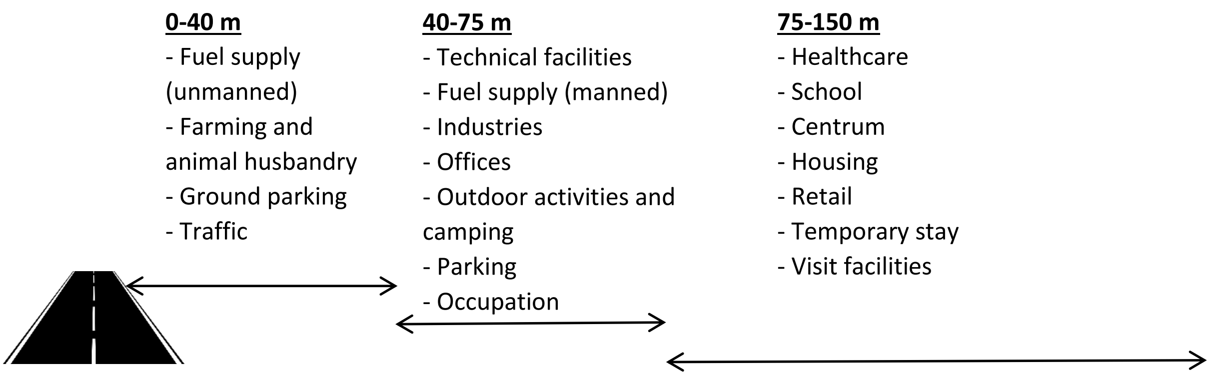

FIGURE 10 - CRITERIUM FOR LAND USE ACCORDING TO STOCKHOLM COUNTY (BASED ON LÄNSSTYRELSEN I STOCKHOM, 2016).

Figure 10 shows that residential buildings are generally suitable for a distance more than 75 meter from a road with dangerous goods transportation. Between 75-150 meters are there normally no need of a risk assessment, there are normally enough to describe the distances from the road to get the risk to be considered. When a risk assessment is needed they can vary in extent, but in general it can be said that the shorter security distance the greater need of a detailed risk assessment. However, the county administration board is considering that security distances is in general preferable compared to other safety actions. In shorter distances the consequences are more important than the probability of an accident (Länsstyrelsen i Stockhom, 2016).

3.3 RBM II

RBM II is used in the Netherlands for calculation of individual and societal risk to investigate if there are any conflicts between transport activities and urban development. The tool has been developed on behalf of the former Ministry of Traffic and Water management and is based on models presented in Yellow Book (PGS2, 2005) and Purple Book (PGS3, 2005). The tool can be used for quantitative risk analysis of road traffic, railway traffic and inland waterways. The categories that are included in RBM II can be seen in Table 3 together with representative substances and quantities. The categories used are from the ADR-S classification 2.1, 2.3, 3 (not fuel-oil) and 6.1. Class 1 and 7 are not included since they are transported in too small amount and class 4, 5, 6.2, 6.3, 8 and 9 since they do not give any lethal effects on relevant distances from the transport link.

TABLE 3 - CATEGORIES INCLUDED IN RBM II (AVIV, 2011).

Category	Scenario	Repr. Subs. and quantities
Flammable liquid	LF1	23 tons Heptane
	LF2	23 tons Pentane
Toxic liquid	LT1	23 tons Acrylonitrile
	LT2	23 tons Propulamine
	LT3	23 tons Acrolein
	LT4	23 tons Metylisocynaat
Flammable gas	GF1	50 m^3 Ethylene oxide
	GF2	50 m^3 n-Butane
	GF3	50 m^3 Propane
Toxic gas	GT2	16 tons Methylmercaptane
	GT3	16 tons Ammonia
	GT4	16 tons Chlorine
	GT5	16 tons Chlorine

Before starting the analysis, the buildings and roads need to be drawn up, this step is carried out manually. Five different building types and four different types of roads are possible to choose from. The building types are residential, business (day), business (day and night) and two event buildings (during workweek or weekend). The types of roads are public road, in built areas, outside built areas and highways. For each of the building and roads there are some standard values of number of people per hectare, fraction of people inside/outside, width of the road and frequency of accidents connected to the type of road. However, even though these values are default they can be changed if necessary. One thing that is not default is the number of transports for each of the hazardous substances, this must be added manually for each of the roads. After these parameters have been specified, RBM II calculates the individual and societal risk and present it as contour lines for individual risk and locations on the road with highest and over the limit values for societal risk. For societal risk it is also possible to get an FN-diagram. The calculations are made automatically but according to the background document from AVIV (2011), the calculations are performed in the following steps:

1. Define points on the road from which the risk is calculated from.

The risk is calculated from a limited amount of points where a possible accident can occur. The points are distributed both over the width and length of the road. Regarding length, the points are located 10 and 25 m apart for individual and social risk respectively. The distribution on the width depends on the width of the road and is different for individual/societal risks:

- If the road is less than 10/25 m, then in middle of the road.
- If the road is between 10/25 and 20/50 m, then two points evenly distributed
- If the road is between 20/50 and 30/75 m, then 3 points evenly distributed
- Etc

2. Define the probability with event trees for different scenarios

An event tree shows the probability of an initial event (an accident with a dangerous goods) followed by different event that can follow. In the end the probability of different scenarios can be calculated as a multiplication of the probability of previous events. The different event trees for a calculation on a road are presented in Appendix A.

3. Calculation of individual and societal risk

The calculation of both individual and societal risk is a multiplication of the probability of fatality, probability of the scenarios and impact area. The probability of fatality is different depending on type of effect. For further information see Appendix A.

What differs individual and societal risk in the calculations are the number of people that are affected in each of the scenarios. Individual risk is obtained by a summation of all the probabilities of the scenarios that cause fatalities. The limits used are 10^{-5} and control value of 10^{-6} for existing sites and 10^{-6} for limit and control value for all new sites. The societal risk is obtained by combinate the consequences with the density of people in the area close to the transport link. In RBM II societal risk is calculated for the probability of an accident with 10 or more fatalities. The calculations are made in day/night and in/out conditions. The limits are set in a FN-diagram with $F = 10^{-2}/N^2$, for example 10^{-4} for 10 fatalities, 10^{-6} for 100 fatalities and so forth. If these limits are extended it must be stated how various factors are assessed and possible eligible measures have been considered.

4. Summation and presentation

The individual and societal risk can be calculated together or separately, and the result can be visualized on the screen. For individual risk the visualization is in form of isolines for risk in evenly power of 10 (see Figure 22 and Figure 23), for societal risk the risk is presented in points to visualize where on the road the risk is below/above the limit. It is also possible to get the societal risk presented as a FN-diagram.

3.4 Spreadsheet calculation

The spreadsheet calculation is a translation of RBM II where the calculations are based on the calculations in RMB II but with additional calculations with substances of class 1 and 5. Moreover, some simplifications were made from the transition to a spreadsheet calculation:

- The impact areas have been simplified into rectangles where the areas are based on the tables given in the end of each subchapter in Appendix A.
- The area of interest has been simplified into rectangles too, and the roads are always perpendicular and on the same distance to the area
- The scenarios were simplified into one substance per ADR-s class, from RBM II the worst-case scenario with the substance with greatest impact were chosen.
- The probability of fatality is also simplified to either one or two levels.
- Different weather classes are not included in the spreadsheet calculation. Instead, the impact areas are calculated according stability category B3 (Unstable weather with a wind speed of 3m/s) in RBM II. The wind distribution is considered with a wind rose. The distribution in the wind rose is collected from the closest weather station given by data from SMHI (2006). In the calculations, the wind is affecting the probability of the different scenarios by multiply the probability of the scenario with the probability of the wind direction towards or parallel to the area of interest. If the wind does not affect the scenario the probability of the wind is set to 1.

The spreadsheet calculations are divided into four steps where all the calculations are made in Excel.

1. Calculation of probability for accidents with different substances

The probability of an accident with any vehicle on a specific type of road is calculated with yearly updated tables from the Swedish Transport Administration regarding personal injury accidents. From these tables it is possible to find a quota over injuries per million axle pair kilometres. The tables are divided into different road authorities, road type, number of lanes, traffic function, traffic environment and speed limit. In the spreadsheet calculations it is assumed that vehicles with dangerous goods are trucks with, in average, 1.1 pairs of axles per vehicle. The probability assumes that some of the accidents are single accident and the rest have two vehicles involved. The share of single accidents is collected from the report "*Farligt gods - Riskbedömning vid transport*" (SRV, 1996). Then, to get the probability of an accident with one vehicle the probability of an accident is multiplied with "$2 - share\ of\ single\ accidents$", this means that if all accidents are single accidents then the probability of an accident is equal to the probability of one vehicle.

To get probability for accidents with different dangerous goods substances probabilities over the likelihood of an emission larger than 100 kg are used, these probabilities are collected from RBM II for class 2.1, 2.3, 3 and 5.1. For class 1 the probability is set to 1 since it is not necessary with emissions over 100kg to cause severe damages in this scenario, thus if there is a release of class 1 it could be severe consequences no matter the weight of the release. Moreover, the number of transports with substances from the different classes must be known. Then, to get the probability of accidents with different substances, equation 4 is used:

$$Risk\ of\ accident\ with\ the\ specific\ substance = number\ of\ transport\ \times risk\ outflow > 100kg\ \times share\ of\ transports\ on\ day\ or\ night\ \times risk\ of\ an\ accident\ with\ one\ vehicle\ \times probability\ of\ wind \quad (4)$$

2. Calculation of probability of different scenarios with event tree

The probability of different scenarios in class 2.1, 2.3 and 3 have been collected from RBM II. Regarding scenarios in class 1 and 5, the probability is based on different reports which are explained further in Appendix B.

3. Calculation of the consequences of the scenarios based on number of fatalities inside and outside

The calculations of consequences are based on impact areas multiplied with probability of fatalities. The impact areas are simplified into rectangles, see Figure 11. Figure 11shows three different locations on an impact area where the area of interest is affected by half of the impact area in 1 and 3 and whole of the area in 2. An approximation has been done so that the area of interest is affected by whole the impact area, as in 2, between the distances from 1 to 3. Accidents outside this distance are not consider in the calculations. If the length of the impact area is greater than the area of interest, then it is the distance of the impact areas that are considered, the distance between 1 and 2 in Figure 12.

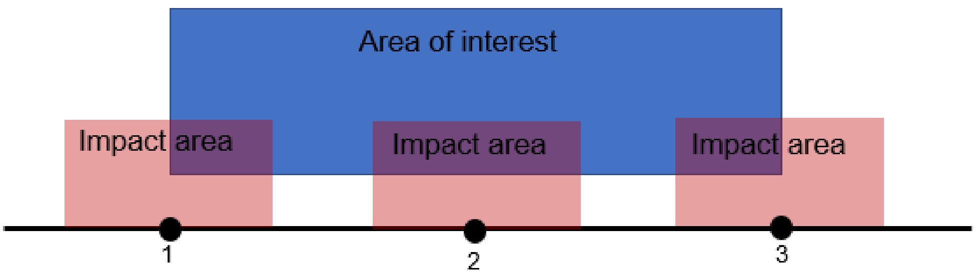

FIGURE 11 - SIMPLIFICATION OF IMPACT AREA IN THE SPREADSHEET CALCULATION.

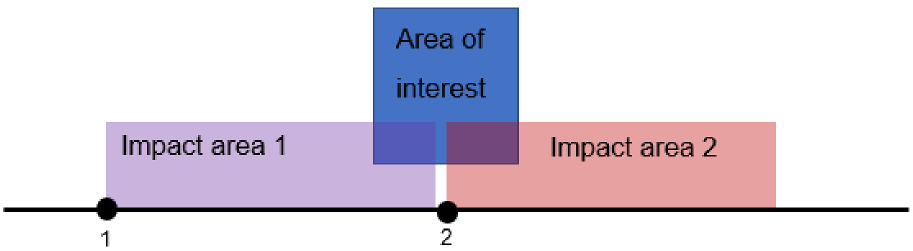

FIGURE 12 - IF IMPACT AREA IS GREATER THAN THE AREA OF INTEREST IN THE SPREADSHEET CALCULATION.

4. Summation of the result as individual and societal risks

The summation of the result is presented in FN-diagram for both individual and societal risks where they are compared with limits. If no limit is stated by the client, the limits presented by Davidsson et al. (1997) are used for both individual and societal risk. Regarding the limit of societal risk, it is adjusted to the length of the road and if the area is on one or both sides of the road.

4 Model development and application

This chapter describes how the GIS-model was developed and how it can be applicated. The GIS-model are divided into two models, GIS-model 1 with impact areas from the spreadsheet calculation and GIS-model 2 with impact areas more similar to RBM II. The structure of the chapter is to first present the requirements and desires on a GIS-model. Later, this chapter provides a general description of GIS and some of its functions. In sub-chapter 4.3 and 4.4, the theoretical background and structure of the calculation of societal and individual risk are described. The chapter ends with two subchapters about validation and a case study.

4.1 Requirements and desires on a GIS-model

To know the requirements and desires on a GIS-model a meeting with Johan Hultman and Herman Heijmans was arranged the 6th of March 2019. On this meeting the following points were mentioned:

- The model must calculate the risks correctly and it should be possible to verify the correctness.
- The model should be transparent, which means that it should be easy to follow the calculation steps. This is mostly a requirement from the authorities so that they know what the numbers and assumptions are based on.
- The model should be user friendly. For example, it should be easy to enter the input data.
- It should be possible to visualise the individual risk on a map to easily show where the limits are. It is also feasible if the result from societal risk could be visualised on a map.
- It should be possible to do risk assessment to evaluate risk reduction measures. For example, easily be able to change the probability of fatality.
- It should be possible to define the areas as inside/outside. It would be an advantage if the area could be rearranged, for example by moving buildings, in order to use the location of the buildings as a risk reductive measure. It is an advantage that the area (and the impact area) does not longer have to be the shape of rectangles.

4.2 Introduction to Geographic Information system

A geographic information system (GIS) is as the name suggest a system that treats geographic information. The system is computer-based and provides the user to capture, store, analyse and present geographic data. In GIS there are two different ways of reducing real world observations into spatial entities, either through vector data model or through raster data model, see Figure 13. In a vector data model, the objects are stored with ordered pairs of coordinates. The simplest form of a vector data is a point which contains one coordinate pair representing a specific location. If two or more coordinate pairs are composed into a sequence it is called a polyline. To represent an area the data is stored as the coordinates for the polyline that surrounds the area, this is normally called a polygon in GIS. In raster data model the spatial entities are organised in array of cells or pixels. In a raster data model, the representative area is divided into a number of cells and every cell in the raster is given a numerical value that corresponds to the surface to be represented. Raster datasets are commonly used for representing continuously surfaces, for example altitude, weather, temperature or population data.

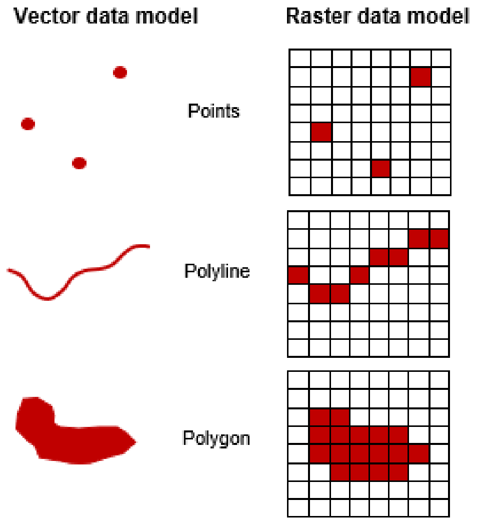

FIGURE 13 - DIFFERENCE BETWEEN VECTOR AND RASTER DATA MODEL.

Geographic data has in general more information than the spatial properties. These properties are called attributes and is information that are connected to the geographic objects. One example of attributes connected to a geographic object are information about speed limits, road number and traffic intensity that are connected to a road.

There are several different GIS software's, in this study the software QGIS was used. QGIS is an open source software which means that anyone have access to it (QGIS, 2019b). In QGIS there are several functions that can be used to analyse and process geographic data, a description of the most relevant functions related to this project will now follow.

Georeferencing and digitizing

Georeferencing is conducted to assigning real-world coordinates to each pixel of a raster or an image, for example a scanned map that has not been projected to geographic coordinates. When georeferencing, points are placed on the image and either manually coordinates can be assessed or coordinates can be fetched from a point in a map. The image is then warped and made to fit the chosen coordinate system. After georeferencing the image can be digitizing through manually create points, polylines and polygons around interesting things on the image, for example create polyline on a road or a polygon around a detail plan (Gandhi, 2019).

Model builder

In the model builder several functions can be put together so that a chain of processes can be wrapped into a single process. No matter how many steps and different algorithms it involves, a model is executed as a single algorithm. Thus, the model builder makes it easier and less time consuming to do the same analysis on several different inputs (QGIS, 2019c).

Points along line
To create points on a given distance along a polyline the function "Points along line" can be used. The result from this function is a point layer with attributes with distance from starting point of polyline and angle of the polyline calculated clockwise from north.

Field calculator
The field calculator in the attribute table can be used to perform calculations on existing values or defined functions, for instance calculating area of a polygon. The results can be written in to a new attribute field, a virtual field, or they can be used to update values in an existing field (QGIS, 2019a).

Geometry with expression
With the function "Geometry with expression" a geometry can be created based on one or several values from the attribute table and an expression that states which geometry that will be created. Two example of geometries that can be created in this function is given in equation 5 and 6. Equation 5 gives a circle with centrum in the current point and with a radius of 10 m. Equation 6 gives an ellipse with centrum in the current point, semi-major axis of 6m, semi-minor axis of 3m and azimuth (angle) gathered from the attribute table with the name "angle".

$$make\_circle(make\_point(\$x, \$y), 10) \tag{5}$$

$$make\_ellipse(make\_point(\$x, \$y), 6, 3, "angle") \tag{6}$$

Merge vector layer / Merge vector layer based on attribute
There are many ways to merge vector layers, two of them used in this project is "Merge vector layer" and "Merge vector layer based on attribute". The latter is merging two vector files based on unique attribute that is present in both data sources. In "merge vector layer" the two data sources do not have to have the same unique attribute since one or more vector layer are chosen manually before the merging.

Intersection
This function extracts the portions of features from the input layer that overlap features in the overlay layer. A new vector layer will be created with attributes from both the input and overlay layer (QGIS, 2019d).

Buffer
If a zone around a layer, for example a road, is to be analysed a useful function to use is a buffer. A buffer can be created on fixed or variable distance and can be created based on a field in the attribute table. The result is saved into an own vector layer that can be used to cut relevant data from other vector layers.

4.3 Societal risk in GIS-model

The GIS-models are based on a combination of RBM II and the spreadsheet calculation. As mentioned before, two GIS-models have been created: one with impact areas copied from the spreadsheet calculation and one that tries to copy the impact areas from RBM II as much as possible.

4.3.1 Theoretical background to societal risk in GIS-model

Since only the impact areas differ between the two GIS-models, their theoretical background and structure are described together in this chapter. This chapter follows the workflow in a risk assessment with the GIS-models and explains the background theory and structure of each step. But firstly, since some extra scenarios were included in GIS-model 2 it was necessary to update the scenario numbers. The scenario numbers and a description of each of them is presented in Table 4. The first or two first numbers in the scenario number are based on the scenario in the spreadsheet calculation, the second number from the end is the wind direction (0=not dependant on wind, 1=wind against the area, 2=wind along the road, 3=wind from the area) and the last number refers to if the scenario is day (0) or night (1).

TABLE 4 - SCENARIO NUMBER USED IN GIS-MODEL. I AND C IN THE DESCRIPTION OF THE SCENARIOS ARE ABBREVIATIONS OF INSTANTANEOUS AND CONTINUOUSLY.

Scenario	Description
100	Explosives
101	Explosives night
200	Jet fire
201	Jet fire night
310	Flash fire I wind against
320	Flash fire I wind along road
330	Flash fire I wind from
311	Flash fire I wind against, night
321	Flash fire I wind along road, night
331	Flash fire I wind from, night
410	Flash fire C wind against
411	Flash fire C wind against, night
520	Flash fire C wind along road
521	Flash fire C wind along road, night
600	Vapor cloud explosion I
601	Vapor cloud explosion I, night
710	Vapor cloud explosion C wind against
711	Vapor cloud explosion C wind against, night
820	Vapor cloud explosion C wind along
821	Vapor cloud explosion C wind along, night
900	BLEVE
901	BLEVE, night
1010	Toxic gases C, wind against
1011	Toxic gases C, wind against, night
1120	Toxic gases C, wind along
1121	Toxic gases C, wind along, night
1210	Toxic gases I wind against
1220	Toxic gases I wind along road
1230	Toxic gases I wind from
1211	Toxic gases I wind against, night
1221	Toxic gases I wind along road, night
1231	Toxic gases I wind from, night
1300	Pool fire big
1301	Pool fire big, night
1400	Pool fire small
1401	Pool fire small, night
1500	Class 5 explosion big
1501	Class 5 explosion big, night
1600	Class 5 explosion small
1601	Class 5 explosion small, night

4.3.1.1 Input from a spreadsheet software

In this first version of GIS-model it is necessary to start by using a spreadsheet software (for example Excel) in order to get the right input values for the work in QGIS. For the input data as well as for the wind distribution and event trees, the spreadsheets from the spreadsheet calculation were copied. This implies that the risk for an accident, number of single accidents, accident frequency per vehicles, probability of outflow larger >100kg, wind distribution etc. are calculated in the same way as for the spreadsheet calculation. From the initial work in a spreadsheet software, two spreadsheets must be created and later imported to QGIS. The first spreadsheet, the input spreadsheet, contains the impact areas and does not have to be changed every risk assessment if there are no changes in impact areas, probability of fatality or average distance between road and area. The input spreadsheet looks different for GIS-model 1 and 2 since their impact areas differs. The second spreadsheet, the output spreadsheet, contains probability of accident for the different scenarios and wind distribution. The input and output spreadsheet must be saved as comma-separated values (CSV) to be able to upload them in QGIS.

4.3.1.2 Initial work in QGIS

Just like in RBM II, some manually work is necessary before the GIS-model can be run. First, to be able to get an accurate model of the area the detailed development plans (or similar types of area plans) must be georeferenced and digitized. Then, the population inside and outside as well as for the first row must be stated in the vector file. This can be done in two ways, either there already exist attributes with these headlines and the numbers are filled in during the digitizing or the field calculator could be used to create new attributes. The road must also be digitized but should not be filled in with for instance transport of dangerous goods since this information already is included in the output file created in a spreadsheet software. The CSV-files must be imported as two new layers (one for each of the file).

When these manually working steps are done the QGIS project should contain at least one polygon with the area of interest, one line corresponding to the road and two CSV-files and the GIS-model is ready to be run.

4.3.1.3 Structure of GIS-model

The actual GIS-models are created in the model builder with one main model and sixteen "sub-model" with the different scenarios. The workflow in the main model is to create points along the road on a specific distance (can be changed manually in the model). Then, all the sub-models are run and the result from each of them are merged into one file. Number of fatalities from the merged filed with the results are merged with the output file and in this file the field calculator is used to calculate the frequency of accident in each of the scenarios as in equation 7.

$$F = F_{accident} \times Wind \times Distance\ between\ points \div 1000 \qquad (7)$$

WHERE $F_{ACCIDENT}$ = PROBABILITY OF THE CURRENT SCENARIO, WIND = PROBABILITY OF WIND DIRECTION, DISTANCE BETWEEN POINTS IS 50 M (CAN BE CHANGED), AND 1000 IS USED TO GET THE RIGHT UNIT

The sub-models are structure in a similar way, a complete description of the structure can be found in Appendix C:
Merge with input data → geometry with expression → Intersect with the area of interest → Calculate the overlaying area (impact area) → calculate number of fatalities on day and night.

The structure in scenarios that are treated as explosives (scenario 10X, 150X and 160X) differs a bit from the rest. These scenarios are based on the same principles as the spreadsheet calculation where it is stated that the first row of buildings protects the buildings behind. Thus, the impact area should be limited by the length of the first row and the buildings width. The solution to this in GIS is to have an input value of average length to area + building width. This value is included in the input spreadsheet. A buffer around the road with the same length as the input value is created in the GIS-model and an intersection between the impact area and this buffer is used to limit the area to this distance from the road.

4.3.1.4 Postprocessing the result

The result from the GIS-models gives a table of frequency and number of fatalities per scenario and can also visualize how much of the area that are impacted by the scenarios. However, a spreadsheet software must be used again to calculate and create a FN-diagram. Advantageously, the table with the result is sorted on number of fatalities in QGIS and copied manually to a spreadsheet software where the cumulative frequency is calculated and plotted against number of fatalities in a FN-diagram.

4.3.2 Comparison of societal risk

Both the spreadsheet calculation and GIS-models are based on RBM II and consequently the three different risk assessment tools have many similarities. There are, however, a few things that differ between them. Thus, this sub-chapter will explain some of the similarities and differences.

4.3.2.1 Calculation of likelihood

The calculation of likelihood in the spreadsheet calculation and GIS-models are very similar. The input data that are imported into GIS are a copy of the input data from the spreadsheet calculation. Hence, the likelihood per km of road is identical for every scenario except for scenario 3XX and 12XX in GIS-model 2. The likelihood in these two scenarios are dependent on the wind distribution in GIS-model 2. What differs between the spreadsheet calculation and the GIS-model in the calculation of likelihood is when multiplying the likelihood per km with the length of the affected road stretch. The length used in the spreadsheet calculation is the longest length of either the area of interest or the impact area. The length used in the GIS-models, and RBM II, is the length between the created points along the road.

The input data that are used in the spreadsheet calculation and GIS-models are partly based on RBM II. The similarities are the accident frequency by class and the event trees. One thing that differs RBM II from the others is the calculation of risk for an initial accident where RBM II base the values on Dutch standards whereas tables from the Swedish Transport Administration is used in the spreadsheet calculation and GIS-models. The major difference between RMB II and the others is that RBM II consider six different weather classes whereas only one is consider in spreadsheet calculation and GIS-model.

4.3.2.2 Calculation of consequences

In all three risk assessment tools the calculation of consequences is a multiplication of population density, probability of fatality and impact area. The main difference between the tools is the size of the impact area and their corresponding probability of fatality. This difference is visualized in Figure 18 - Figure 18. Since class 1 and 5 are not included in RBM II, they are not included in the figures for this tool either. Moreover, in these classes the impact areas assume that it is only the first row of buildings that are affected. In the spreadsheet calculation this assumption is consider through limiting the length of the impact area with the minimum distance of radius of impact area or distance to road + 30 m (assumed width of first row). In the GIS-models this assumption is considered through a buffer zone around the road of a given distance (normally 30 m based on the same assumed width of the first row). One other difference in these two classes is that in the spreadsheet calculation the population is given per meter and in GIS it must be calculated as population per square meter.

In Figure 14 - Figure 18 only the weather category B3 in RBM II is visualised for the scenarios that are affected by weather category, these are named “RBM II, B3”. This is because the impact area in the spreadsheet calculation and GIS-models are based on this weather category. Thus, RBM II have other impact areas for these scenarios, both smaller and larger than seen in figures. Tables with the impact areas for the other weather categories are presented in Appendix A.

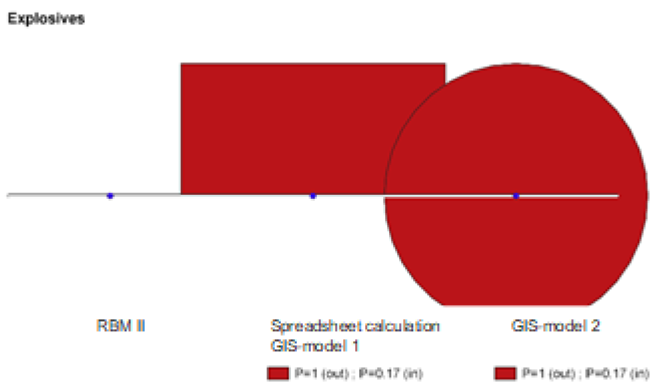

FIGURE 14 - COMPARISON OF IMPACT AREA, CLASS 1.

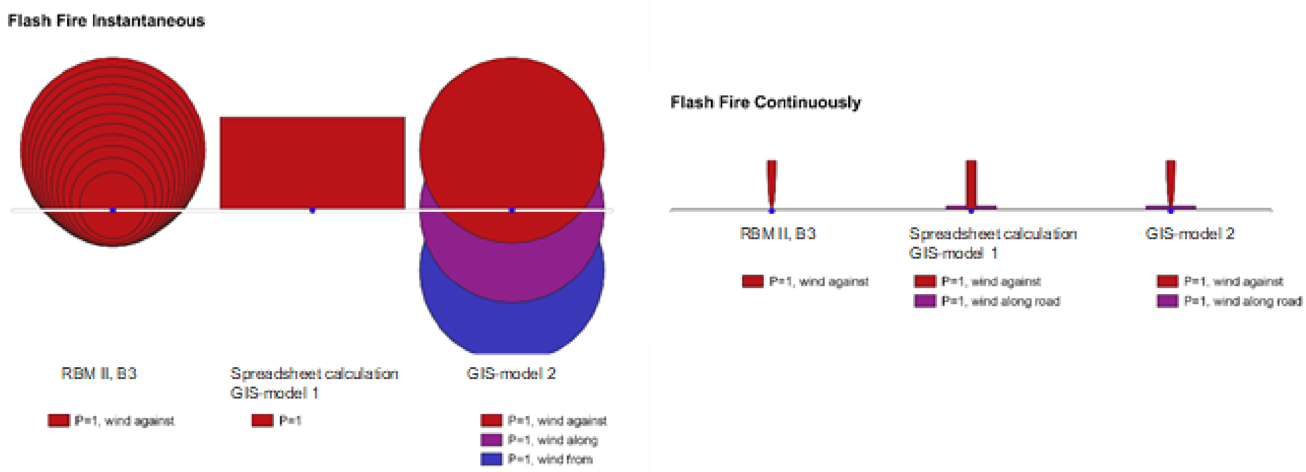

FIGURE 15 - COMPARISON OF IMPACT AREA, CLASS 2.1.

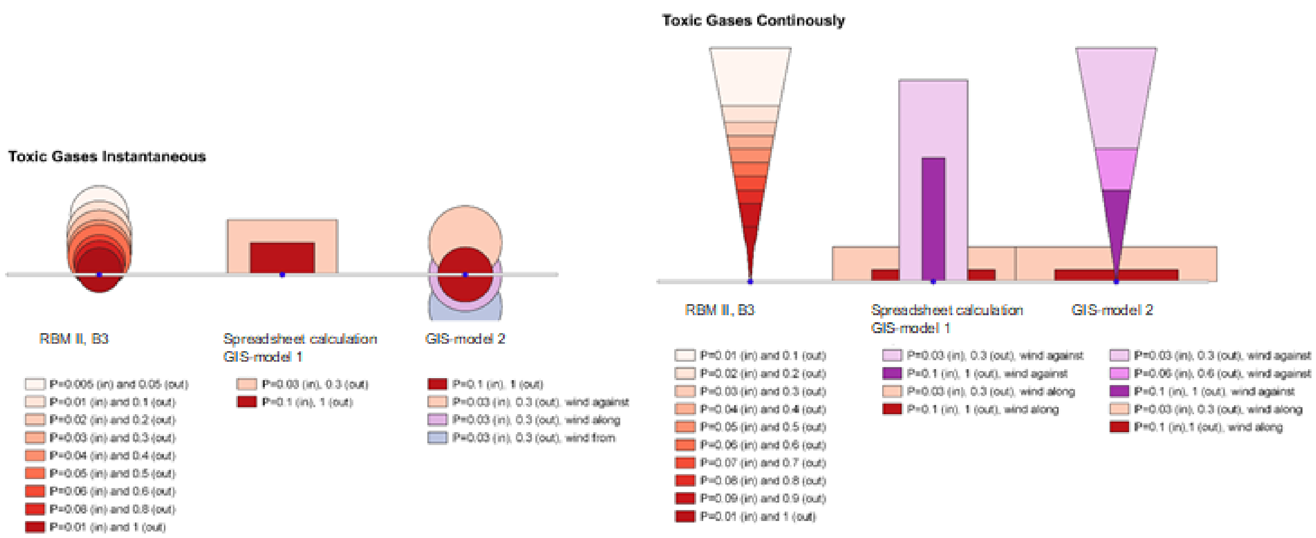

FIGURE 16 - COMPARISON OF IMPACT AREA, CLASS 2.3.

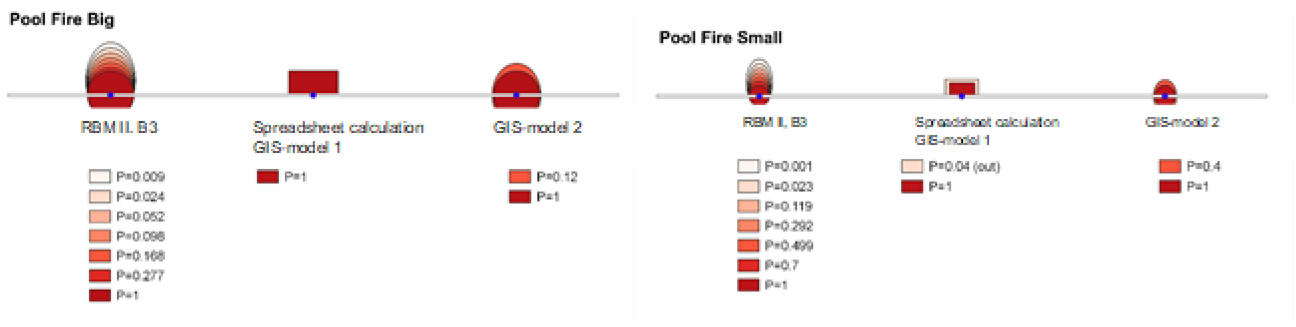

FIGURE 17 - COMPARISON OF IMPACT AREA, CLASS 3.

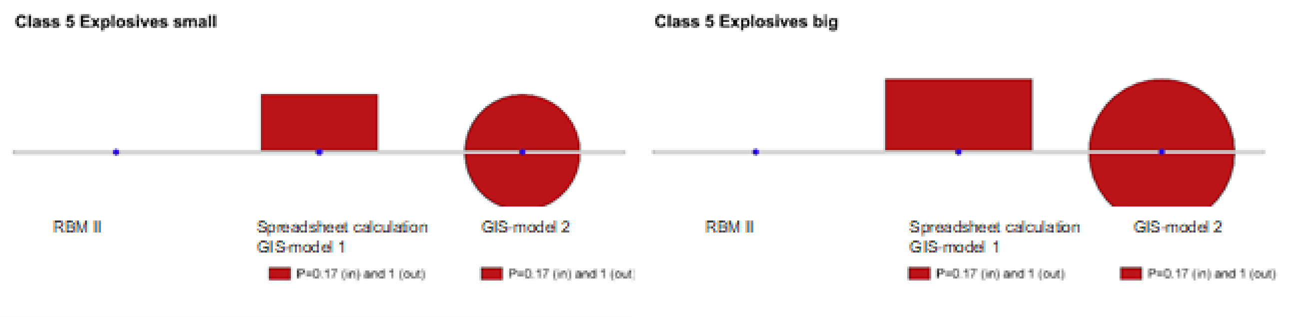

FIGURE 18 - COMPARISON OF IMPACT AREA, CLASS 5.

4.4 Individual risk in GIS-model

Individual risk is not dependant on the shape or population in the area of interest. Thus, many of the advantages that can be assessed in GIS are not useful in the calculation of the individual risk. Consequently, the easiest way of calculation the individual risk is to do it in a spreadsheet software. Later, the result from the calculation can be uploaded in GIS to visualize the individual risk. Regarding the calculation equation 8 is used to calculate the individual risk (IR) on a specific distance x from the road.

$$IR(x) = F_{accident} \times wind \times w\,(x) \div share\ transports\ daytime \qquad (8)$$

WHERE $F_{ACCIDENT}$ = PROBABILITY OF THE CURRENT SCENARIO, WIND = PROBABILITY OF WIND DIRECTION, W =WIDTH, DEFAULT VALUE FOR SHARE OF TRANSPORTS DAYTIME IS 70%

The calculations differ between the two GIS-models since GIS-model 1 use impact areas from the spreadsheet calculation and GIS-model 2 impact areas from RBM II. In GIS-model 1 the width, w(x), in equation 8 is the length along the road for the different impact areas. Since the impact area is the shape of a rectangle the individual risk will be the same from the road up to the width of the impact areas from the road into the area of interest.

In GIS-model 2 most of the shapes were simplified into circles where the width was calculated according to Figure 19. Since the width is dependent on the distance from the road, x, the individual risk was calculated at a distance of 5 m. For scenario 1XX, 15XX and 16XX the individual risk was limited by a maximum length just like the impact area for societal risk. For scenarios were the centrum of the circle was not on the road the width in the individual risk calculations was limited by a minimum value. Up to the minimum value the width was equal to the diameter of the circle and after the minimum value the width was calculated according to Figure 19. In scenarios 4XX, 5XX, 10XX and 11XX the individual risk was calculated according to rectangles, similar to GIS-model 1. A table with all the radius/width and max/min values can be found in Appendix D.

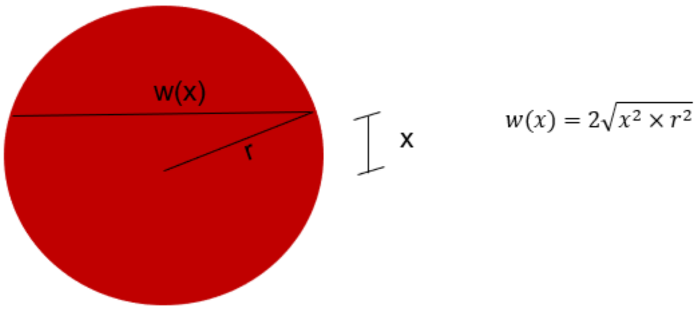

FIGURE 19 - CALCULATION OF W(X) FOR INDIVIDUAL RISK IN GIS-MODEL 2.

4.5 Validation

Two validations have been conducted, one against RBM II and one against the spreadsheet calculation. In the validation against RBM II classes 2.1, 2.3 and 3 were treated separately. However, class 3 gave so small fatalities and frequency that the result could not be seen in the FN-diagram from RBM II (smallest N=10, lowest frequency=1E-09). The input paraments and size of the area was increased but the results was still not showed in FN-diagram. Because of this, class 3 was excluded in the validation against RBM II. In the validation against the spreadsheet calculation all classes were analysed at the same time.

4.5.1 Validation against RBM II

To validate the models against RBM II the same area of 100x100 m with a road 50 m away from the road was created in RBM II and QGIS. The same input values were used, see Table 5, and the result was compiled into FN-diagrams, see Figure 20 and Figure 21. Regarding individual risk the result can be seen in Figure 22 and Figure 23.

TABLE 5 - INPUT VALUES FOR VALIDATION AGAINST RBM II.

Area of interest	100x100 m, 50 m from road.
	Residential building located in Eindhoven
Road	Initial accident frequency: 1.87E-07
	1000 transports of in the investigated class per year
	Outside of built area
Population	Inside day: 600
	Outside day: 200
	Inside night: 1140
	Outside night: 60

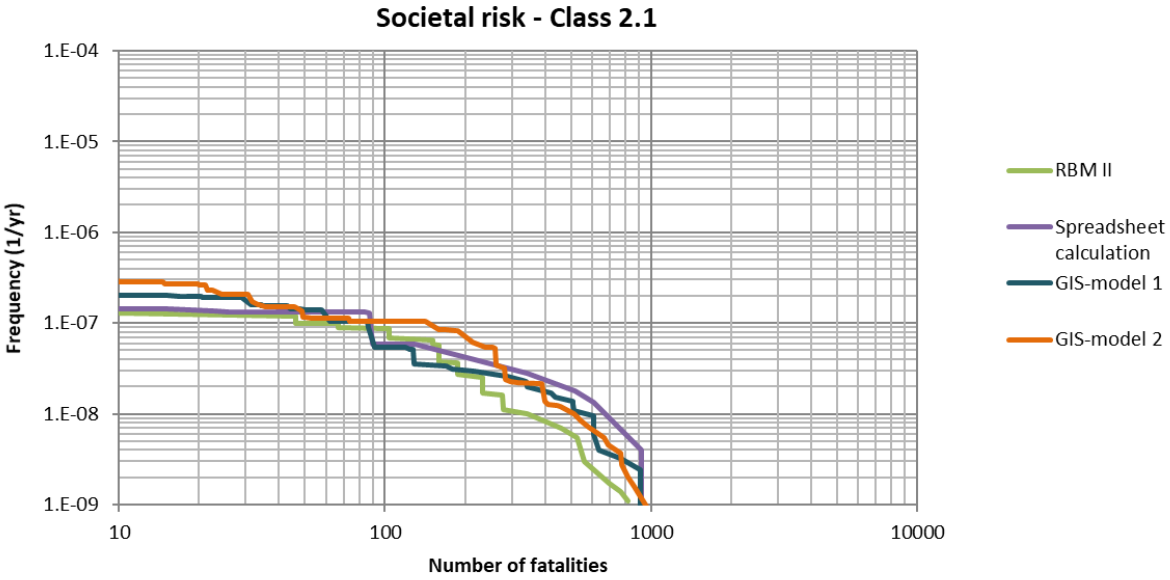

FIGURE 20 - RESULT SOCIETAL RISK VALIDATION AGAINST RBM II, CLASS 2.1.

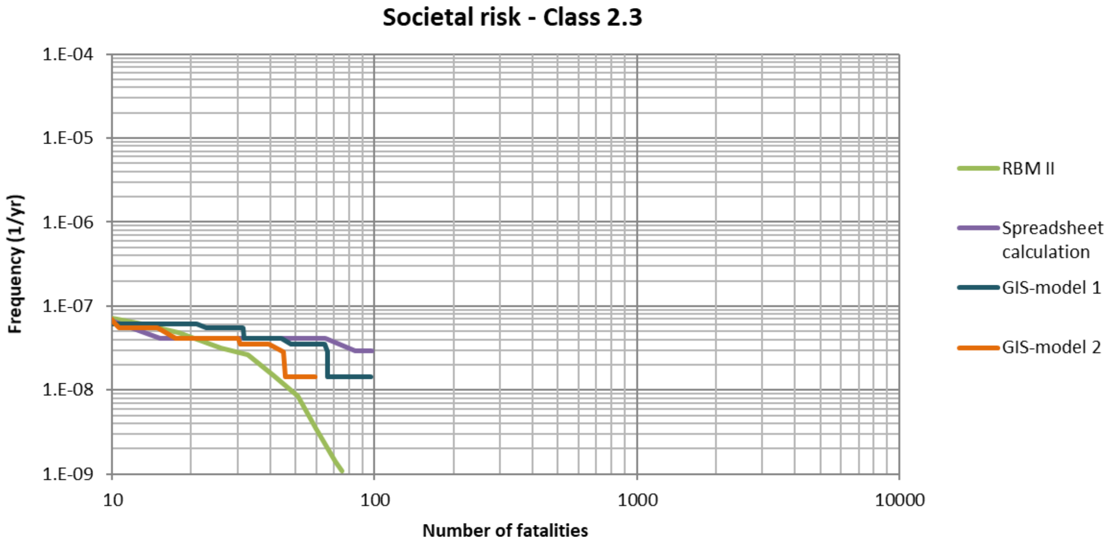

FIGURE 21 - RESULT SOCIETAL RISK VALIDATION AGAINST RBM II, CLASS 2.3.

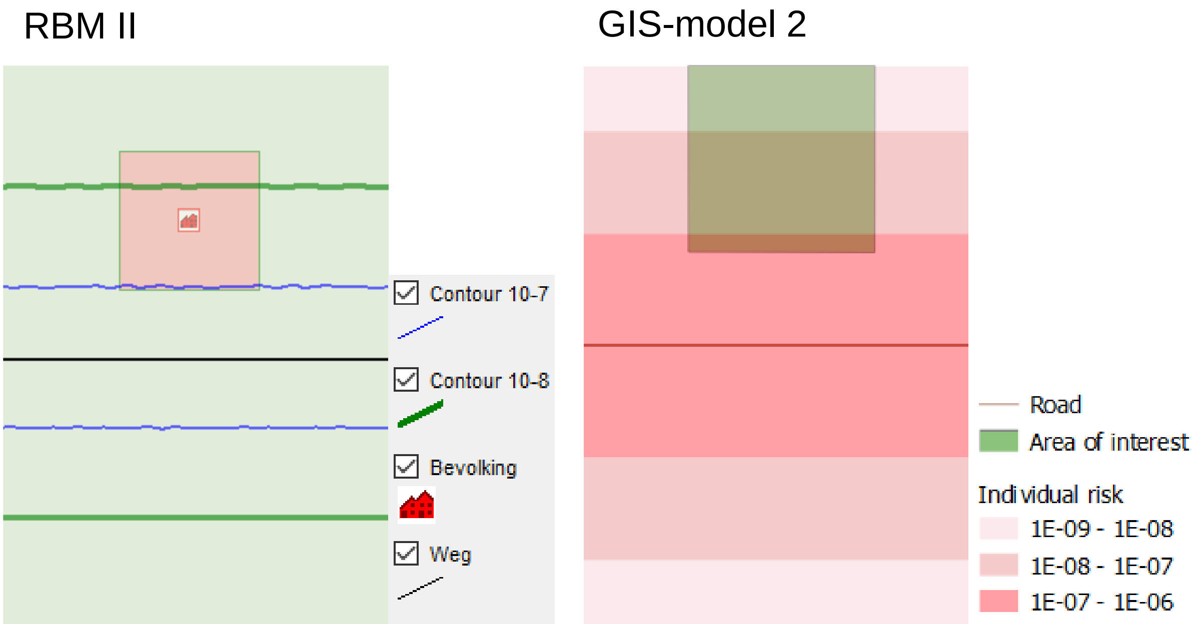

FIGURE 22 - RESULT INDIVIDUAL RISK VALIDATION AGAINST RBM II, CLASS 2.1. FIGURE NOT IN SCALE.

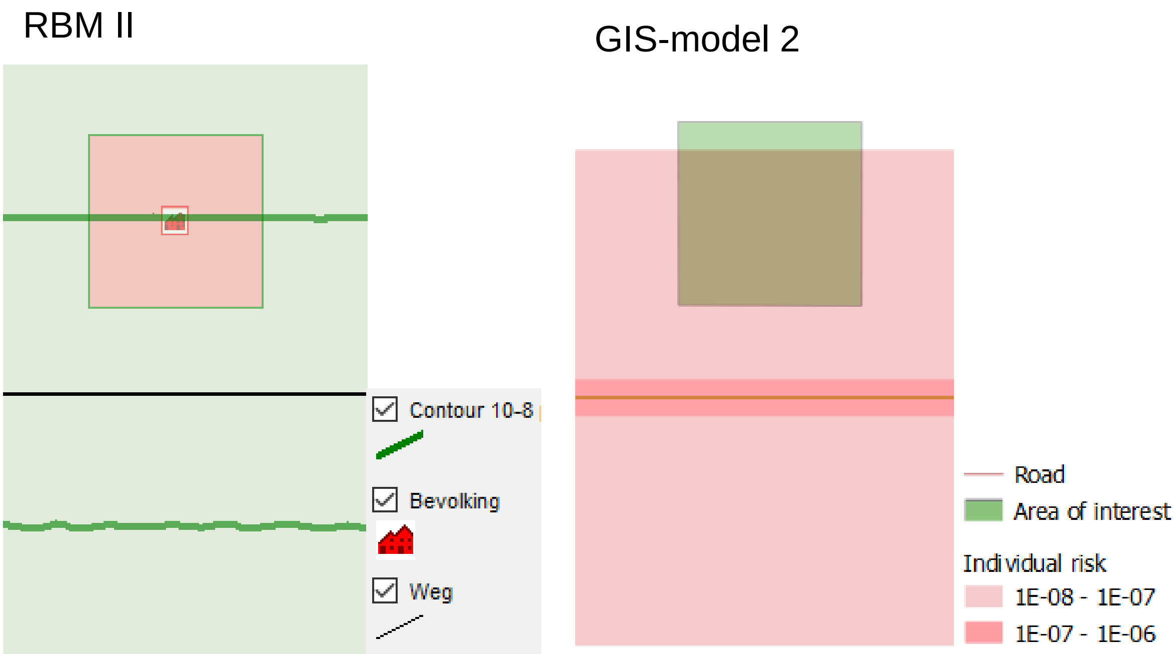

FIGURE 23 - RESULT INDIVIDUAL RISK VALIDATION AGAINST RBM II, CLASS 2.3. FIGURE NOT IN SCALE.

Reflexions

The estimated societal risk levels show that both the GIS-models overestimate the risks in comparison to RBM II. This is probably a good thing since the RBM II calculation take into account more types of weather classes and thus the societal risk can increase a bit if other locations were used. At around 100 fatalities, GIS-model 1 is below the risk from RBM II (and thus underestimate the risk), this is because of the

BLEVE scenario where the impact area differs between them. The difference in impact areas in the BLEVE scenario are further discussed in the validation against spreadsheet calculation.

The results from the individual risk are very similar between RBM II and GIS-model 2, the contours for the risks are approximate on the same distance from the road. Once again, the GIS-models overestimate the result in most cases. However, the individual risk in RBM II is only displayed as contours of evenly power of ten, which is a very rough value to compare the GIS-models against. Ideally, the individual risk would be compared with a table or a diagram, but this cannot be extracted from the RBM II calculation.

4.5.2 Validation against spreadsheet calculation

To validate the GIS-model against the spreadsheet calculation three hypothetic cases with a rectangular area and a road perpendicular to the area were created. The area of interest and the road was created as a square and a straight line to be able to create the same shapes in both risk assessment calculations. Then, when having the same number of populations, probability of initial accident, number of transports of dangerous goods etc, the result from the GIS-models should correspond with the spreadsheet calculation, see Table 6.

TABLE 6 - INPUT VALUES FOR VALIDATIONS AGAINST SPREADSHEET CALCULATION.

	Validation 1	Validation 2	Validation 3
Frequency accident	1.9E-07	3.7E-07	3.7E-07
Wind station	Tomtabacken	Falsterbo	Idre Fjäll
Number of transports per class	100	500	500
Size of area	Inside: 100x100m, 50m from road	Inside: 50x55m, 20m from road	Inside: 250*250m, 50m from road
	Outside: 100x100m, 50m from road.	Outside: 100x100m, 10m from road	Outside: 300*300 m, 20m from road
Population / Population night / first row / first row night	Inside: 600 / 1140 / 372 / 594 Outside: 200 / 60 / 28 / 6		

The result for validation of case 1 for societal and individual risk can be seen in Figure 24 and Figure 27, respectively. Only the result from case 1 is presented in this chapter since the general findings were similar in the other cases, the full result from all the validations can be found in Appendix E. Moreover, a comparison of number of fatalities (N) and frequency of the different scenarios (F) regarding societal risk can be seen in Figure 25 and Figure 26. In the comparison of N the maximum number of fatalities (N max) is used for the GIS-models. N max is used since the accident is assumed to occur in the middle of the area in the spreadsheet calculation and thus correspond to the maximum number of fatalities in the GIS-models where the accident is calculated 50 m apart from each other. Regarding the frequency of the scenarios the frequency (F) from the spreadsheet calculation is compare with the sum of frequency (F total) from the GIS-models. Thus, if the accident occurs outside of the area but still affects the area they are included in the GIS-models but not in the spreadsheet calculation.

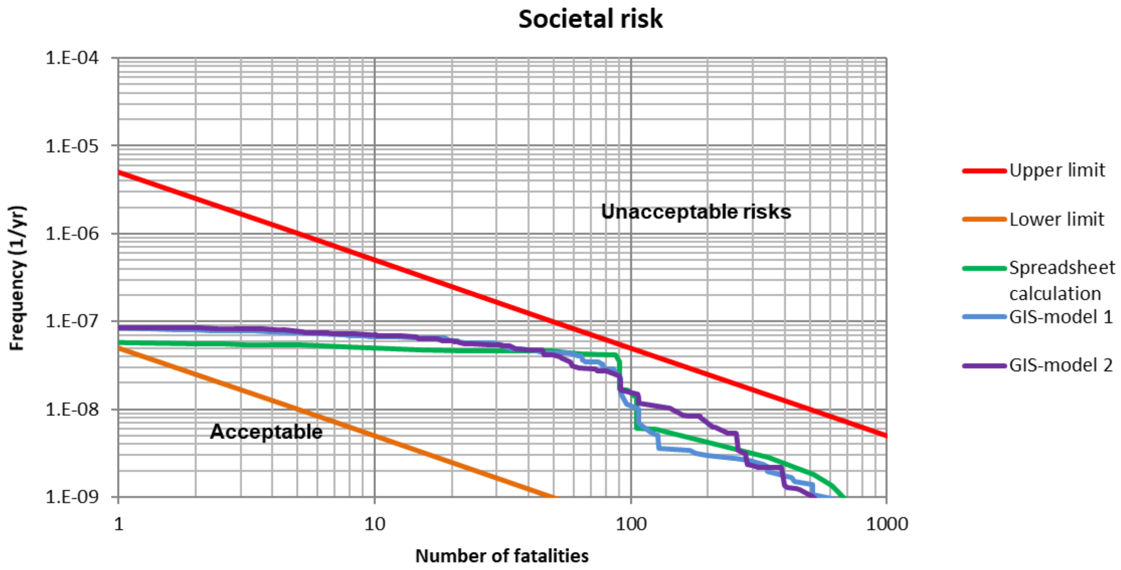

FIGURE 24 – FN-DIAGRAM OF THE IMAGINARY VALIDATION CASE 1.

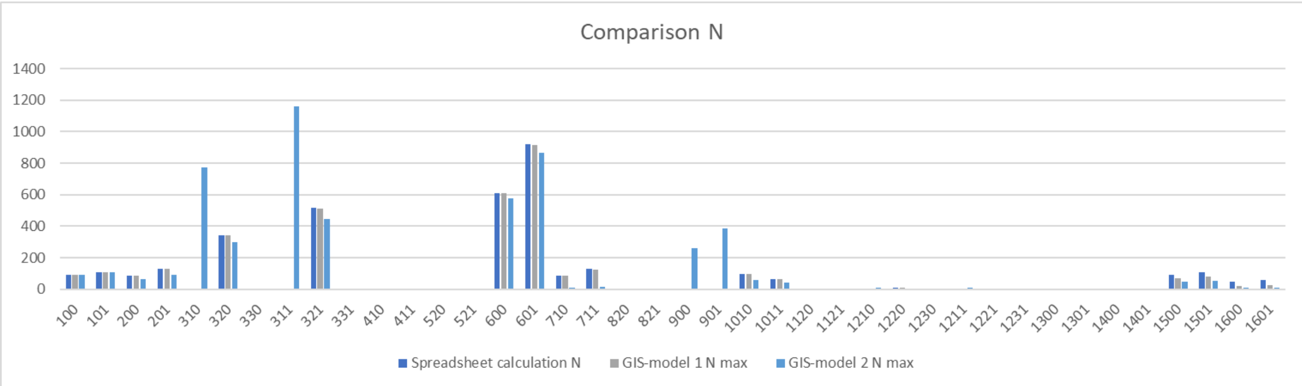

FIGURE 25 - COMPARISON OF NUMBER OF FATALITIES IN THE VALIDATION CASE 1.

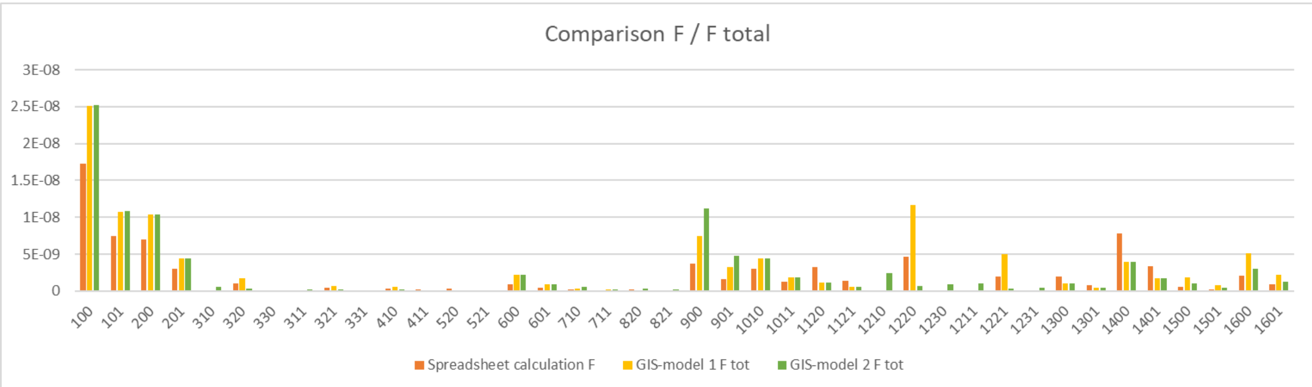

FIGURE 26 - COMPARISON OF FREQUENCY OF THE SCENARIOS IN THE VALIDATION CASE 1.

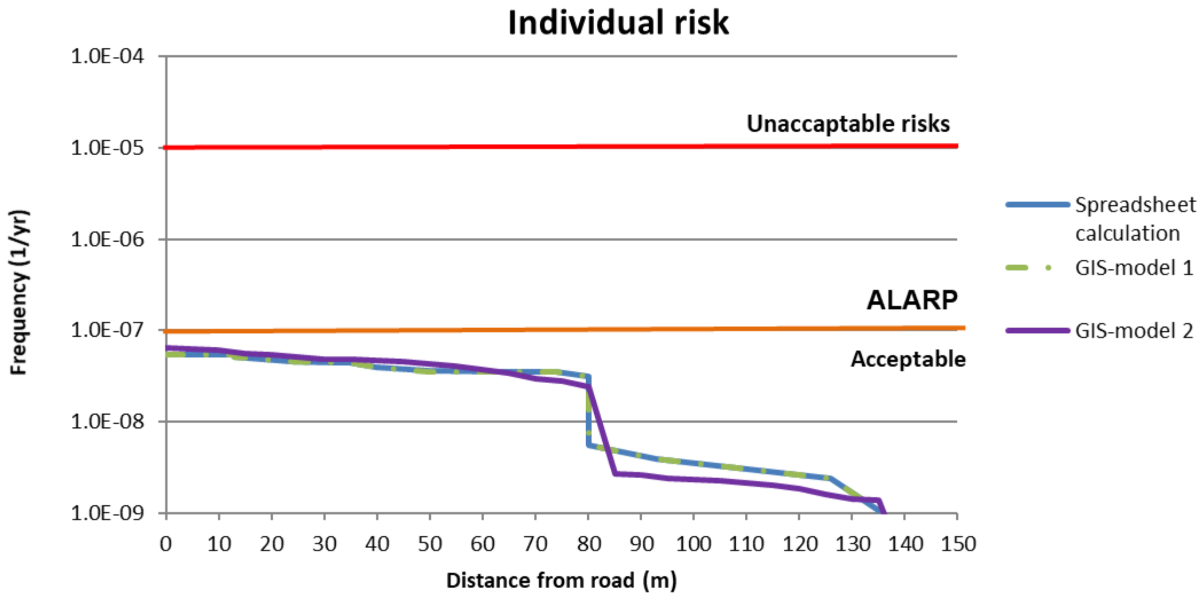

FIGURE 27 - RESULT FOR THE INDIVIDUAL RISK IN VALIDATION CASE 1.

Reflexions

As seen from Figure 24, the models generate similar FN. However, there are some general differences. To start with, for GIS-model 1 and the spreadsheet calculation the number of fatalities is the same for 2XX-14XX. This is expected since the impact areas are the same and the comparison only includes the maximum number of fatalities in the GIS-model 1. The biggest difference between these two models is the scenarios with explosions (1XX, 15XX, and 16XX). In the spreadsheet calculation the population in these scenarios are calculated as population per m whereas in GIS the population is specified in population per square meter. Thus, when the same input value for the population is used the number of fatalities can differ between them. A consequence of this is that the input value in the GIS-models for population on the first row might need to be modified to correspond better with the spreadsheet calculation.

In general, the impact areas are smaller in GIS-model 2 compared to the spreadsheet calculation. The smaller impact areas result in a lower N max in Figure 26. However, two changes have been made which are reflected in the figures above. First, scenario 3 and 12 in the spreadsheet calculation have been split so that it is dependent on the wind direction. This gives a higher N max if looking at the maximum fatality in scenarios starting with 3 or 12. But, since it is dependent on the wind distribution these scenarios are connected with a lower probability. The other change that has been done is to increase the radius in scenario 9XX (BLEVE) to correspond with the impact area from RBM II. An increase in radius gives a higher number of fatalities as well as higher frequency.

As seen from Figure 27 the individual risk from the different risk assessments are very similar. This is because all the calculations were done with the same spreadsheet approach. Thus, GIS does not provide any additional help in the calculation of the risk. However, individual risk in GIS-model 2 are calculated as circles which results in a lower individual risk further away from the road. GIS can be used to visualize how the individual risk is declining with an increasing distance from the road. An example of such a visualization can be seen in Figure 22 and Figure 23 in the validation against RBM II. These figures show the individual risk on an even power of ten. However, if the risk would exceed any of the limits the visualization could be set to intervals corresponding to the limits so that it can easily be seen how far into the area the risk is above the limits.

4.6 Case study

The case study is conducted in a real case where the risk already has been assessed with the spreadsheet calculation by Norconsult. The case study is an area south of Mariestad that consist of three detailed development plans (Area A, B and C), see Figure 28. The detailed development plans are close to several roads where dangerous goods are transported; E20, Sanbäcksvägen and Göteborgsvägen. Dp Hindesberg (Area C) is also close to a railway, Kinnekullebanan, but this part of the risk assessment is not included since the GIS-models are created for roads. The same population, number of transports and probability of initial accidents were used in the spreadsheet calculation and GIS-models. The full report from Norconsult, with numbers on population, transports and probability of initial accident, can be found in Norconsult (2018).

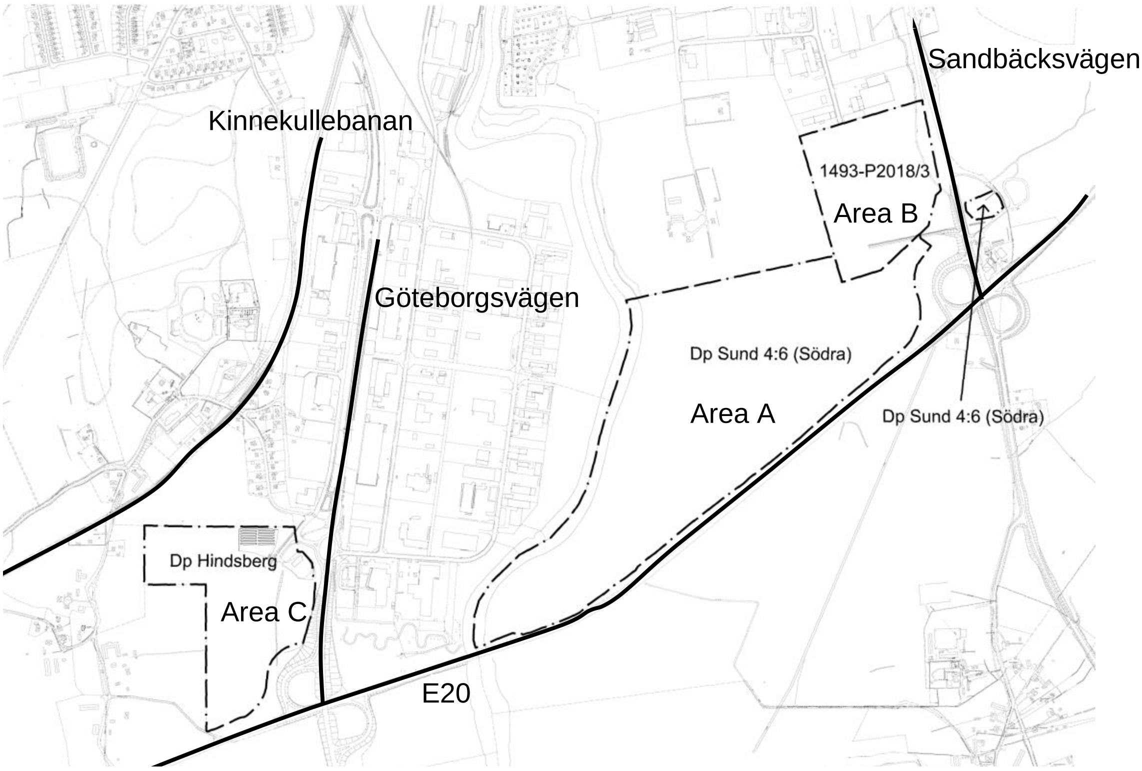

FIGURE 28 - DETAIL PLANS FOR THE AREA IN THE CASE STUDY (MODIFIED FROM NORCONSULT, 2018).

In the spreadsheet calculation, the areas for the detailed development plans were simplified into rectangles according to Table 7. Area B was expanded to contain the small part of Dp Sund 4:6 that is east of Sandbäcksvägen and the part of Area A that is closest to Sandbäcksvägen. This was done to simplify the calculations and to take into account that Area A is affected by Sandbäcksvägen as well. In GIS, the detailed development plans were georeferenced and digitized so that the area correspond to Figure 28. However, according to the background information some parts of the areas are reserved for nature and cannot be constructed. Moreover, it should be a security distance to buildings of 50 m from E20 according to earlier risk assessment on the road. Thus, the nature area and an area of 50 m from E20 are considered to only be outside in GIS.

TABLE 7 - COMPARISON OF SIZE OF THE DETAILED DEVELOPMENT PLANS.

		Spreadsheet calculation [m²]	GIS-model [m²]
Area A	Area inside	178,500	303,466
	Area outside	273,000	447,149
Area B	Area inside	15,000	91,923
	Area outside	180,000	107,254
Area C	Area inside	68,000	123,274
	Area outside	145,600	130,641

4.6.1 Results societal risk in the case study

The estimated societal risk levels are presented in Figure 29-Figure 32. The results from the GIS-models for Area B and Sandbäcksvägen are the total risks from Sandbäcksvägen on all the affected detailed development plans. Thus, for both GIS-models the risk in Figure 30 is a summation of the risk in B, the small part of Sund 4:6 east of Sandbäcksvägen and Area A that are exposed to risks from Sandbäcksvägen. Consequently, three different calculations were conducted and were compiled before the FN-curve was created.

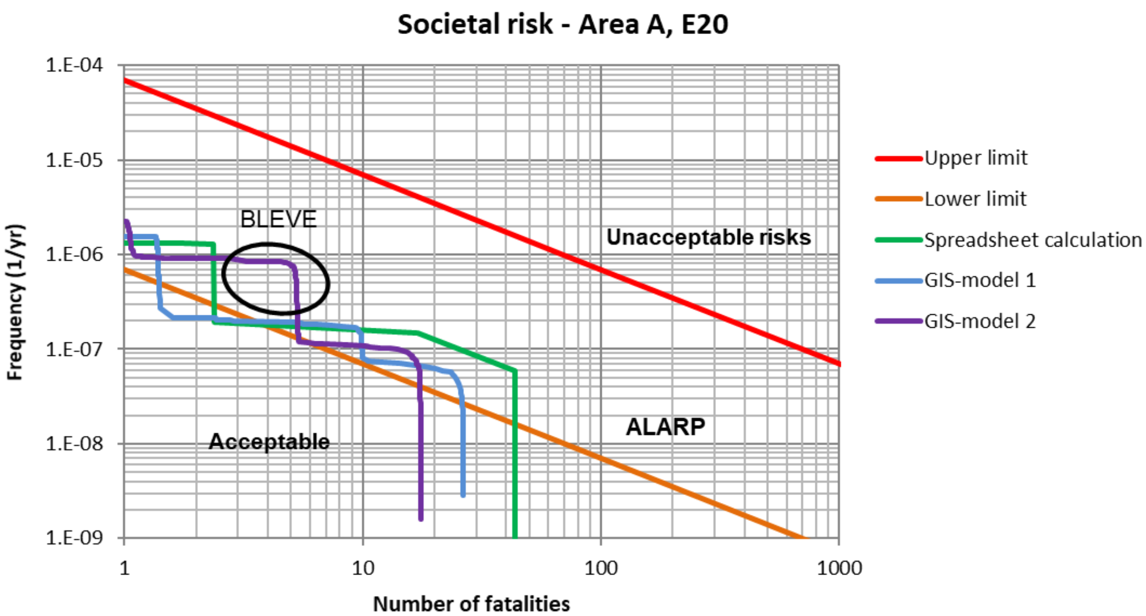

FIGURE 29 - AREA A – E20.

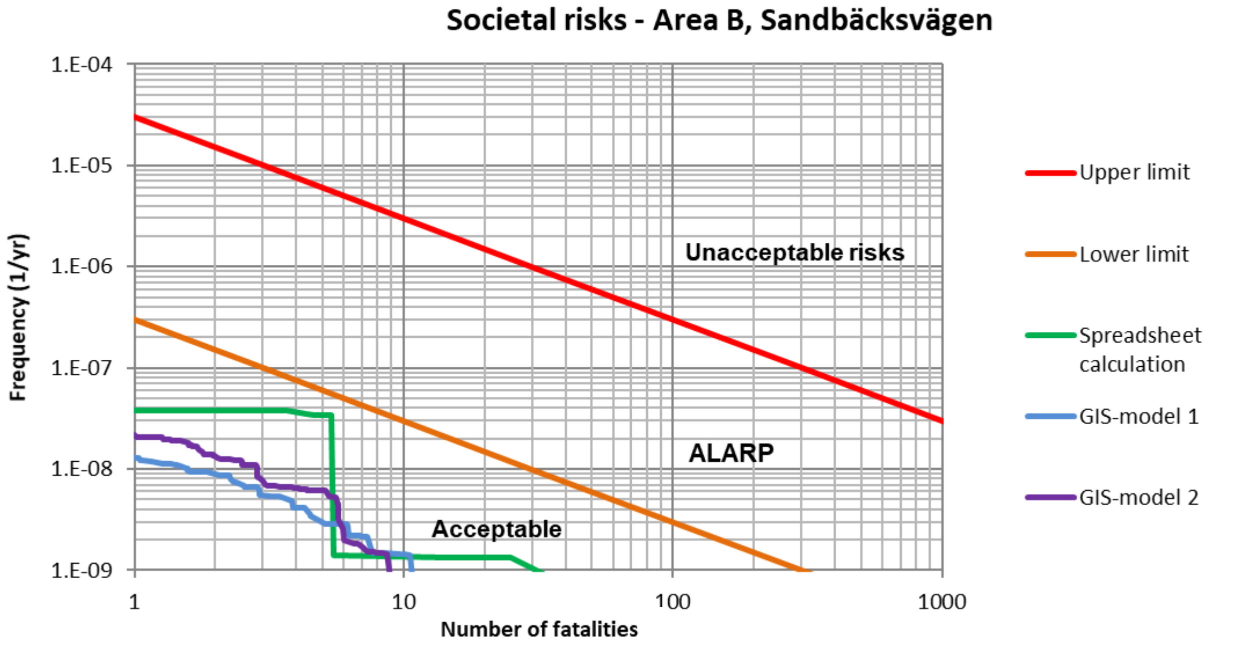

FIGURE 30 - AREA B – SANDBÄCKSVÄGEN.

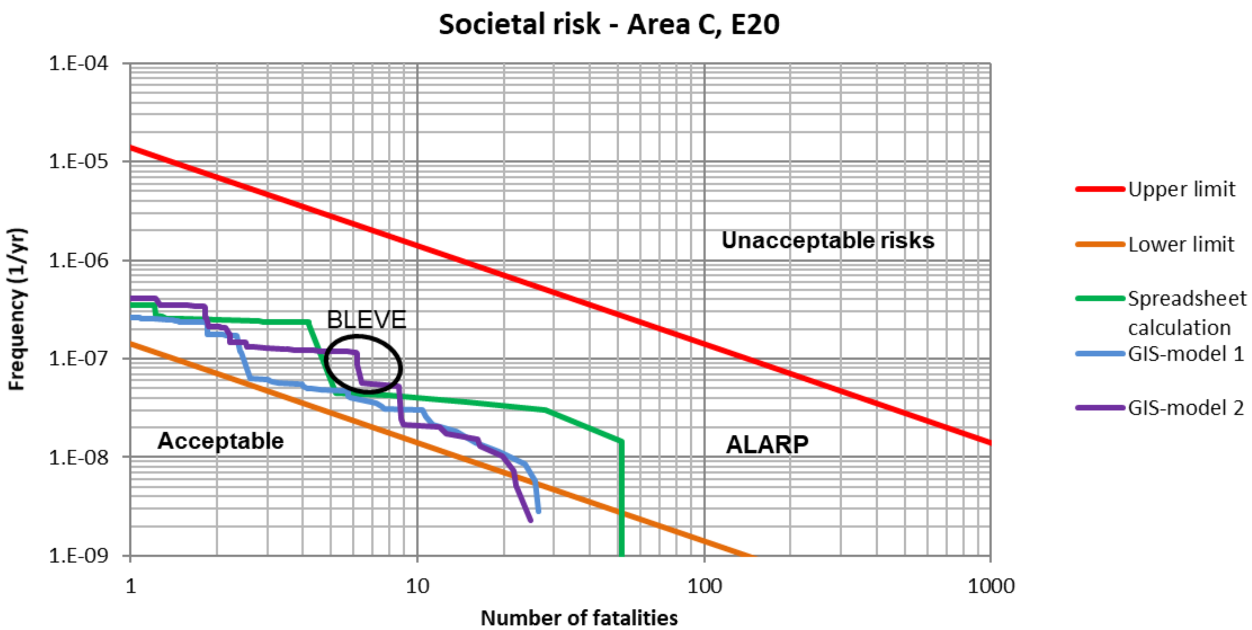

FIGURE 31 - AREA C - E20.

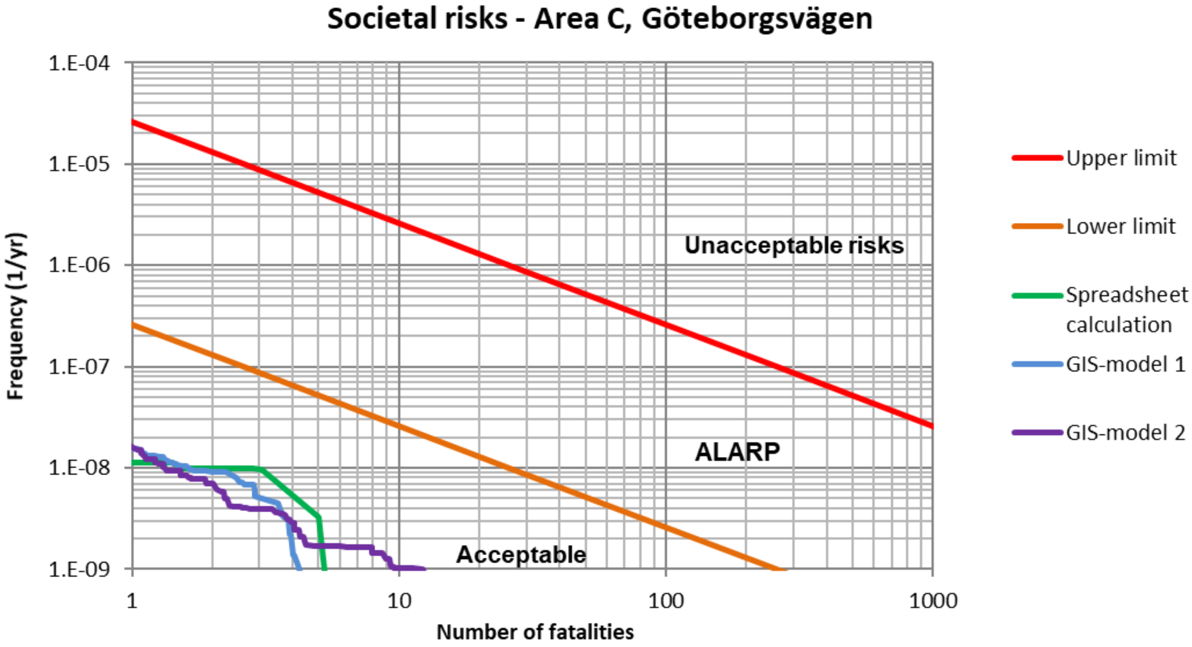

FIGURE 32 - AREA C – GÖTEBORGSVÄGEN.

Reflexions

In general, the models provide similar results. The risks are approximately on the same distance from the risk limits and the assessments thus results in the same overall conclusions. However, the exact numbers differ between the models. In general, both GIS-models provide lower risk levels than the spreadsheet calculation with a few exceptions. In accordance with the validation the main exception is the BLEVE case in GIS-model 2. This is clear in Figure 29 and Figure 31 where the curve from GIS-model 2 exceeds the curve from spreadsheet calculation. The points where the curve from the GIS-model 2 exceeds the spreadsheet calculation is due to the fatalities in the BLEVE scenario.

In Figure 31, around N=5, the difference when using a simplified area or using the area from the detail plan is clearly visualized. In the spreadsheet calculation the area was simplified into a rectangle which was located 15 m from the road. Thus, in the case of a big pool fire the spreadsheet calculation gives an impact area of 432 m^2 and a frequency that is calculated on length of Area B. However, when using the area from the detailed development plan the closest distance to the road is 19 m at the north of Area B and the distance is increasing further south. Thus, the biggest impact area for a pool fire calculated with GIS-model 2 is 188 m^2 and the frequency is just calculated on 200 m of the area (it is only four of the investigation points that have an impact area that reaches Area B). Consequently, the frequency and number of fatalities for a pool fire is higher in the spreadsheet calculation compared to the GIS-models. This explains the big difference between the models in Figure 31.

One reason for why the GIS-models in general result in lower risk levels than the spreadsheet calculation is that the size of the detailed development plans does not match. The GIS-models have a bigger area for all analysed areas except for Area A and B outside. When the same population is used in the risk assessments and the areas are bigger the population density will be smaller. Thus, to analyse how this affects the result a new risk assessment was conducted for Area A. This time the population was recalculated so that the population density was the same. The result can be seen in Figure 33.

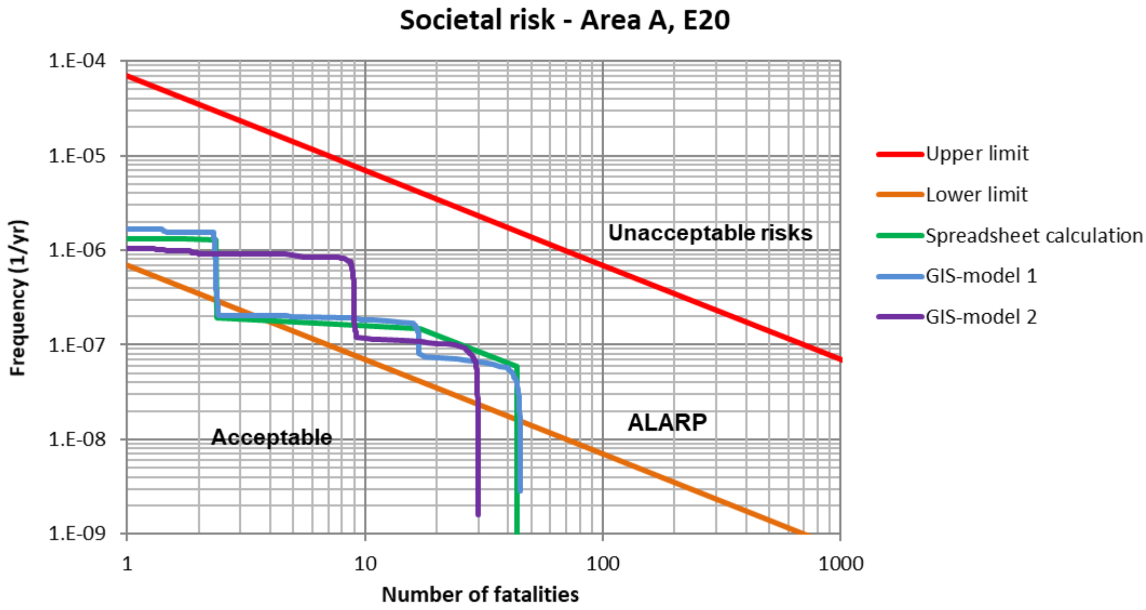

FIGURE 33 - AREA A - E20, SAME POPULATION DENSITY.

As seen from Figure 33, GIS-model 1 and the spreadsheet calculation correspond very well with each other when the population density is the same. There are only two points where they differ from each other. The first point is between 1 and 2.4 fatalities where GIS-model 1 results in slightly higher values. This is probably because the GIS-models have points outside of the area of interest which can give a higher frequency, see Figure 26. The second point where they differ is between 17 and 44 fatalities in Figure 33 where the spreadsheet calculation has a slightly higher risk. This is because the spreadsheet calculation only calculated one point per scenario and make a linear interpolation between these points. In the spreadsheet calculation there is no scenario that gives fatalities between 17 and 44. In the GIS-models a lot more points are assessed which gives more points in the FN-diagram and thus a smother curve.

Also when comparing GIS-model 2 and the spreadsheet calculations some differences can be seen. The main difference is the case with the bigger impact area for the BLEVE scenario (N<9 in Figure 33). Also, the maximum fatality differs between GIS-model 2 and the spreadsheet calculation. In the spreadsheet calculation the maximum fatalities are in scenario 600 (Flash fire instantaneous). The greater amount of fatalities in the spreadsheet calculation is because the impact area is the shape of a rectangle that encloses the circle that represent the impact area in GIS-model 2, see Figure 18.

It should also be noted that risk associated with Areas A and C are in the ALARP-region, which means that reasonable actions should be taken. Thus, in the report from Norconsult (2018) several risk reduction measures are suggested. Moreover, the new risk if the measures are implemented is calculated. The measures are included in the risk assessment through a reduction of the probability of fatalities in the scenarios that are affected by the measures. The same method was used in the GIS-models and the results can be seen in Figure 34.

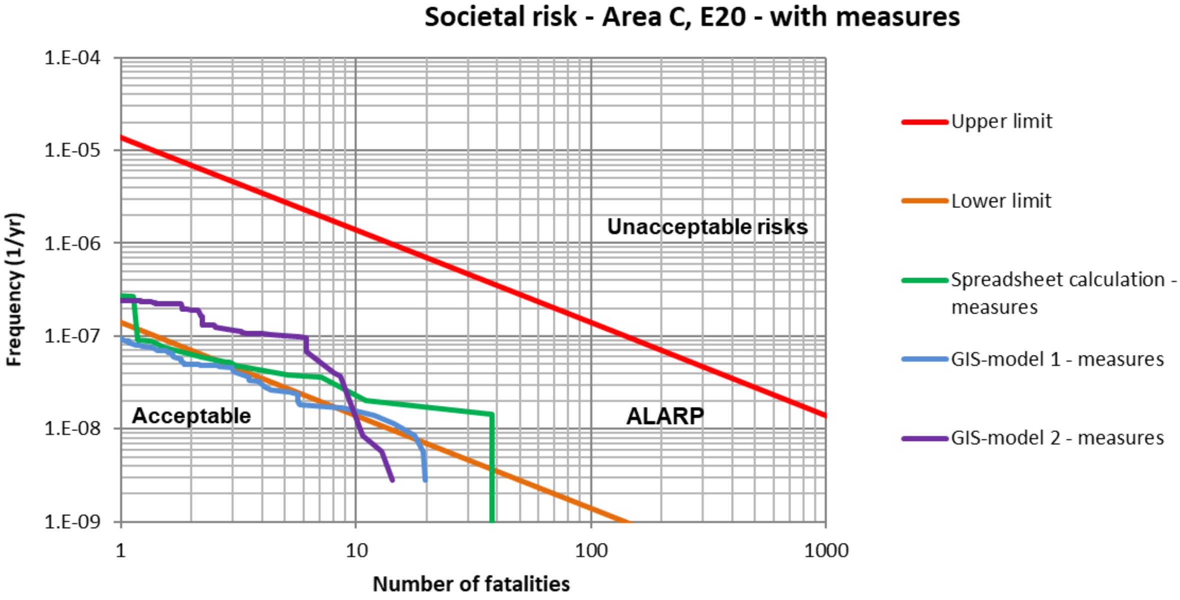

FIGURE 34 - AREA C - E20, WITH MEASURES.

By comparing Figure 31 and Figure 34 it is clear that the measures are working efficiently on GIS-model 1 but not as efficiently on GIS-model 2. Once again, this is because of the BLEVE scenario which is not affected by the measures. Consequently, when GIS-model 2 have a greater impact from a BLEVE the measures will not be as efficient in this risk assessment. However, the suggested measures include fire-resistance material which will lower the probability for fatalities in a BLEVE as well. The lower probability for fatalities in the BLEVE scenario is not included in Figure 34.

One benefit with the GIS-models is that the spreading of the impact area can be visualized. Different scenarios can be visualized depending on what is most interesting in the specific case but typically the ones that are closes to the ALARP limits. This can be useful to see where measures should be implemented or, if the risk is assessed in an early stage, rearrange the location of buildings in the detailed development plan. A visualization made by GIS-model 2 of flash fire instantaneous from the case study of Area A can be seen in Figure 35.

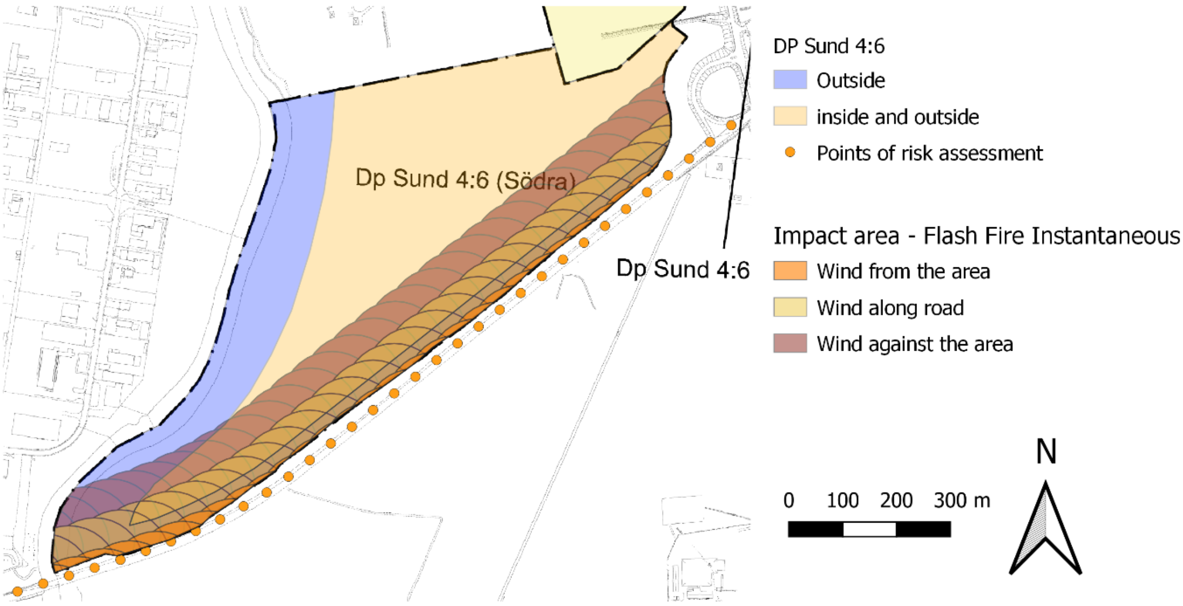

FIGURE 35 - VISUALIZATION OF IMPACT AREA FROM GIS-MODEL 2.

4.6.2 Results individual risk in case study

The result for the individual risk can be seen in Figure 36-Figure 38. Only one risk assessment per road was conducted since the individual risk is affected just by the transported amount of dangerous goods and the distance to the area. The transported amount of dangerous goods is not dependant on which area that is assessed, and it is only two areas (Area A and C) that are affected by the same road and they have the same distance to the road.

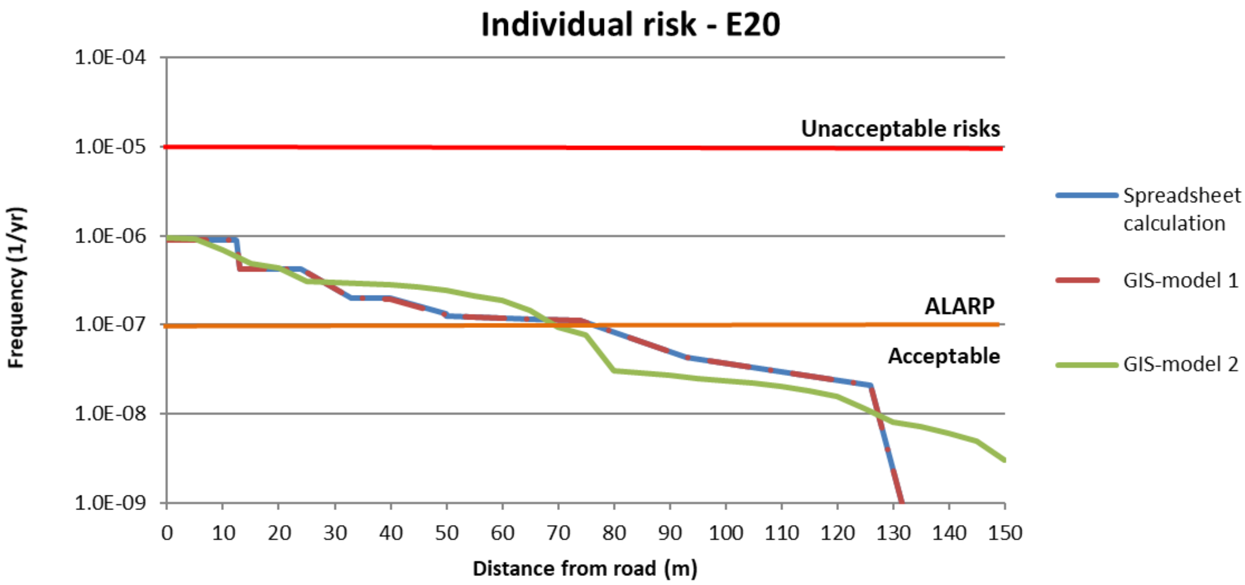

FIGURE 36 - INDIVIDUAL RISK E20.

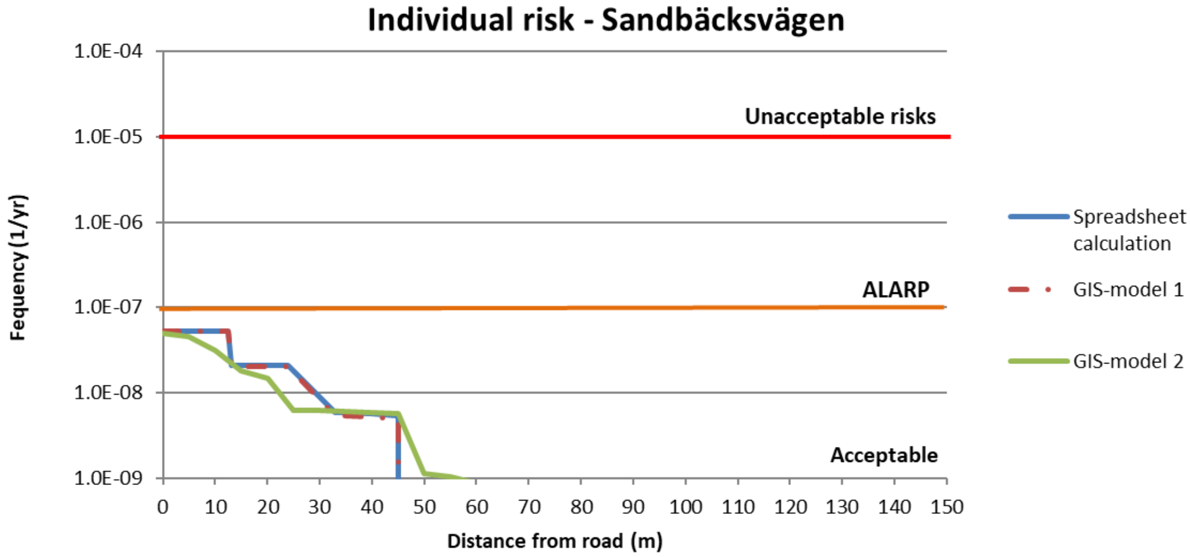

FIGURE 37 - INDIVIDUAL RISK SANDBÄCKSVÄGEN.

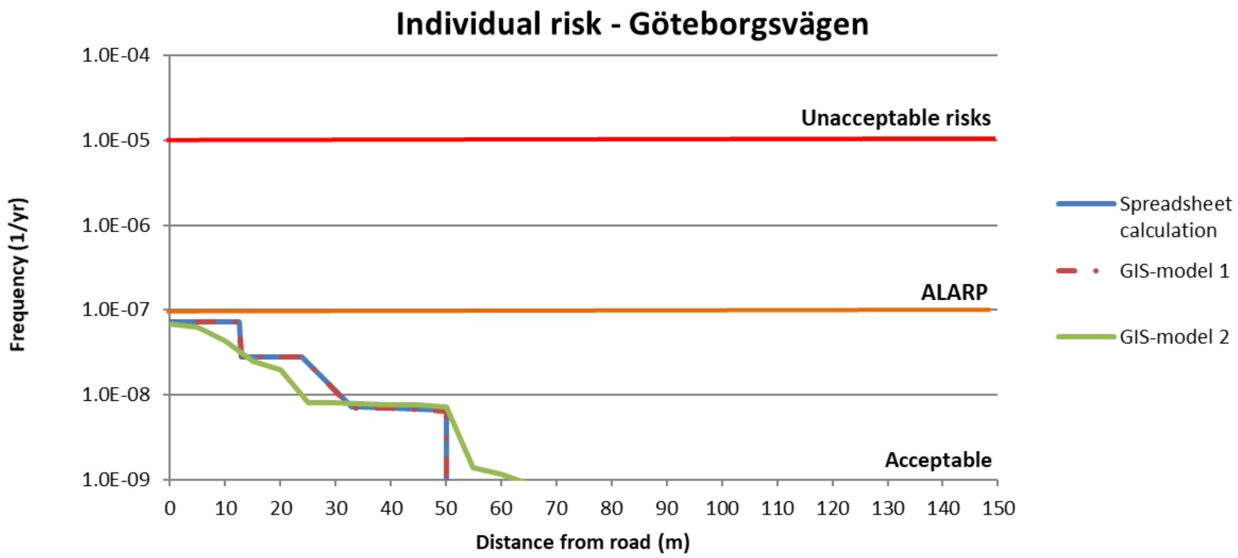

FIGURE 38 - INDIVIDUAL RISK GÖTEBORGSVÄGEN.

Reflexions

As can be seen in Figure 36-Figure 38 the individual risk for the different risk assessment calculations are very similar. For the same reasons as for the validation against the spreadsheet calculation GIS does not provide any additional help in the calculation of the risk. However, GIS can once again be used to visualize how the individual risk is declining with an increasing distance from the road, this can be seen in Figure 39. The figure also shows the individual risk as evenly power of ten, but if it is only interesting to see how far into the area the risk limits are exceeds a visualization as Figure 40 can be used.

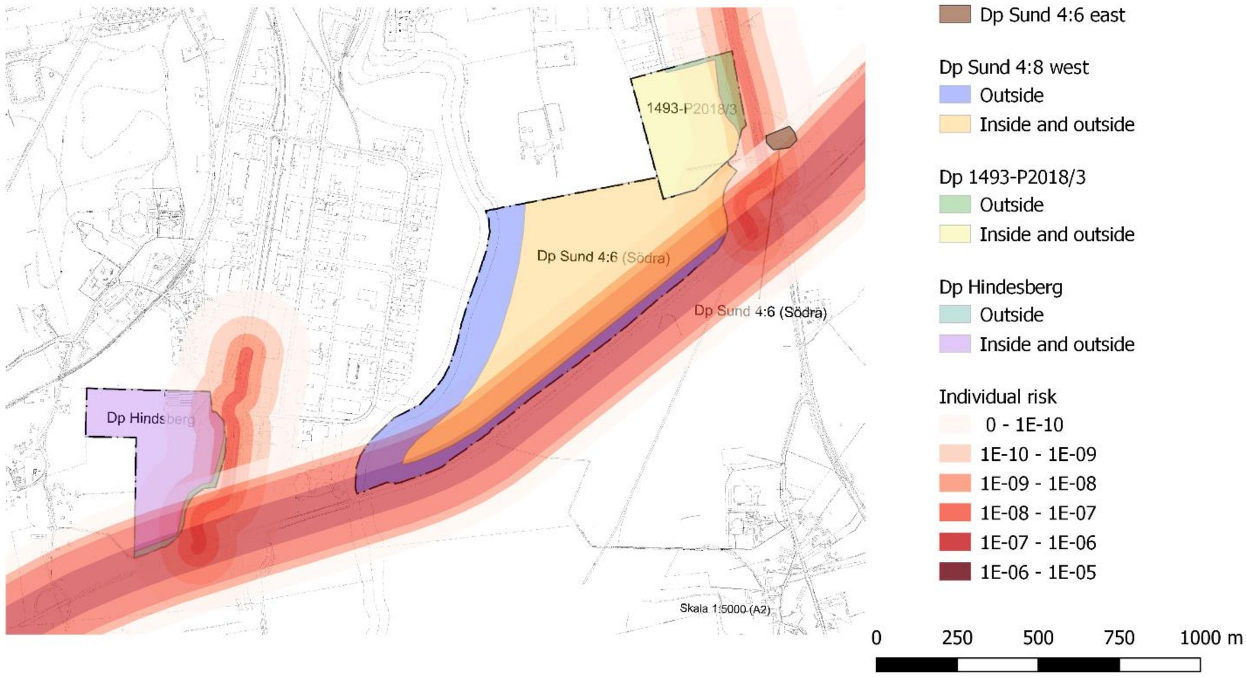

FIGURE 39 - VISUALIZATION INDIVIDUAL RISK CASE STUDY.

FIGURE 40 - VISUALIZATION INDIVIDUAL RISK CASE STUDY, LIMITS.

5 Discussion and conclusion

The result from the validation and the case study are presented and commented previously in the report. This chapter is focused on GIS in general and its potential to be used in future risk assessments. The chapter is structured to first discuss the requirements and desires presented in chapter 4.1. Later, a general conclusion and a suggestion of further development and studies are presented.

5.1 Reflections on requirements and desires

- **The model must calculate the risks correctly and it should be possible to verify the correctness.**

According to the validation and case study, the risk is in accordance with both RBM II and spreadsheet calculation. Compared with the RBM II, the GIS-models overestimates the risk in both class 2.1 and 2.3. Compared to the spreadsheet calculation the societal risk level in the GIS-models are in general a bit lower, with exception for the BLEVE-scenario. The lower risk level is due to some of the assumptions made in the spreadsheet calculation:

- The impact areas have been simplified into rectangles; in GIS the impact areas can have any shape just as in GIS-model 2. Thus, in many cases the impact areas are smaller in GIS-model 2 compare with the spreadsheet calculation (and GIS-model 1).
- The area of interest has been simplified into rectangles, and the roads are always perpendicular and on the same distance to the area. Just as for the impact areas the area of interest and road can be modified to any shape. Moreover, the area and road can be digitalized from the detail plan and thus be more in line with reality.

The spreadsheet calculation is based on conservative assumptions where at least two of the them can be minimized in GIS and provide the conditions for calculation the risks more in detailed. At the same time, risk assessment will always be associated with assumptions and simplifications. Even though two assumptions can be created more correctly it is important to still have a safety margin.

It is also important to point out that the GIS-model have been validated and compared against RBM II and spreadsheet calculation in a limited number of risk assessment. Before using the model in a real risk assessment, it is recommended to compare it with more real case scenarios that have been assessed with the spreadsheet calculation to know how the risk changes when the shape of area, road, frequency etc changes. Moreover, it is important to remember that the validations are against the two models used today and assumes that they calculate the risk correctly. Thus, even though the GIS-models results in a lower risk, compared to the spreadsheet calculations, its result can be more realistic.

- **The model should be transparent, which means that it should be easy to follow the calculation steps. This is mostly a requirement from the authorities so that they know what the numbers and assumptions are based on.**

It is possible to follow the calculation procedure if the model is opened and reviewed. However, this requires that the authorities have access to the model and have knowledge about GIS. Thus, it could be better to describe the calculation procedure in words. A description of how the risk is assessed with the spreadsheet calculation is attached as an appendix for all the risk assessment made using the tool. A similar description can be made for the GIS-model and be attached as appendix in a risk assessment report.

- **The model should be user friendly. For example, it should be easy to enter the input data.**

If the person doing the risk assessment is familiar with QGIS and a spreadsheet software, then it is fairly easy. The benefit is that it is almost the same working procedure every risk assessment. The drawback is that you must change between two software's, one spreadsheet software and GIS. This requires knowledge in two software's and requires some extra manual steps when importing and exporting tables.

The GIS-models takes more time to run than the spreadsheet calculation, about 6 minutes (depending on length of road and size of area) compared to instantly for the spreadsheet calculation. During the time when the model is running nothing else can be done in GIS, however the tables can be compiled together in the spreadsheet software.

It is also important to remember that this is a first version of a GIS-model. The model can be developed to make it more user friendly and probably also modified to be less time consuming. One feature that can be developed is that the whole risk assessment can be made in GIS. This could happen if it would be easier to create and modify tables in GIS that do not have a geographic location. Today, it is possible to create these kinds of table but not in an easy and user friendly way. Also, the processing of the results, such as creating FN-diagram, must be easier than it is today.

Another feature that can increase the user friendliness is that some of the input values can be gathered from GIS-files. For example, national statistics of transport data per road could be in the form of a GIS-file. This would increase the user friendliness but most importantly increase the correctness of the input data. GIS-data already exist today but just for one month. As Trafikanalys (2015) concluded in their report an extended mapping of dangerous goods flow in Sweden requires a clear assignment and financing of a new collection.

- **It should be possible to visualise the individual risk on a map to easily show where the limits are. It is also feasible if the result from societal risk could be visualised on a map.**

It is very easy to visualise the individual risk. The result from the calculation of individual risk can, with a few manual steps, be visualised on the map, see for example Figure 22, Figure 23, Figure 39 and Figure 40.

The societal risk can be visualised to show how much of the area that is exposed by the scenario, see Figure 35. This kind of visualization can be useful to see where measures should be implemented or, if the risk is assessed in an early stage, chose the locations for buildings where the risks are low. The GIS-model can also be modified to show the whole impact area if that is necessary.

- **It should be possible to do risk assessment to evaluate risk reduction measures. For example, easily be able to change the probability of fatality.**

It is possible to change the probability of fatality easily. It is just to change the input spreadsheet and run the model again. This is the method used in the case study both in the spreadsheet calculation and GIS-model.

In GIS, there are potentials to evaluate the measures in different ways as well. One way to evaluate a measure could be to create polygons as a protection zone where the measure is reducing the probability of fatalities. For example, if a non-combustible noise protection were to be built the area behind it could be drawn as a protection zone and the probability of fatalities could be reduced on the affected ADR-s classes. However, one problem with this is that the impact area would change shape and spread more lengthwise instead and thus affect the area of interest in a different place. One other risk reduction measure that can be used in GIS is rearranging of buildings, more about this in under the next point.

- **It should be possible to define the areas as inside/outside. It would be an advantage if the area could be rearranged, for example by moving buildings, in order to use the location of the buildings as a risk reductive measure. It is an advantage that the area (and the impact area) does not longer have to be the shape of rectangles.**

The areas are defined with populations inside and outside. Thus, if the area is only inside the population outside is set to zero. The areas can be drawn with polygons at any location and with any shape. Thus, it is possible to rearrange the area if desired and the area (and impact area) does not have to be the shape of rectangles. Moreover, by using the visualization of the societal risk (the spreading of the impact areas), the location of the buildings can more easily be decided.

5.2 Conclusion

The aim of this master thesis has been to examine the potential to use GIS as a tool to assess the risk of transport of dangerous goods. A first version of such a GIS-model have been developed in the GIS-software QGIS. The first version was divided into two models, one with impact areas copied from the spreadsheet calculation and one with impact areas more similar to RMB II.

It was found that a GIS-based approach can be used to assess the risk of transportation of dangerous goods. The validation against the spreadsheet calculation as well as against RBM II showed that the risks were in the same risk spectrum. Compared with the spreadsheet calculation, the GIS-model 2 in general gave a smaller risk, with exception to the BLEVE scenario. This is due to different shapes of the impact area. Compared with RBM II both the GIS-models gave a slightly higher risk due to conservative simplifications. The comparison in the case study also showed that the GIS-models can be used in a real case scenario.

GIS have several features which can advantageously be used in a risk assessment. The biggest advantages compared with the spreadsheet calculation is that the area of interest and the impact area can have any shape. The area of interest can also be digitalized with the detail plan in the background which can give a more realistic area. The result can also be visualized on a map, for example with the detailed development plan as background, to be able to interpret the result more easily.

The GIS-models are also connected with some drawbacks. For example, the risk assessment takes longer time to run, it requires some knowledge in QGIS and not all of the calculations can easily be made in GIS. However, this is a first version of GIS-model and there are several functions that can be developed.

5.3 Further development and studies

The GIS-models can be developed to be more user-friendly. It would be feasible if the whole risk assessment could, easily, be made in GIS. This requires an easier way to create and modify tables in GIS. Moreover, the GIS-models can be developed to treat measures in a different way. As mentioned in the discussion, the measures could be drawn as a polygon which specify the protection area with smaller probability of fatalities. However, this requires some changes in the models and requires further development.

As also mentioned earlier, the GIS-models should be evaluated using more case studies before using it in a real risk assessment. This should be done to investigate how the model reacts when the conditions and prerequires are changed.

Regarding further studies, it would be interesting to investigate the potential of other GIS-software's. This thesis show that a GIS-based risk assessment has many advantages, but these advantages is connected to GIS in general and not the GIS-software used here. Moreover, it would be interesting to investigate the need of and potential to develop a national risk assessment tool in Sweden, such as RBM II in the Netherlands. This would give a more uniform calculation of the risk on a national level and the potential to develop a more complete risk assessment software.

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Appendix A – RBM II, background theory

This appendix describes, more in detail, the background theory of RBM II. The appendix is divided to first describe the calculation of probability of fatalities, then the probability of the different scenarios followed by the calculation of the size of the impact areas.

A.1 Probability of fatalities

The probability of fatalities in RBM II is different depending on type of effect. According to AVIV (2011) the three effects that are considered in the program are:

- Toxic
- Direct fire (gas fire, jet flame, pool fire, BLEVE) and heat radiation (pool fire, jet flame and BLEVE)
- Explosions

In the end of this chapter a table with probability of fatality for all three effects can be seen.

Regarding toxic effect the probability of fatalities is based on probit functions, equation A.1, which is dependent of concentration and exposure time. The relationship between fatality for a toxic event and probit function can be seen in equation A.2. For people that are inside the probability of fatality is 10% of the probability outside, see Table A.1. Fatalities with less than 1% probability are not considered.

$$\begin{gathered}\mathrm{Pr} = \mathrm{a} + \mathrm{b} \times \ln(C^n \times t) \\ \textit{where } a, b \textit{ and } n \textit{ are constants depending on type of substance,} \\ C = concentration, t = time\end{gathered} \quad \text{(A.1)}$$

$$\mathrm{Pt} = 0.5\left[1 + \mathrm{erf}\left(\frac{Pr-5}{\sqrt{2}}\right)\right] \quad \text{(A.2)}$$

In case of a flash fire the probability of fatality is 100% within the size of the combustible area both inside and outside. It is assumed that there will not be any victims outside of this area. For a direct fire exposure in the scenarios with jet flame, pool fire and BLEVE, the probability of fatality is 100%. Moreover, in these scenarios all people exposed of more than a heat radiation of 35 kW/m^2 will be killed. For individual risk the probability of fatality for heat radiation is calculated with equation A.3 and A.4. For societal risk outside it is assumed that the protection of clothes will lead to a probability of fatality of 14% of the calculated individual risk.

$$\begin{gathered}\mathrm{Pr} = -38.48 + 2.56 \times \ln\left(q^{\frac{4}{3}} \times t\right) \\ where\ q = heat\ radiation, t = time\end{gathered} \quad \text{(A.3)}$$

$$\begin{gathered}\mathrm{Pb} = 0.5\left[1 + \mathrm{erf}\left(\frac{Pr-5}{\sqrt{2}}\right)\right] \\ where\ \mathrm{erf} = error\ function\end{gathered} \quad \text{(A.4)}$$

Regarding explosion the probability is divided into three different areas. For an overpressure of 0.3 bar, the probability of fatality will be 100% both inside and outside. For an overpressure between 0.1 and 0.3 bar the risk will be 2.5% inside and 0% outside. Overpressure below 0.1 bar will not give any fatalities.

Table A.1. Probability of fatalities (AVIV, 2011).

<table>
<tr><td></td><td colspan="2">Inside</td><td>Outside</td></tr>
<tr><td>Toxic</td><td colspan="2"></td><td></td></tr>
<tr><td>Pt > 0.01</td><td colspan="2">0.1*Pt</td><td>Pt</td></tr>
<tr><td>Pt < 0.01</td><td colspan="2">0</td><td>0</td></tr>
<tr><td>Flash fire</td><td colspan="2"></td><td></td></tr>
<tr><td>In direct fire</td><td colspan="2">1</td><td>1</td></tr>
<tr><td>Not direct fire</td><td colspan="2">0</td><td>0</td></tr>
<tr><td>Explosion</td><td colspan="2"></td><td></td></tr>
<tr><td>Overpressure > 0.3 bar</td><td colspan="2">1</td><td>1</td></tr>
<tr><td>0.3 bar > Overpressure > 0.1 bar</td><td colspan="2">0.025</td><td>0</td></tr>
<tr><td>Overpressure < 0.1 bar</td><td colspan="2">0</td><td>0</td></tr>
<tr><td rowspan="2">BLEVE, pool fire, jet flame</td><td colspan="2">Societal risk</td><td rowspan="2">Individual risk</td></tr>
<tr><td>Inside</td><td>Outside</td></tr>
<tr><td>In direct fire</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Heat radiation > 35 kW/m²</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Heat radiation < 35 kW/m²</td><td>0</td><td>0.14*Pb</td><td>Pb</td></tr>
</table>

A.2 Probability of different scenarios

The probability of different scenarios is calculated with event trees (AVIV, 2011). Depending on the sequence of events for the different types of categories the event trees contains different headlines. However, what is common for each of the categories are the initial accident frequency and relevant outflow headline. Initial accident frequency is based on standard values for different types of roads, these can be seen in Table A.2. Relevant outflow is based on number of transports multiplied with probability of an outflow greater than 100 kg and transport during day/night. The probability of an outflow greater than 100 kg for the different types of roads can be seen in Table A.2. Below the tables follows the event tree for class 2.1, 2.3 and 3.

Table A.2. Probability of an initial accident and outflow greater than 100kg with the different types of roads (AVIV, 2011).

Road category	Initial accident frequency	Probability of outflow >100kg	
		Pressurized	Atmospheric
Generic road	1.5×10^{-7}	0.052	0.101
In built areas	3.6×10^{-7}	0.034	0.077
Outside built areas	1.5×10^{-7}	0.006	0.021
High way	8.3×10^{-8}	0.043	0.093

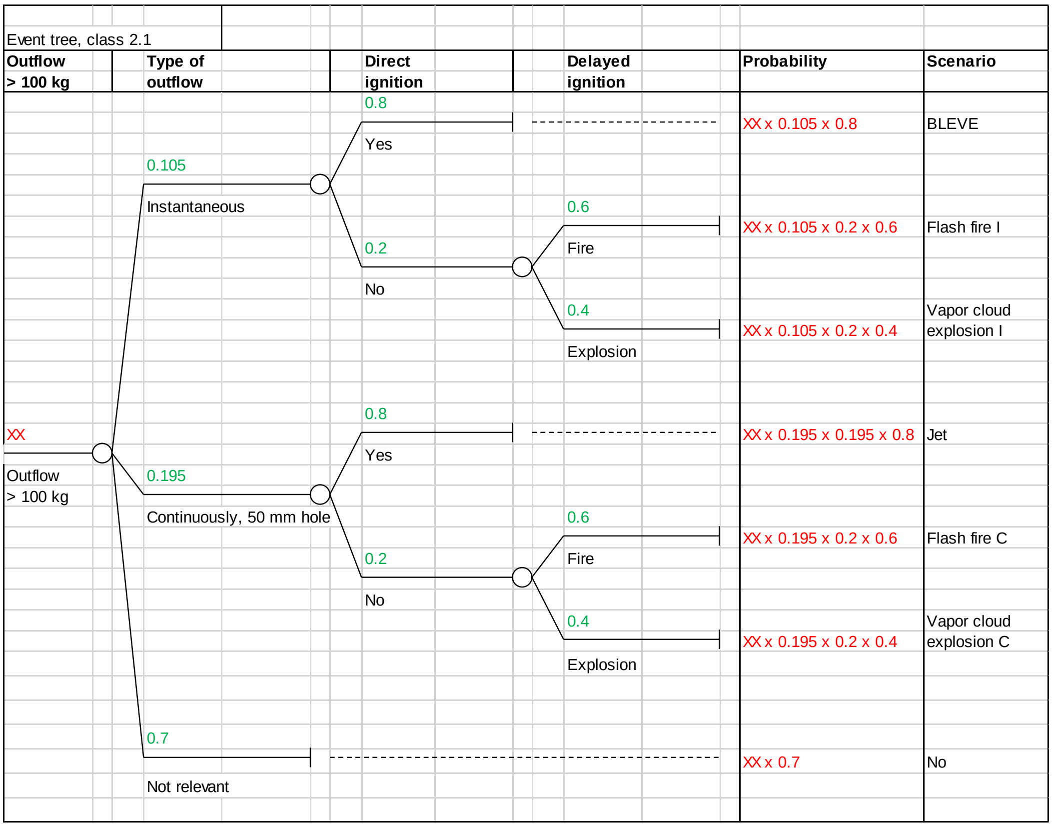


Figure A.1. Event tree for class 2.1.

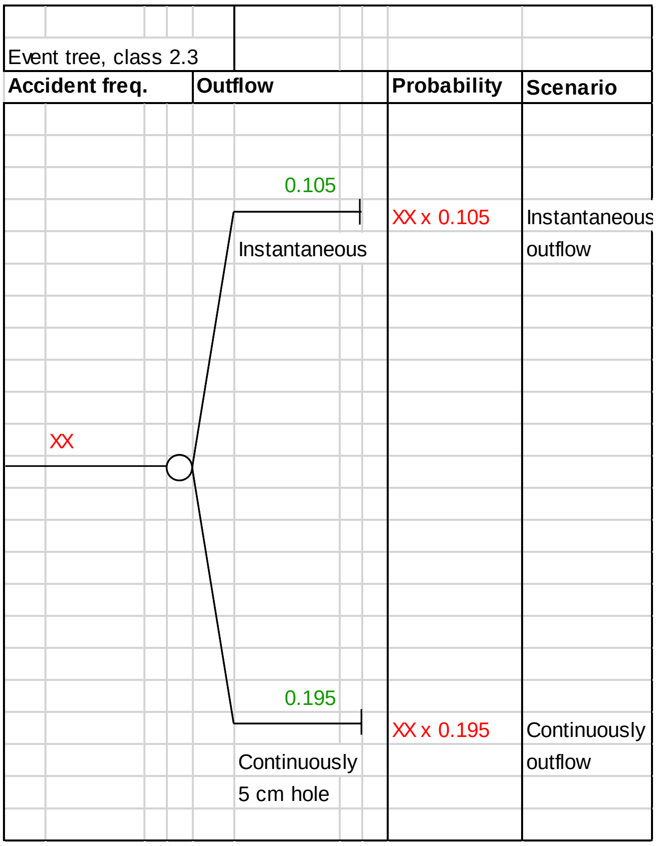


Figure A.2. Event tree for class 2.3.

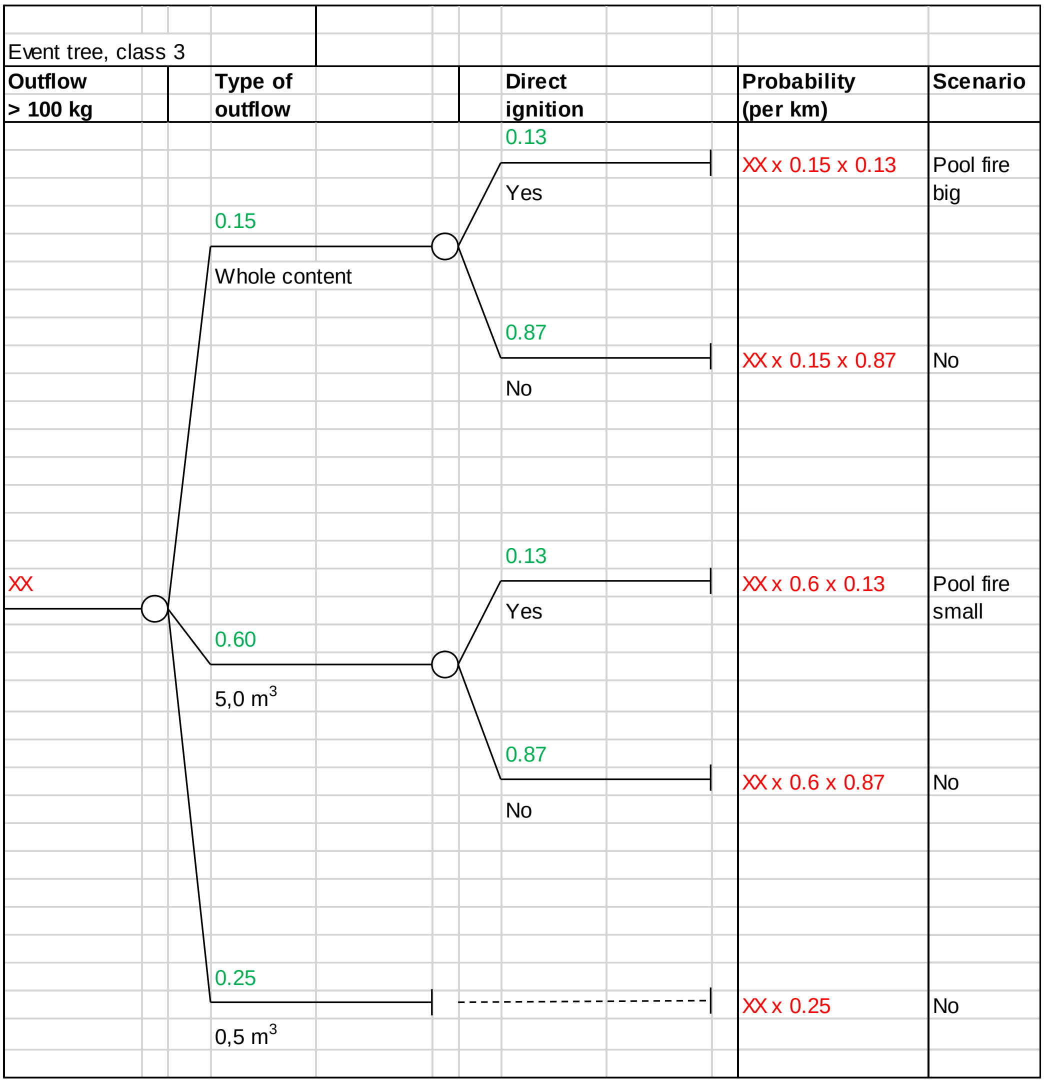


Figure A.3. Event tree class 3.

A.3 Impact area

This chapter present a description of how the calculation of impact areas is done in RBM II. The impact areas are based on outflow, evaporation and dispersion models from the Yellow Book (PGS2, 2005). For a full description of the models, follow the references to the pages in the book.

Before calculating the impact area, the outflow of the substances must be known. For continuously outflow it is assumed that the gas will leak out from a 5 cm hole and the amount of the outflow are calculated with Bernoulli equation (PGS2, 2015, page 2.121). Regarding the instantaneously outflow, it is assumed that the whole mass is released from the tank. One part of the continuously and instantaneously outflow condenses into liquid, this part is not included in the calculation of gas cloud in RBM II. Regarding liquids it is assumed that the accident scenarios results in a pool with constant size and the ground conditions are flat which means that the liquid is spreading evenly in all directions. The outflow of non-boiling liquids is also resulting in pools where evaporation takes place. The evaporation is calculated according to the model from MacKay and Matsugu described in the Yellow book (PGS2, 2005, page 3.77).

In the end of each of the subchapter a table of impact areas are presented, these are the numbers that are used as a starting point in the spreadsheet calculation and in the GIS-model.

A.3.1 Jet flame

In the scenario with jet flame it is assumed that the flame is horizontal with heat radiation as the greatest danger. The outflow is assumed to be both as gas and liquid. The length of the flame is calculated with the correlation of lower flammability limit (LPG) integral for jet fire, see equation A.5. The flame is represented as an ellipse with a length of L and diameter of D, the diameter is set to be the length divided with 8.

$$L = 18.8 \times m^{\frac{1}{3}} \qquad (A.5)$$

$$Where \frac{L}{D} = 8 \; and \; m \; is \; the \; source \; strength$$

The method for calculating the heat load, q, in the surrounding is calculated with equation A.6.

$$q = \tau \times E \times F \qquad \text{(A.6)}$$

The atmospheric transmissivity τ is calculated according to the Yellow Book (PGS2, 2005, page 6.47) and is dependent on the distance from flame and object as well as concentration of CO_2 and H_2O. For jet flame the radiation strength E is assumed to be 180 kW/m2 independent of size of flame and type of gas. The visibility factor F between flame and object is calculated with geometry, and is dependent on the diameter of flame, length of flame, deflection angle, distance between flame and object and orientation between flame and object.

The impact area for a jet flame is calculated as ellipse were q=35 kW/m2 and is shown in table A.3.

Table A.3. Impact area for a jet flame in RBM II.

Property		Value	Unit
Source strength		30.67	kg/s
Flame length		58.91	m
Flame radius		3.68	m
Radiation intensity		180	kW/m2
Distnace to centrum		29.45	m
P	Half length	Half width	Middle point
1	0	0	
1	35.07	13.14	29.45
0.99	35.44	15.8	29.45
0.9	36.21	20.06	29.45
0.5	37.74	26.21	29.45
0.1	40.21	33.41	29.45
0.01	43.16	40.19	29.45

A.3.2 Flash fire

RBM II determine the size of the combustible area of the vapor cloud by calculating the LFL. The combustible area is limited by LFL, thus by calculating LFL the size of the area is known. The size until LFL is calculated with a dispersion model. Depending on the gas, the dispersion is either calculated with Gaussian neutral model (PGS2, 2005, page 4.32) or heavy gas dispersal model. The heavy gas dispersal model is based on the distribution model presented by Cox and Carpenter (PGS2, 2005, page 4.45). The dispersion is dependent on the weather class and atmospheric stability, five different classes, see table A.4. Moreover, the size of the combustible area is also dependent on the type of release, if the release is instantaneously or continuous.

Table A.4. Impact area for flash fire continuous release.

Weather category	B3	D1,5	D5	D9	E5	F1,5
Distance	Diameter					
0	0	0	0	0	0	0
10	5	5.5	5.3	4.1	5.2	5.5
20	6.7	7.4	7.2	5.6	7.1	7.4
30	7.7	8.4	8.4	6.6	8.3	8.4
40	8.3	8.9	9.1	7.2	9	8.9
50	8.5		9.6	7.7	9.5	
60			9.8	7.9	9.7	

Table A.5 Impact area for flash fire instantaneously release.

Weathercategory	B3	D1,5	D5	D9	E5	F1,5
Distance	Diameter					
0	0	0	0	0	0	0
5	66.7	84.4	57.2	49.3	57.2	84.4
10	84.8	111	70.7	58.9	70.7	111
15	99.6	132.8	81.8	66.8	81.8	132.8
20	112.2	152	91.3	73.6	91.3	169.7
25	123.5	169.7	99.9	79.7	99.9	185.9
30	133.9	185.9	107.7	85.3	107.7	
35	143.7		115	90.6	115	
40	152.9		121.8	95.5	121.8	
45	161.7		128.3	100.2	128.3	
50	170		134.4	104.6	134.4	
55	177.9		140.3	108.9	140.3	
60	185.5		146.1	113	146.1	
65			151.7	116.9	151.7	
70			157.1	120.7	157.1	
75			162.3	124.4	162.3	
80			167.4	128	167.4	
85			172.3	131.4	172.3	
90			177.1	134.8	177.1	
95			181.8	138.2	181.8	
100			186.4	141.4	186.4	
105			190.8	144.6	190.8	
110				147.7		
115				150.8		
120				153.8		
125				156.8		
130				159.7		
135				162.5		
140				165.4		
145				168.1		
150				170.8		
155				173.5		
160				176.2		
165				178.8		
170				181.3		
175				188.3		
180				200.2		
185				205.5		
190				207.7		

A.3.3 Vapor cloud explosion

In RBM II the impact area of a vapor cloud explosion is calculated with a correlation model, see equation A.7 and A.8. The correlation model is based on an evaluation of three vapor explosions where the gas cloud can be characterized as partially encapsulated for explosion. The model is dependent on the mass M of the cloud above the LFL-contour. The impact areas are circular and are calculated were the pressure wave is 0.3 and 0.1 bar. Distance to centrum for the circular impact areas are calculated with a dispersion model, same as for flash fire. Explosion centrum for continuously scenarios are assumed to be half of the distance to LFL-contour in the wind direction. For instantaneous scenarios the centrum is assumed to be equal to the gas cloud centrum when it has reached its greatest extent.

$$R_{0.3\ bar} = 0.03 \times (0.1 \times M \times H_c)^{\frac{1}{3}} \quad \text{(A.7)}$$

$$R_{0.1\ bar} = 0.06 \times (0.1 \times M \times H_c)^{\frac{1}{3}} \quad \text{(A.8)}$$

$Where:$

$R_{0.3\ bar} = distance\ to\ overpressure\ of\ 0.3\ bar$

$R_{0.1\ bar} = distance\ to\ overpressure\ of\ 0.1\ bar$

$M\ is\ mass\ in\ the\ cloud\ above\ the\ LFL$

$H_c\ is\ heat\ enthalpy$

Table A.6. Impact area for vapor cloud explosion small.

Property	Value	Unit
Probability	0.0156	-
Mass in cloud	295	kg
Radius 0.3 bar	33	m
Radius 0.1 bar	67	m

Table A.7. Impact area for vapor cloud explosion big.

Property	Value	Unit
Probability	0.0084	-
Mass in cloud	15895	kg
Radius 0.3 bar	126	m
Radius 0.1 bar	252	m

A.3.4 BLEVE

In the scenario of a BLEVE, it is the heat radiation that is considered in RBM II (AVIV, 2011). Other effects of a BLEVE, such as overpressure, smoke and toxic by-products, are not considered in the program. Only heat radiation is considered since its impact area is much larger than the other effects and is a much larger threat. A fireball is used to model the heat radiation and is modelled as a circular shape in RBM II. The circle has a constant radius of R during an effective fire time of t, see equation A.9.

$$R = 3.24 \times M^{0.325} \quad \text{(A.9)}$$
$$t = 0.852 \times M^{0.26}$$

The heat load is calculated with the same equation as previously (equation A.6) but with another visibility factor and radiation strength. The visibility factor at distance r from the centrum of the fire ball is calculated according to equation A.10. The radiation strength is calculated based on the radiation fraction Fs and combustion energy MHc, see equation A.11. The radiation fraction is dependent on the substance vapor pressure P. There are two different P that could happen in a BLEVE, either a "cold" or "warm" BLEVE could occur. In a "cold" BLEVE P is the same as the vapor pressure in standard ambient temperature. In a "warm" BLEVE P is calculated with equation A.12. The impact area is calculated as circular areas with contours were q=35 kW/m2, see table A.8.

$$F = \frac{D^2}{r^2} \quad \text{(A.10)}$$
$$Where\ D = 2R$$

$$\pi \times D^2 \times E \times t = F_s \times M \times H_c \quad \text{(A.11)}$$
$$Where\ F_s = 0.00325 \times P^{0.32}$$

$$P = 1.4 \times [P_v(T = 308K) + 1.7] \quad \text{(A.12)}$$

Table A.8. Impact area of a BLEVE.

Property	Value	Unit
Mass in BLEVE	17928	kg
Failure pressure	629634	N/m2
Temperature	282	K
Radius fireball	78.15	m
Fire time	10.87	s
SEP	212.16	kW/m2
Distance to 35 kW/m2	50.76	m
P	Radius [m]	
1	78.15	
0.439	81.46	
0.34	87.96	
0.246	94.66	
0.163	101.56	
0.098	108.66	
0.053	115.96	
0.025	123.46	
0.01	131.16	
0.004	139.06	

A.3.5 Toxic gas

The concentration of toxic gas is calculated with one of the dispersion models in which the concentration C is a function of the distance x from emission point and distance y from the cloud axis. To simplify the calculations, the program uses an effective width of the toxic gas cloud. For a continuously release the effective width is calculated according to equation A.13. In other words, the effective with is calculated so that the area under the blue curve (calculated cloud) in Figure A.4 correspond to the area under the red curve (effective width cloud).

$$P_{di}(x,0) \times effective\ width = \sum P_t(x,y)dy \tag{A.13}$$

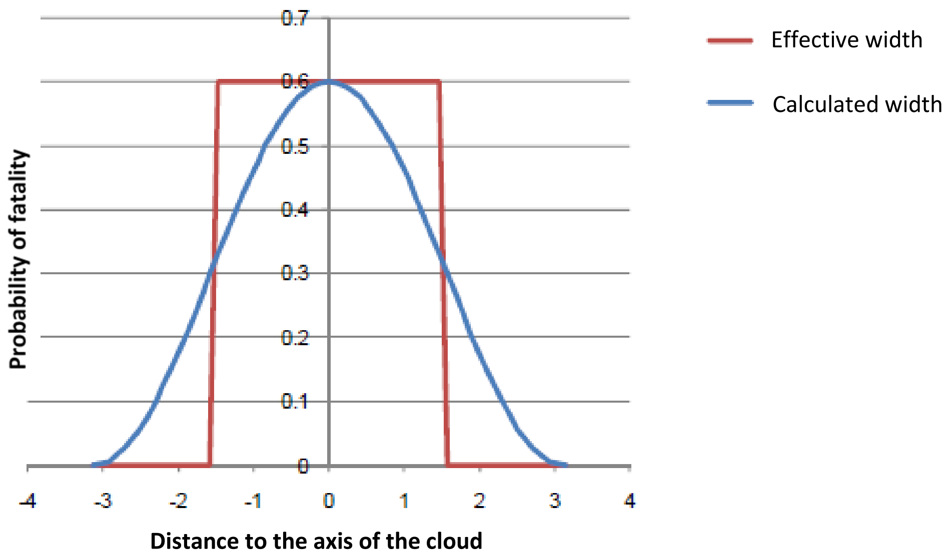


Figure A.4. Simplification of gas cloud. Translated from (AVIV, 2011).

In the case of an instantaneously outflow, the effective width takes into account the passage time of the sagging and increasing cloud. This function depends on the distance x to the outflow point and the distance y in the width to the cloud axis.

Table A.8. Impact area for weather category B3, continuously outflow.

Distance	Width [m]	P (death) in	P (death) out
10	2.4	0.1	1
11	2.6	0.1	1
15	3.4	0.1	1
20	4.3	0.1	1
25	5.4	0.1	0.998
30	6.3	0.1	0.996
35	7.4	0.099	0.992
40	8.7	0.099	0.986
45	11.8	0.098	0.979
50	14.1	0.097	0.972
55	15.5	0.096	0.962
60	16.9	0.095	0.95
65	18.5	0.094	0.936
70	20.1	0.092	0.92
75	21.8	0.09	0.902
80	23.5	0.088	0.88
85	25.3	0.086	0.856
90	27	0.083	0.83
95	28.7	0.08	0.803
100	30.5	0.077	0.774
105	32.2	0.074	0.743
110	34	0.071	0.711
115	35.8	0.068	0.679
120	37.6	0.064	0.645
125	39.4	0.061	0.611
130	41.1	0.058	0.577
135	43	0.054	0.542
140	44.8	0.051	0.508
145	46.6	0.047	0.474
159	51.7	0.038	0.384
174	57.3	0.03	0.296
192	64.1	0.021	0.208
211	71.4	0.014	0.137
232	79.5	0.008	0.082
255	88.6	0.004	0.044
281	98.9	0.002	0.021
309	109.8	0.001	0.008

Table A.9. Impact area for weather category B3, instantaneously outflow.

Distance [m]	Diameter [m]	P (death) in	P (death) out
5	48.6	0.097	0.975
10	54.4	0.082	0.818
15	56.8	0.061	0.612
20	69.1	0.049	0.485
25	69.9	0.034	0.34
30	70.2	0.024	0.237
35	70.8	0.016	0.165
40	70.3	0.012	0.115
45	70.8	0.008	0.081
50	69.5	0.006	0.058
55	66.1	0.004	0.042
60	64.7	0.003	0.03
65	63.5	0.002	0.022
70	60.2	0.002	0.016
75	67.2	0.001	0.012
80	72.9	0.001	0.009

A.3.6 Pool fire

Only the heat radiation is considered in RBM II, this is due to the same reason as BLEVE. The heat radiation is calculated with equation A.6 with the same atmospheric transmission and visibility factor but with another radiation strength. The radiation strength is calculated with equation A.14 and is a function of the pool diameter D. Two different size of the diameters are considered, one small outflow which result in a diameter of 20 m and one large outflow resulting in a diameter of 46m.

$$E = 140e^{-0.12D} + 20(1 - e^{-0.12\times D}) \quad \text{(A.14)}$$

The result is dependent on the weather classes and has the shape of ellipse where q=35 kW/m2, see Table A.10 and A.11.

Table A.10. Impact area of Pool fire big.

	B3				D1,5			
P	Middle point	Half length	Half width		P	Middle point	Half length	Half width
1	0.33	23.33	22.99		1	0.26	23.25	22.99
0.166	2.25	25.24	22.99		0.097	2.25	25.24	23.35
0.07	4.49	27.49	23.55		0.029	4.49	27.49	24.66
0.027	6.84	29.84	24.36		0.008	6.84	29.84	26.28
0.009	9.29	32.28	25.37					
D5					D9			
P	Middle point	Half length	Half width		P	Middle point	Half length	Half width
1	0.38	23.37	22.99		1	0.42	23.41	22.99
0.221	2.25	25.24	22.99		0.277	2.25	25.24	22.99
0.113	4.49	27.49	23.08		0.168	4.49	27.49	22.99
0.054	6.84	29.84	23.6		0.098	6.84	29.84	23.1
0.023	9.29	32.28	24.18		0.052	9.29	32.28	23.41
0.009	11.84	34.83	24.93		0.024	11.84	34.83	23.86
					0.009	14.49	37.48	24.39
E5								
P	Middle point	Half length	Half width		F1,5			
1	0.38	23.37	22.99		P	Middle point	Half length	Half width
0.221	2.25	25.24	22.99		1	0.26	23.25	22.99
0.113	4.49	27.49	23.08		0.097	2.25	25.24	23.35
0.054	6.84	29.84	23.6		0.029	4.49	27.49	24.66
0.023	9.29	32.28	24.18		0.008	6.84	29.84	26.28
0.009	11.84	34.83	24.93					

Table A.11. Impact area for Pool fire small.

	B3				D1,5			
P	Middle point	Half length	Half width		P	Middle point	Half length	Half width
1	0.35	10.35	10		1	0.28	10.28	10
0.796	0.77	10.77	10		0.707	0.77	10.77	10
0.49	2.61	12.61	10.17		0.319	2.61	12.61	10.84
0.231	4.55	14.55	10.89		0.1	4.55	14.55	12.09
0.08	6.6	16.6	11.74		0.022	6.1	17.1	13.72
0.019	8.67	18.82	12.9		0.003	7.66	19.83	15.72
0.003	10.49	21.49	14.47					
D5					D9			
P	Middle point	Half length	Half width		P	Middle point	Half length	Half width
1	0.4	10.39	10		1	0.43	10.43	10
0.602	2.61	12.61	10.01		0.7	2.61	12.61	10
0.356	4.55	14.55	10.34		0.499	4.55	14.55	10.07
0.163	6.6	16.6	10.9		0.292	6.6	16.6	10.32
0.052	8.75	18.74	11.61		0.119	8.75	18.74	10.78
0.009	10.99	20.99	12.72		0.023	10.99	20.99	11.53
					0.001	13.34	23.34	13.07
E5					F1,5			
P	Middle point	Half length	Half width		P	Middle point	Half length	Half width
1	0.4	10.39	10		1	0.28	10.28	10
0.602	2.61	12.61	10.01		0.707	0.77	10.77	10
0.356	4.55	14.55	10.34		0.319	2.61	12.61	10.84
0.163	6.6	16.6	10.9		0.1	4.55	14.55	12.09
0.052	8.75	18.74	11.61		0.022	6.1	17.1	13.72
0.009	10.99	20.99	12.72		0.003	7.66	19.83	15.72

A.3.7 Toxic liquids

For toxic liquids it is assumed that the accident scenario is resulting in a pool with a constant size. The diameter of the pool is either 20 or 46 m for a small or a large outflow respectively. The toxic liquid is evaporation with one of the dispersion models and later distributed in the same way as for toxic gases.

Appendix B - Spreadsheet calculation, theoretical background

This appendix describes, more in detail, the theoretical background to the spreadsheet calculation. The appendix is structured based on the ADR-S classes that are analysed in the risk assessment and each of the sub-chapters describes how the probability of fatalities, probability of the different scenarios and size of impact areas are calculated in each of the classes.

B.1 Class 1

In an accident with a transport of dangerous goods either one of these scenarios can happen:

- No fire or explosion
- Explosion due to the mechanical impact at the accident
- Fire in vehicles which does not lead to an explosion
- Fire in vehicles which does lead to an explosion

These scenarios can be seen in the event tree in Figure B.1. The probability of an explosion due to the mechanical impact at the accident is based on reports by ERM (2008) and FOA (2000). These studies show that the speed that is required for a shock to cause an explosion is similar to the speed of bullets in guns (approximate 500 m/s or 1800 km/h), however these speeds can be lower at increased temperatures. Another study with falling weights from a drop of 12 m on explosives based on nitro-glycerine have showed that the probability for ignition were below 0.1%. As a result of all these studies the probability used for this event were set to be 0.1%.

The probability of a fire in a vehicle is calculated with statistics from USA since there are no reliable statistics from Sweden. According to NFPA (2010), FEMA (2008) and USCB (2012) there were 1.6 million traffic accidents (3.1% of all accidents) with trucks on highways in USA during the period 2005-2009. During the same period 1.13 million accidents caused a fire in a vehicle, 72.6 thousand of these accidents included a truck. Thus, according to these statistics, 4.5% (72 600 / 1 600 000) of the accidents with trucks led to a fire. It is this number that is used in the event tree in figure 5.3. The probability that the fire will lead to a detonation of the explosives is roughly estimated to 10%.

The impact area is calculated with an explosion with 16 tons of TNT. 16 tons are used since it is the maximum weight that is allowed to transport on the roads in Sweden. The overpressure from the explosion is calculated with Hopkinson scaling law, see equation B.1, together with figures of overpressure verses scaling distance given by SRV (2005). With 16 tons of TNT the overpressure in different distances from explosion centrum can be seen in table B.1.

$$Z = \frac{R}{M^{\frac{1}{3}}} \tag{B.1}$$

$$Where\ R = distance\ to\ explosion\ centre\ and\ M = amount\ of\ explosives$$

Table B.1. Reflected and unreflected pressure and impulse density as a function of the distance to the explosion centre.

Distance [m]	Z [m/kg$^{1/3}$]	p^+ [kPa]	p_r [kPa]	i^+ [kPas]	i_r [kPas]
25	1.0	900	5000	4.8	14.0
50	2.0	200	750	2.3	6.3
63	2.5	120	400	1.8	4.3
75	3.0	80	220	1.6	3.3
100	4.0	45	110	1.3	2.6
125	5.0	33	70	1.0	2.0
150	6.0	23	50	0.9	1.8
175	6.9	20	40	0.8	1.5
200	7.9	15	33	0.7	1.3

According to EAI (1997) buildings that are exposed for an overpressure of more than 25-35 kPa will collapse. According to table 5.1 the overpressure (p+) is over 25-35 kPa until 125 m, this is the distance used in the spreadsheet calculation where it is assumed that buildings closest to the road will have severe damages. The buildings behind the first row are assumed to be protected and will not have as severe damages. The size of the area along the road where house will collapse is calculated based on the distance to the houses and Pythagorean theorem. In the building on the first row it is assumed that one sixth of the people will die. This number comes from FOA (1997) which assumes that half the buildings which are severe damage will collapse and in these areas about one third of the people staying there are killed.

Fatalities outside could either be caused directly by the overpressure or by indirect injuries such as a fall due to the pressure wave or get hit by falling object. Humans are handling pressure relatively good and the fatalities due to lung injury could happen up to 180 kPa and 50% are assumed to be killed at 260 kPa (FOA, 1997). According to FOA (1997) a 70 kg person will get head injuries on 50 m from the explosion. At a distance of 75 m the probability has decreased till 50% and on 90 m 10%. It is also assumed that people that are outside close to buildings that are assumed to collapse will be killed.

To sum up, for societal risk it is assumed that 17% (approximate 1/6) will be killed inside those houses that are assumed to collapse in the explosion. Houses in the first row are assumed to collapse up to a distance of 125 m. All people that are outside and close to the buildings that are assumed to collapse will be killed. The distance is dependent on the distance between transport link and the house as well as the buildings width.

Regarding individual risk the probability is calculated with the assumption that the accident must occur within 250 m of the road closest to the person. People are assumed to be killed if they are in the area around the buildings that are expected to collapse, the calculations are the same as for societal risk.

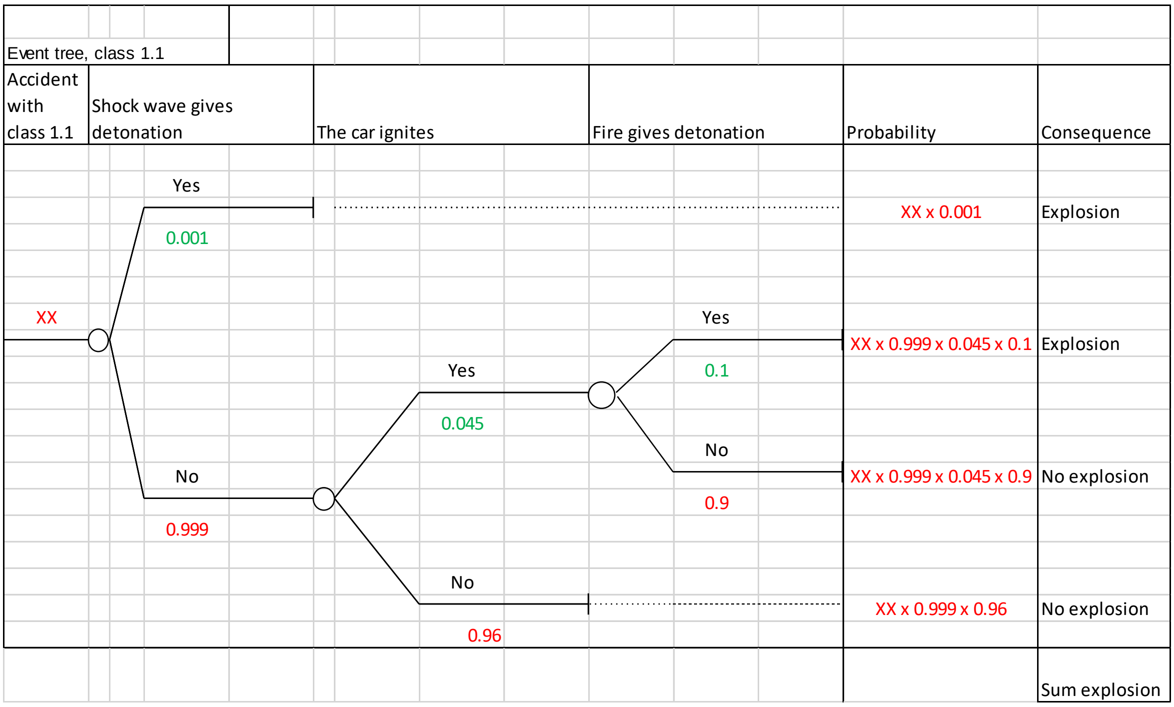


Figure B.1. Event tree for class 1.

B.2 Class 2

This classification is included in RBM II and the event trees used in the spreadsheet calculation are the same as the described event trees in Appendix A. Thus, only the consequences and how the impact area have been translated to a spreadsheet format will be explained in this chapter. The length and width of the impact areas are a simplification of the impact areas in RBM II and are in general a bit larger which give a more conservative calculation.

B.2.1 Jet flame

The impact for a jet flame is calculated in an area of 45 m in the direction of the road and 74 m from the road. All people, both inside and outside, in this area are assumed to be killed.

B.2.2 Flash fire – instantaneous release

When the gas is released instantaneously it is assumed that wind will have little or no effect on the spreading. For a flash fire instantaneous it is assumed that the gas cloud has its centrum on the place of accident and will have a size of 185x185 m. All people inside of the gas cloud are assumed to be killed. Thus, in an area of 185 along the road and 93 m from the road all people are assumed to be killed in the societal risk. For individual risk an individual will be killed if the accident occurs within 93 m from the person and if the person is less than 93 m from the road. The impact area has been chosen with margin from the numbers presented from RBM II. This is partly due to take into account that the gas cloud can be transported with the wind before it ignites.

B.2.3 Flash fire – continuously release

This scenario is based on a release from a 5 cm hole in the tank. It is assumed that the flammable gas is not ignited immediately but is spreading in the direction of the wind from the place of the accident. Since the wind is affecting the accident sequence two different scenarios are analysed. If the wind is against the area the gas is transported towards it, this scenario is analysed in flash fire KT. If the wind is in the direction of the road the gas is transported along the road, this is analysed in scenario flash fire KL. In all other wind direction, the gas is transported away from the area and will not give any consequences to the area of interest.

The impact area for both scenario KT and KL are 50x10 m in the direction of the wind. This is the area where it is assumed that the gas has spread before the LFL is reached and the gas is ignited. In this area it is assumed that all people will be killed, both inside and outside. Thus, the impact area for both individual and societal risk for scenario KT are 10 m along the road and 50 m from the road. For scenario KL the impact area is 50 m along the road and 5 m from the road.

B.3.4 Vapor cloud explosion – instantaneous release

This scenario is similar to scenario flash fire M, but in this scenario the consequences will not be a fire but an explosion. The impact area is calculated from RBM II were an overpressure of 0.3 bar will occur, the impact area in the spreadsheet calculation is formed to include the whole circular area described in chapter 4.3.2. This result in a rectangular with the size 252 m along the road and 126 m from the road. The probability of fatality is set to 100% for both individual and societal risks. For societal risk the contour of 0.1 bar from RMB II is used as well, this area has a size of 504 m along the road and 252 m from the road, the probability of fatality in the area is assumed to be 3% for the people inside.

B.3.5 Vapor cloud explosion - continuously release

This scenario is similar to flash fire KT and KL, but with an explosion instead of a fire. The circular contour from RBM II for an overpressure of 0.3 Bar is translated in the same way as for instantaneous release. To consider the wind, the centrum for the impact area is moved. If the wind is facing the area of investigation, directly or diagonally, the gas is transported against the area and the centrum is assumed to be moved 33 m from the road, this is vapour cloud explosion KT. If the wind is in the direction of the road the centrum is assumed to be moved 33 m along the road instead, this is vapour cloud explosion KL. All the other wind directions are moving the gas from the area and are not included. Thus, in scenario KT the impact area is 66 m both along and from the road. In scenario KL, the impact area is 33 m from the road and 66 m along the road. The probability of fatality in the impact area is 100%. No contours of 0.1 Bar is used, and thus there is just one size of impact area for this scenario.

B.3.6 BLEVE

For BLEVE the circular shape in RBM II is translate into an 80x80 m square in the spreadsheet calculation. In this area it is assumed that all people will be killed. Thus, the impact area for both individual and societal risk are 80 m along the road and 40 m from the road. A second impact area is used for societal risk with a size of 110x55 m with a probability of fatalities of 7%. The centrum of the BLEVE is located on the road for both of the impact areas.

B.3.7 Toxic gases

Toxic gases are split into three different scenarios: gas cloud M, gas cloud KT and gas cloud KL. For gas cloud M, the whole tank is released instantaneously and due to the rapid course of event, the wind direction is judged to be of less importance. However, the impact areas have been adapted to consider the wind in different directions. The impact area is split into two, both with centrum on the place of accident. The first area is assumed to have the size 70x70 m and the second impact area have the size of 120x120 m. For individual risk, the probability of fatality is 100% in the first impact area which equals to a distance 70 m along the road and 35 m from the road. In the second impact area the probability of fatality is 30%. For societal risk, the probability of fatality is 100% outside and 10% inside in the first impact area. In the second impact area the probability is 30% and 3%.

For scenario gas cloud KT and KL the gas is released continuously through a 5 cm hole in the tank. The cloud is spreading in the direction of the wind. The first impact area has a size of 25x135 m in the direction of the wind and the second 75x220 m in the direction of the wind. The wind distribution is calculated in the same way as for flash fire (scenario KL and KT). For individual risk, the probability of fatality is 100% in impact area 1. For societal risk the probability of fatality is 100% outside and 10% inside for impact area 1 and 30% outside and 3% inside for impact area 2.

B.4 Class 5

In class 5, it is assumed that the transports are with ammonium nitrate which, when mixed with diesel oil, can lead to an explosion corresponding to 3 tons of TNT at a large emission of ammonium nitrate and about the half at a smaller emission. The corresponding amount of TNT is overestimating the explosion since the mixture that will occur after an accident will not be enough to produce an effective explosive, which requires a fairly precise mixture of these substances. The consequences of an explosion depend on the emission of oxidizing substances. The amount of flammable liquid, for example diesel oil, is of less importance since an explosive mixture requires less amount of flammable liquid. For a substance in class 5 to cause an explosion, several conditions must be met:

1. A significant emission of oxidizing substances must occur
2. Emission of diesel oil must occur
3. The mixture must ignite.

These steps with the corresponding probability can be seen in the event tree for class 5 in Figure B.2. The probabilities are based on statistics for thin-walled tankers and are gathered from RBM II.

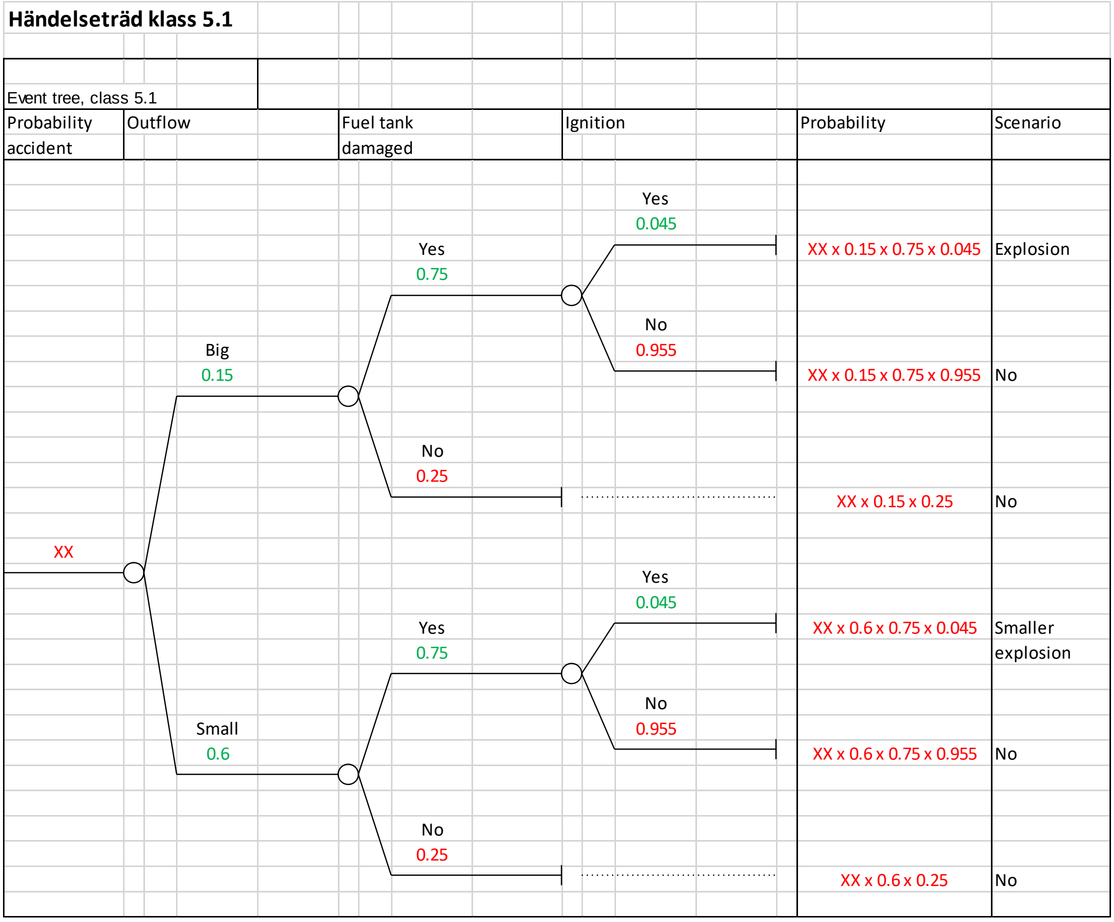


Figure B.2. Event tree for class 5.

Appendix C - GIS-model, calculation of societal risk

Before using the GIS-models, two spreadsheets need to be created, one with input data which determine the size of the impact areas and one that is used to compile the result and calculate the frequency. These spreadsheets are different for the two GIS-models, Table C1 and C2 gives an example of spreadsheets for GIS-model 1 and Table C3 and C4 gives an example of spreadsheets for GIS-model 2. How the notation in the input data is used can be seen in the equations of the impact areas given in Appendix C.1.

Table C1. Input data for GIS-model 1.

		Impact area 1				Impact area 2				
Scenario	Description	P_1_in	P_1_out	length_1	width_1	P_2_in	P_2_out	length_2	width_2	D
1	Explosives	0.17	1.00	260	130	0.00	0.00	260	130	80
2	Jet fire	1.00	1.00	45	74	0.00	0.07	66	80	
3	Cloud fire M	1.00	1.00	185	93	0.00	0.00	185	93	
4	Cloud fire K, wind perpendicular road	1.00	1.00	10	50	0.00	0.00	10	50	
5	Cloud fire K, wind along road	1.00	1.00	50	5	0.00	0.00	50	5	
6	Gas explosion M	1.00	1.00	252	126	0.03	0.00	504	252	
7	Gas explosion K, wind perpendicular road	1.00	1.00	66	66	0.03	0.00	66	66	
8	Gas explosion K, wind along road	1.00	1.00	66	33	0.03	0.00	66	33	
9	BLEVE	1.00	1.00	80	40	0.00	0.07	110	55	
10	Toxic gases K, wind perpendicular road	0.10	1.00	25	135	0.03	0.30	75	220	
11	Toxic gases K, wind along road	0.10	1.00	135	13	0.03	0.30	220	38	
12	Toxic gases M	0.10	1.00	70	35	0.03	0.30	120	60	
13	Pool fire big	1.00	1.00	48	24	0.00	0.00	48	24	
14	Pool fire small	1.00	1.00	25	13	0.00	0.04	33	17	
15	Class 5 explosion big	0.17	1.00	144	72	0.00	0.00	250	125	80
16	Class 5 explosion small	0.17	1.00	104	57	0.00	0.00	125	63	80

Table C2. Output spreadsheet for GIS-model 1.

Scenario	Description	F_accident	wind
1	Explosives	7.19E-08	1.00
2	Jet fire	6.94E-08	1.00
3	Flash Fire I	5.61E-09	1.00
4	Flash Fire C, wind perpendicular road	1.04E-08	1.00
5	Flash Fire C, wind along road	1.04E-08	0.27
6	Vapor Cloud Explosion I	3.74E-09	1.00
7	Vapor Cloud Explosion C, wind perpendicular road	6.94E-09	0.34
8	Vapor Cloud Explosion C, wind along road	6.94E-09	0.27
9	BLEVE	3.74E-08	1.00
10	Toxic gases C, wind perpendicular road	8.68E-08	0.34
11	Toxic gases C, wind along road	8.68E-08	0.27
12	Toxic gases I	4.67E-08	1.00
13	Pool fire big	1.97E-08	1.00
14	Pool fire small	7.86E-08	1.00
15	Class 5 explosion big	5.10E-09	1.00
16	Class 5 explosion small	2.04E-08	1.00
17	Explosives, night	3.08E-08	1.00
18	Jet fire, night	2.98E-08	1.00
19	Flash Fire I, night	2.40E-09	1.00
20	Flash Fire C, wind perpendicular road, night	4.46E-09	0.34
21	Flash Fire C, wind along road, night	4.46E-09	0.27
22	Vapor Cloud Explosion I, night	1.60E-09	1.00
23	Vapor Cloud Explosion C, wind perpendicular road	2.98E-09	0.34
24	Vapor Cloud Explosion C, wind along road, night	2.98E-09	0.27
25	BLEVE, night	1.60E-08	1.00
26	Toxic gases C, wind perpendicular road, night	3.72E-08	0.34
27	Toxic gases C, wind along road, night	3.72E-08	0.27
28	Toxic gases I, night	2.00E-08	1.00
29	Pool fire big, night	8.42E-09	1.00
30	Pool fire small, night	3.37E-08	1.00
31	Class 5 explosion big, night	2.19E-09	1.00
32	Class 5 explosion small, night	8.75E-09	1.00

Table C3. Input data for GIS-model 2.

		Impact area 1				Impact area 2				Impact area 3				Constant
Scenario	Description	P_1_in	P_1_out	D_1	R_1	P_2_in	P_2_out	D_2	R_2	P_3_in	P_3_out	D_3	R_3	c
1	Explosives	0.17	1		130									50
2	Jet fire	1	1	36.2	20	0.5	0.5	40.1	33.3					29.45
3	Flash Fire I	1	1	60	92.8	1	1	0	92.8	1	1	-60	92.8	
4	Flash Fire C	1	1	0	0									
4	Flash Fire C	1	1	10	5									
4	Flash Fire C	1	1	20	6.7									
4	Flash Fire C	1	1	30	7.7									
4	Flash Fire C	1	1	40	8.3									
4	Flash Fire C	1	1	50	8.5									
41	Flash Fire C	1	1											
5	Flash Fire C, wind along	1	1	50	5									
6	Vapor Cloud Explosion I	1	1		126	0.025	0		252					
7	Vapor Cloud Explosion C, wind against	1	1	16.5	33	0.025	0	33.5	67					
8	Vapor Cloud Explosion C, wind along	1	1	0	33	0.025	0	0	67					
9	BLEVE	1	1	0	80	0.3	0.3	0	108					
10	Toxic gases C, wind against	0.1	1	0	0	0.06	0.6	0	0	0.03	0.3	0	0	
10	Toxic gases C, wind against	0.1	1	100	31	0.06	0.6	100	31	0.03	0.3	100	31	
10	Toxic gases C, wind against	0.1	1			0.06	0.6	145	47	0.03	0.3	145	47	
10	Toxic gases C, wind against	0.1	1			0.06	0.6			0.03	0.3	255	88	
101	Toxic gases C, wind against	0.1	1			0.06	0.6			0.03	0.3			
11	Toxic gases C, wind along	0.1	1	135	13	0.03	0.3	220	38					
12	Toxic gases C	0.1	1	0	60	0.03	0.3	30	70					
13	Pool fire big	1	1	24	23	0.12	0.12	31.3	24					0
14	Pool fire small	1	1	11	10	0.4	0.4	16.2	11.5					0
15	Class 5 explosion big	0.17	1		72									50
16	Class 5 explosion small	0.17	1		57									50

Table C4. Output spreadsheet for GIS-model 2.

Scenario	Description	F_accident	Wind
100	Explosives	7.19361E-08	1.00
101	Explosives night	3.08298E-08	1.00
200	Jet fire	6.94294E-08	1.00
201	Jet fire night	2.97554E-08	1.00
310	Flash fire I wind against	5.60776E-09	0.34
320	Flash fire I wind along road	5.60776E-09	0.27
330	Flash fire I wind from	5.60776E-09	0.38
311	Flash fire I wind against, night	2.40332E-09	0.34
321	Flash fire I wind along road, night	2.40332E-09	0.27
331	Flash fire I wind from, night	2.40332E-09	0.38
410	Flash fire C wind against	1.04144E-08	0.34
411	Flash fire C wind against, night	4.46332E-09	0.34
520	Flash fire C wind along road	1.04144E-08	0.27
521	Flash fire C wind along road, night	4.46332E-09	0.27
600	Vapor cloud explosion I	3.7385E-09	1.00
601	Vapor cloud explosion I, night	1.60222E-09	1.00
710	Vapor cloud explosion C wind againts	6.94294E-09	0.34
711	Vapor cloud explosion C wind againts, night	2.97554E-09	0.34
820	Vapor cloud explosion C wind along	6.94294E-09	0.27
821	Vapor cloud explosion C wind along, night	2.97554E-09	0.27
900	BLEVE	3.7385E-08	1.00
901	BLEVE, night	1.60222E-08	1.00
1010	Toxic gases C, wind against	8.67867E-08	0.34
1011	Toxic gases C, wind against, night	3.71943E-08	0.34
1120	Toxic gases C, wind along	8.67867E-08	0.27
1121	Toxic gases C, wind along, night	3.71943E-08	0.27
1210	Toxic gases I wind against	4.67313E-08	0.34
1220	Toxic gases I wind along road	4.67313E-08	0.27
1230	Toxic gases I wind from	4.67313E-08	0.38
1211	Toxic gases I wind against, night	2.00277E-08	0.34
1221	Toxic gases I wind along road, night	2.00277E-08	0.27
1231	Toxic gases I wind from, night	2.00277E-08	0.38
1300	Pool fire big	1.96546E-08	1.00
1301	Pool fire big, night	8.42342E-09	1.00
1400	Pool fire small	7.86185E-08	1.00
1401	Pool fire small, night	3.36937E-08	1.00
1500	Class 5 explosion big	5.10265E-09	1.00
1501	Class 5 explosion big, night	2.18685E-09	1.00
1600	Class 5 explosion small	2.04106E-08	1.00
1601	Class 5 explosion small, night	8.74739E-09	1.00

Before the risk can be assessed with the GIS-models, the area of interest and road must be digitalized, and the population needs to be defined. The notation that must be used for the population can be seen in Table C5, how these are used in the calculation of fatalities can be seen in Equation C5-C12. Moreover, the area needs to be calculated. The area is calculated by using the field calculator with the expression "*$area*".

Table C5. Notation and explanation of population.

Notation	Explanation
pop_in	Population inside
pop_out	Population outside
pop_in_n	Population inside on night
pop_out_n	Population outside on night
pop_1_in	Population on first row, inside
pop_1_out	Population on first row, outside
pop_1_in_n	Population on first row, inside and night
pop_1_ou_n	Population on first row, outside and night

The societal risk in the GIS-models are calculated in a similar way in both GIS-model 1 and 2. The structure is that one main model, see Figure C1, creates points along the polyline input (the road) on a specific distance. Then, all the sub-models are run and the result from each of them are merged into one file. Number of fatalities from the merged filed with the results are merged with the output file and on this file the field calculator is used to calculate the frequency of accident in each of the scenarios as in Equation C1.

$$F = F_{accident} \times Wind \times Distance\ between\ points \div 1000 \qquad (C1)$$

The sub-models are structure in a similar way, see Figure C2:

1. Merge with input data

For all scenarios and in both models this first step is the same: the input with the points along line is given a scenario number and the given scenario number is used to merge the input data to get the correct values for the specific scenario.

2. Create impact area

This is the step with biggest difference both between GIS-model 1 and 2 and also within GIS-model 2. The differences in GIS-model 2 are because the impact areas are based on different shapes. However, the common thing with all sub-models is that the function "Geometry with expression" are used. The formulas that are used within "Geometry with expression" can be seen in next chapter, Appendix C.1.

Exp. Maximum spreading for the scenarios with explosives

This step is only included for the scenarios with explosives since these scenarios are based on the background theory to the spreadsheet calculation where it is stated that the first row of buildings protects the buildings behind. Thus, the impact area should be limited by the length of the first row and the buildings width. The solution to this in GIS is to have an input value of average length to area + building width, value "D" in Table C1 and "c" in Table C2. A buffer around the road with the same length as the input value is created in the GIS-model and an intersection between the impact area and this buffer is used to limit the area to this distance from the road. Moreover, a new area is calculated in order to get a new population density in step 5.

3. Intersect with the area of interest

The feature intersect is used to get the overlapping field between impact area and the area of interest. If two or more impact areas are used, the "id" field is updated to know which fields that are impact area 1, 2, 3 and so forth.

4. Calculate the impact area (for those with two or more impact areas)

For the scenarios with two or more impact areas the intersection between impact area and area of interest are merged and the area of the overlapping field are calculated according to Equation C2-C4. The equations are based on maximum five polygons (areas of interest), this could be updated if more polygons need to be used.

Impact area 1:

$$if("id"\ is\ '1', \$area, 0) \qquad (C2)$$

Impact area 2: (C3)

$$case\ when\ "id" = 2\ and\ "id\_2" = 1\ then\ \$area\ -\ sum("IA1", "Distance", "id\_2" = 1)\ else\ ''\ end\ ||\ case\ when\ "id" = 2\ and\ "id\_2" = 2\ then\ \$area\ -\ sum("IA1", "Distance", "id\_2" = 2)\ else\ ''\ end\ ||\ case\ when\ "id" = 2\ and\ "id\_2" = 3\ then\ \$area\ -\ sum("IA1", "Distance", "id\_2" = 3)\ else\ ''\ end\ ||\ case\ when\ "id" = 2\ and\ "id\_2" = 4\ then\ \$area\ -\ sum("IA1", "Distance", "id\_2" = 4)\ else\ ''\ end\ ||\ case\ when\ "id" = 2\ and\ "id\_2" = 5\ then\ \$area\ -\ sum("IA1", "Distance", "id\_2" = 5)\ else\ 0\ end$$

Impact area 3: (C4)

$$case\ when\ "id" = 3\ and\ "id\_2" = 1\ then\ \$area\ -\ sum("IA1" + "IA2", "Distance", "id\_2" = 1)\ else\ ''\ end\ ||\ case\ when\ "id" = 3\ and\ "id\_2" = 2\ then\ \$area\ -\ sum("IA1" + "IA2", "Distance", "id\_2" = 2)\ else\ ''\ end\ ||\ case\ when\ "id" = 3\ and\ "id\_2" = 3\ then\ \$area\ -\ sum("IA1" + "IA2", "Distance", "id\_2" = 3)\ else\ ''\ end\ ||\ case\ when\ "id" = 3\ and\ "id\_2" = 4\ then\ \$area\ -\ sum("IA1" + "IA2", "Distance", "id\_2" = 4)\ else\ ''\ end\ ||\ case\ when\ "id" = 3\ and\ "id\_2" = 5\ then\ \$area\ -\ sum("IA1" + "IA2", "Distance", "id\_2" = 5)\ else\ 0\ end$$

5. Calculate number of fatalities on day and night

The number of fatalities is calculated on each of the impact areas according to equation C5-C12:

If one impact area:

N: $"P\_1\_in" * \$area * "pop\_in"/"Area" + "P\_1\_out" * \$area * "pop\_out"/"Area"$ (C5)

N, night: $"P\_1\_in" * \$area * "pop\_in\_n"/"Area" + "P\_1\_out" * \$area * "pop\_out\_n"/"Area"$ (C6)

If one impact area and scenario with explosives:

N: $"P\_1\_in" * \$area * "pop\_1\_in"/"Area" + "P\_1\_out" * \$area * "pop\_1\_out"/"Area"$(C7)

N, night: $"P\_1\_in" * \$area * "pop\_1\_in\_n"/"Area" + "P\_1\_out" * \$area * "pop\_1\_ou\_n"/"Area"$ (C8)

If two impact areas:

N: $"IA1" * "P\_1\_in" * "pop\_in"/"Area" + "IA1" * "P\_1\_out" * "pop\_out"/"Area" + "IA2" * "P\_2\_in" * "pop\_in"/"Area" + "IA2" * "P\_2\_out" * "pop\_out"/"Area"$(C9)

N, night: $"IA1" * "P\_1\_in" * "pop\_in\_n"/"Area" + "IA1" * "P\_1\_out" * "pop\_out\_n"/"Area" + "IA2" * "P\_2\_in" * "pop\_in\_n"/"Area" + "IA2" * "P\_2\_out" * "pop\_out\_n"/"Area"$ (C10)

If three impact areas:

N: $"IA1" * "P\_1\_in" * "pop\_in"/"Area" + "IA1" * "P\_1\_out" * "pop\_out"/"Area" + "IA2" * "P\_2\_in" * "pop\_in"/"Area" + "IA2" * "P\_2\_out" * "pop\_out"/"Area" + "IA3" * "P\_3\_in" * "pop\_in"/"Area" + "IA3" * "P\_3\_out" * "pop\_out"/"Area"$ (C11)

N,night: $"IA1" * "P\_1\_in" * "pop\_in\_n"/"Area" + "IA1" * "P\_1\_out" * "pop\_out\_n"/"Area" + "IA2" * "P\_2\_in" * "pop\_in\_n"/"Area" + "IA2" * "P\_2\_out" * "pop\_out\_n"/"Area" + "IA3" * "P\_3\_in" * "pop\_in\_n"/"Area" + "IA3" * "P\_3\_out" * "pop\_out\_n"/"Area"$ (C12)

After the fatalities are calculated for each of the impact areas they are summed together according to Equation C13. They are summed based on distance from the start of the road. For example, impact area 1 and 2 on a distance 50 m are summed together.

$sum("N\_area", "distance")$ (C13)

Lastly, the scenario numbers are updated to match the output spreadsheet, Table C1 or C2, in order to merge them together based on attribute in the main model.

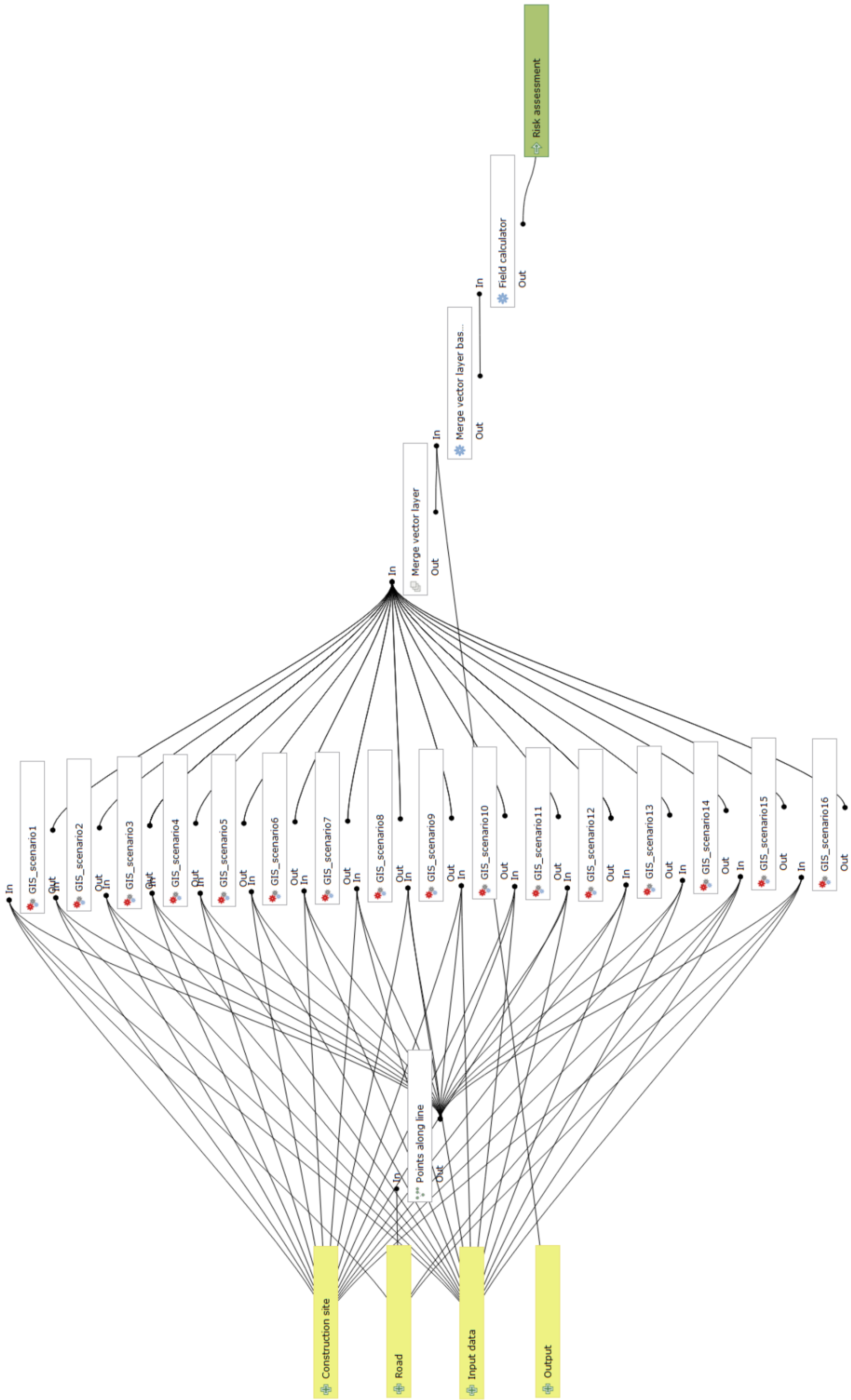


Figure C1. Structure of main model.

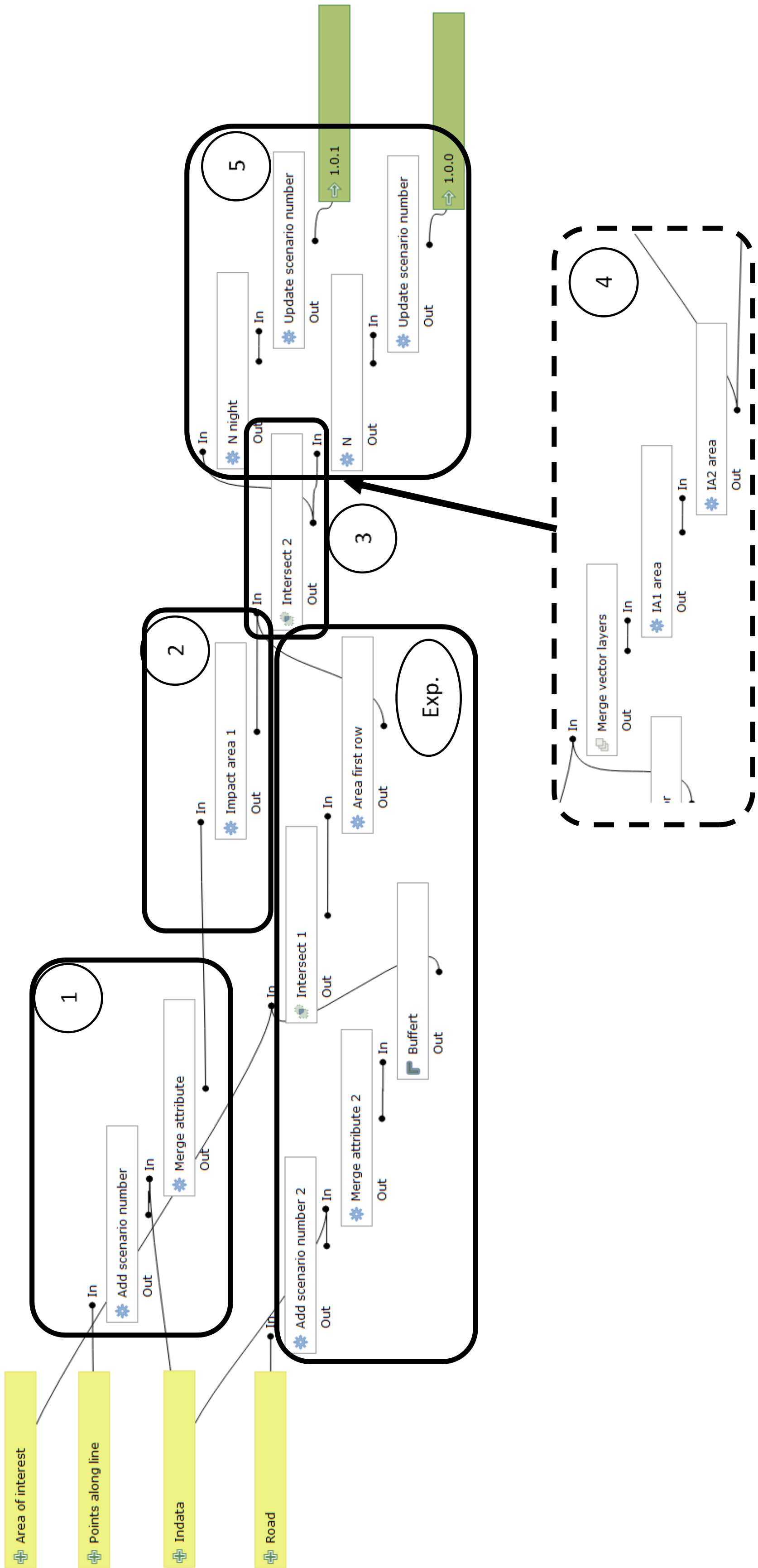


Figure C2. Structure of the sub-models.

C.1 Equations for creating impact areas.

C.1.1 GIS-model 1 (all sub-models)

Impact area 1:

$$make\_polygon(make\_line(make\_point(\$x + sin(radians("angle")) * "length\_1"/2, \$y + cos(radians("angle")) * "length\_1"/2), make\_point(\$x + sin(radians("angle" + 180)) * "length\_1"/2, \$y + cos(radians("angle" + 180)) * "length\_1"/2), make\_point(\$x + sin(radians("angle" + 180)) * "length\_1"/2 + sin(radians("angle" + 90)) * "width\_1", \$y + cos(radians("angle" + 180)) * "length\_1"/2 + cos(radians("angle" + 90)) * "width\_1"), make\_point(\$x + sin(radians("angle")) * "length\_1"/2 + sin(radians("angle" + 90)) * "width\_1", \$y + cos(radians("angle")) * "length\_1"/2 + cos(radians("angle" + 90)) * "width\_1")))$$

Impact area 2:

$$make\_polygon(make\_line(make\_point(\$x + sin(radians("angle")) * "length\_2"/2, \$y + cos(radians("angle")) * "length\_2"/2), make\_point(\$x + sin(radians("angle" + 180)) * "length\_2"/2, \$y + cos(radians("angle" + 180)) * "length\_2"/2), make\_point(\$x + sin(radians("angle" + 180)) * "length\_2"/2 + sin(radians("angle" + 90)) * "width\_2", \$y + cos(radians("angle" + 180)) * "length\_2"/2 + cos(radians("angle" + 90)) * "width\_2"), make\_point(\$x + sin(radians("angle")) * "length\_2"/2 + sin(radians("angle" + 90)) * "width\_2", \$y + cos(radians("angle")) * "length\_2"/2 + cos(radians("angle" + 90)) * "width\_2")))$$

C.1.2 GIS-model 2:

1XX, 15XX and 16XX

$$make\_circle(make\_point(\$x, \$y), "R\_1")$$

2XX, 13XX, 14XX

Impact area 1:

$$make\_ellipse(make\_point(\$x + sin(radians("angle" + 90)) * "c", \$y + cos(radians("angle" + 90)) * "c"), "D\_1", "R\_1", "angle" + 90)$$

Impact area 2:

$$make\_ellipse(make\_point(\$x + sin(radians("angle" + 90)) * "c", \$y + cos(radians("angle" + 90)) * "c"), "D\_2", "R\_2", "angle" + 90)$$

31X

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * "D\_1", \$y + cos(radians("angle" + 90)) * "D\_1"), "R\_1")$$

32X

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * "D\_2", \$y + cos(radians("angle" + 90)) * "D\_2"), "R\_2")$$

33X

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * "D\_3", \$y + cos(radians("angle" + 90)) * "D\_3"), "R\_3")$$

4XX

$$make\_point(\$x + sin(radians(“angle” + 180)) * ”R\_1”/2 + sin(radians(“angle” + 90)) * ”D\_1”, \$y + cos(radians(“angle” + 180)) * ”R\_1”/2 + cos(radians(“angle” + 90)) * ”D\_1”)$$

and

$$make\_point(\$x + sin(radians(“angle”)) * ”R\_1”/2 + sin(radians(“angle” + 90)) * ”D\_1”, \$y + cos(radians(“angle”)) * ”R\_1”/2 + cos(radians(“angle” + 90)) * ”D\_1”)$$

These equations are merged together and the feature “Points to line” followed by “Lines to polygons” are used to get the impact area.

5XX

$$make\_polygon(make\_line(make\_point(\$x + sin(radians("angle")) * "D\_1"/2, \$y + cos(radians("angle")) * "D\_1"/2), make\_point(\$x + sin(radians("angle" + 180)) * "D\_1"/2, \$y + cos(radians("angle" + 180)) * "D\_1"/2), make\_point(\$x + sin(radians("angle" + 180)) * "D\_1"/2 + sin(radians("angle" + 90)) * "R\_1", \$y + cos(radians("angle" + 180)) * "D\_1"/2 + cos(radians("angle" + 90)) * "R\_1"), make\_point(\$x + sin(radians("angle")) * "D\_1"/2 + sin(radians("angle" + 90)) * "R\_1", \$y + cos(radians("angle")) * "D\_1"/2 + cos(radians("angle" + 90)) * "R\_1")))$$

6XX, 8XX, 9XX

Impact area 1:

$$make\_circle(make\_point(\$x, \$y), "R\_1")$$

Impact area 2:

$$make\_circle(make\_point(\$x, \$y), "R\_2")$$

7XX

Impact area 1:

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * "D\_1", \$y + cos(radians("angle" + 90)) * "D\_1"), "R\_1")$$

Impact area 2:

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * "D\_2", \$y + cos(radians("angle" + 90)) * "D\_2"), "R\_2")$$

10XX

Impact area 1:

$$make\_point(\$x + sin(radians("angle" + 180)) * "R\_1"/2 + sin(radians("angle" + 90)) * "D\_1", \$y + cos(radians("angle" + 180)) * "R\_1"/2 + cos(radians("angle" + 90)) * "D\_1")$$

and

$$make\_point(\$x + sin(radians("angle")) * "R\_1"/2 + sin(radians("angle" + 90)) * "D\_1", \$y + cos(radians("angle")) * "R\_1"/2 + cos(radians("angle" + 90)) * "D\_1")$$

Impact area 2:

$$make\_point(\$x + sin(radians("angle" + 180)) * "R\_2"/2 + sin(radians("angle" + 90)) * "D\_2", \$y + cos(radians("angle" + 180)) * "R\_2"/2 + cos(radians("angle" + 90)) * "D\_2")$$

and

$$make\_point(\$x + sin(radians("angle")) * "R\_2"/2 + sin(radians("angle" + 90)) * "D\_2", \$y + cos(radians("angle")) * "R\_2"/2 + cos(radians("angle" + 90)) * "D\_2")$$

Impact area 3:

$$make\_point(\$x + sin(radians("angle" + 180)) * "R\_3"/2 + sin(radians("angle" + 90)) * "D\_3", \$y + cos(radians("angle" + 180)) * "R\_3"/2 + cos(radians("angle" + 90)) * "D\_3")$$

and

$$make\_point(\$x + sin(radians("angle")) * "R\_3"/2 + sin(radians("angle" + 90)) * "D\_3", \$y + cos(radians("angle")) * "R\_3"/2 + cos(radians("angle" + 90)) * "D\_3")$$

For the different impact areas, the equations are merged together and the feature "Points to line" followed by "Lines to polygons" are used to get the impact area.

11XX

Impact area 1:

$$make\_polygon(make\_line(make\_point(\$x + sin(radians("angle")) * "D\_1"/2, \$y + cos(radians("angle")) * "D\_1"/2), make\_point(\$x + sin(radians("angle" + 180)) * "D\_1"/2, \$y + cos(radians("angle" + 180)) * "D\_1"/2), make\_point(\$x + sin(radians("angle" + 180)) * "D\_1"/2 + sin(radians("angle" + 90)) * "R\_1", \$y + cos(radians("angle" + 180)) * "D\_1"/2 + cos(radians("angle" + 90)) * "R\_1"), make\_point(\$x + sin(radians("angle")) * "D\_1"/2 + sin(radians("angle" + 90)) * "R\_1", \$y + cos(radians("angle")) * "D\_1"/2 + cos(radians("angle" + 90)) * "R\_1")))$$

Impact area 2:

$$make\_polygon(make\_line(make\_point(\$x + sin(radians("angle")) * "D\_2"/2, \$y + cos(radians("angle")) * "D\_2"/2), make\_point(\$x + sin(radians("angle" + 180)) * "D\_2"/2, \$y + cos(radians("angle" + 180)) * "D\_2"/2), make\_point(\$x + sin(radians("angle" + 180)) * "D\_2"/2 + sin(radians("angle" + 90)) * "R\_2", \$y + cos(radians("angle" + 180)) * "D\_2"/2 + cos(radians("angle" + 90)) * "R\_2"), make\_point(\$x + sin(radians("angle")) * "D\_2"/2 + sin(radians("angle" + 90)) * "R\_2", \$y + cos(radians("angle")) * "D\_2"/2 + cos(radians("angle" + 90)) * "R\_2")))$$

121X

Impact area 1:

$$make\_circle(make\_point(\$x, \$y), "R\_1")$$

Impact area 2:

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * "D\_2", \$y + cos(radians("angle" + 90)) * "D\_2"), "R\_2")$$

122X

Impact area 1:

$$make\_circle(make\_point(\$x, \$y), ”R\_1”)$$

Impact area 2:

$$make\_circle(make\_point(\$x + sin(radians(“angle” + 90)) * 0, \$y + cos(radians(“angle” + 90)) * 0), ”R\_2”)$$

123X:

Impact area 1:

$$make\_circle(make\_point(\$x, \$y), "R\_1")$$

Impact area 2:

$$make\_circle(make\_point(\$x + sin(radians("angle" + 90)) * -1 * "D\_2", \$y + cos(radians("angle" + 90)) * -1 * "D\_2"), "R\_2")$$

Appendix D – GIS-model, calculation of individual risk

The individual risk is calculated with Equation D1 in both the GIS-models. What differs between them is how w(x) are calculated. In GIS-model 1 the width, w(x), in equation D1 is the length along the road for the different impact areas, "lengt_1" in Table D1. Since the impact area is the shape of a rectangle the individual risk will be the same from the road up to the width, "width_1" in Table D1, of the impact areas from the road into the area of interest.

$$IR(x) = F_{accident} \times wind \times w\,(x) \div share \qquad (D1)$$

In GIS-model 2 most of the shapes were simplified into circles. Since the width is dependent on the distance from the road, x, the individual risk was calculated at a distance of 5 m. For scenario 1XX, 15XX and 16XX the individual risk was limited by a maximum length just like the impact area for societal risk. For scenarios were the centrum of the circle was not on the road the width in the individual risk calculations was limited by a minimum value. Up to the minimum value the width was equal to the diameter of the circle and after the minimum value the width was declining as in a circle. In scenarios 4XX, 5XX, 10XX and 11XX the individual risk was calculated according to rectangles, similar to GIS-model 1. A table with all the radius/width and max/min values can be seen in Table D2. The equation of the width, w(x), in the different scenarios for GIS-model 2 can be seen in Appendix D.1.

Table D1. Example of table for calculation of individual risk in GIS-model 1.

Scenario	Description	F_accident	wind	length_1	width_1	Share
1	Explosives	9.20E-09	1.00	240	80	0.7
2	Jet fire	1.06E-06	1.00	45	74	0.7
3	Cloud fire M	8.52E-08	1.00	185	93	0.7
4	Cloud fire K, wind perpendicular road	1.58E-07	0.28	10	50	0.7
5	Cloud fire K, wind along road	1.58E-07	0.21	50	5	0.7
6	Gas explosion M	5.68E-08	1.00	252	126	0.7
7	Gas explosion K, wind perpendicular road	1.06E-07	0.53	66	66	0.7
8	Gas explosion K, wind along road	1.06E-07	0.21	66	33	0.7
9	BLEVE	5.68E-07	1.00	80	40	0.7
10	Toxic gases K, wind perpendicular road	8.49E-09	0.53	25	135	0.7
11	Toxic gases K, wind along road	8.49E-09	0.21	135	13	0.7
12	Toxic gases M	4.57E-09	1.00	70	35	0.7
13	Pool fire big	3.29E-06	1.00	48	24	0.7
14	Pool fire small	1.32E-05	1.00	25	13	0.7
15	Class 5 explosion big	2.31E-08	1.00	104	80	0.7
16	Class 5 explosion small	9.25E-08	1.00	55	80	0.7

Table D2. Radius/width and max/min values for GIS-model 2. Bold values mean that the values are width and min in respectively column. Max/min value for 100, 1500 and 1600 are based on distance to area of interest (outside) and width on buildings on first row, the rest of the values are fixed.

Scenario	Description	Radius/width	Max/min
100	Explosives	130	80
200	Jet fire	37	**30**
310	Flash fire I wind against	93	**60**
320	Flash fire I wind along road	93	0
330	Flash fire I wind from	93	**-60**
410	Flash fire C wind against	**17**	**50**
520	Flash fire C wind along road	**50**	5
600	Vapor cloud explosion I	126	0
710	Vapor cloud explosion C wind againts	33	**16.5**
820	Vapor cloud explosion C wind along	33	0
900	BLEVE	80	0
1010	Toxic gases C, wind against	**25**	**135**
1120	Toxic gases C, wind along	**135**	**13**
1210	Toxic gases I wind against	60	0
1220	Toxic gases I wind along road	60	0
1230	Toxic gases I wind from	60	0
1300	Pool fire big	24	0
1400	Pool fire small	11	0
1500	Class 5 explosion big	72	80
1600	Class 5 explosion small	57	80

D.1 Equations for w(x) in GIS-model 2

1XX, 15XX, 16XX

$$w(x) = IF(\text{“}max/min\text{”} >= \$x\ ;\ IF(\ \$x <= \text{“}Radius/width\text{”}\ ;\ 2 * sqrt(\text{“}Radius/width\text{”}\hat{}2 - \$x\hat{}2); 0); 0)$$

2XX, 3XX, 6XX, 7XX, 8XX, 9XX

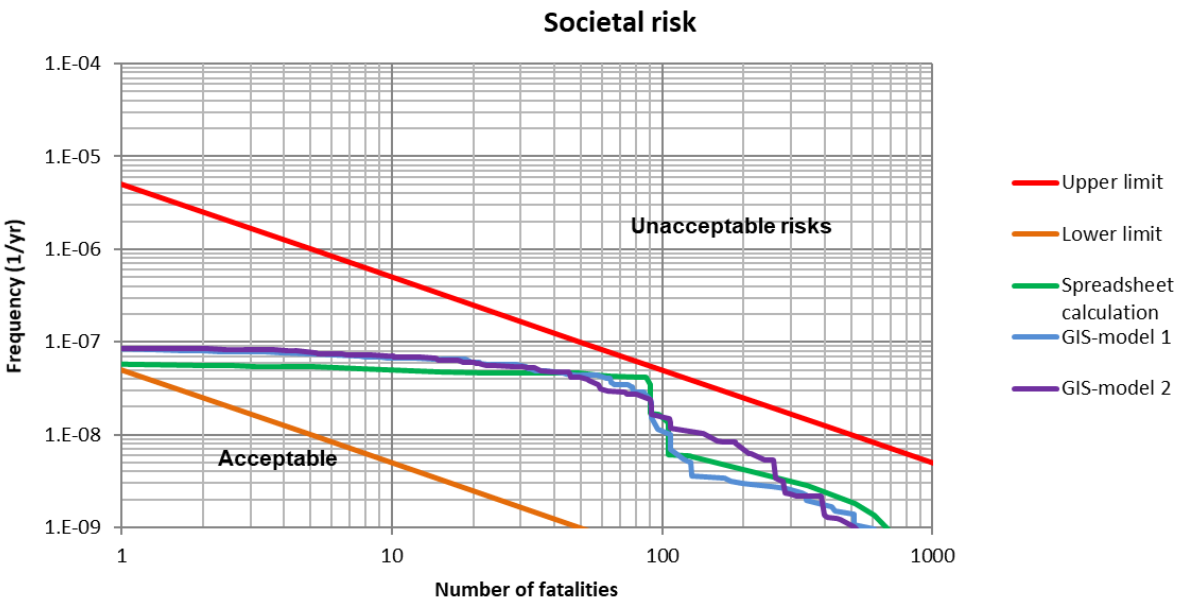
$$w(x) = IF(\$x >= \text{“}max/min\text{”}\ ;\ IF((\$x - \text{“}max/min\text{”}) <= \text{“}Radius/width\text{”}\ ;\ 2 * sqrt(\text{“}Radius/width\text{”}\hat{}2 - (\$x - \text{“}max/min\text{”})\hat{}2\ ;\ 0);\ \text{“}Radius/width\text{”})$$

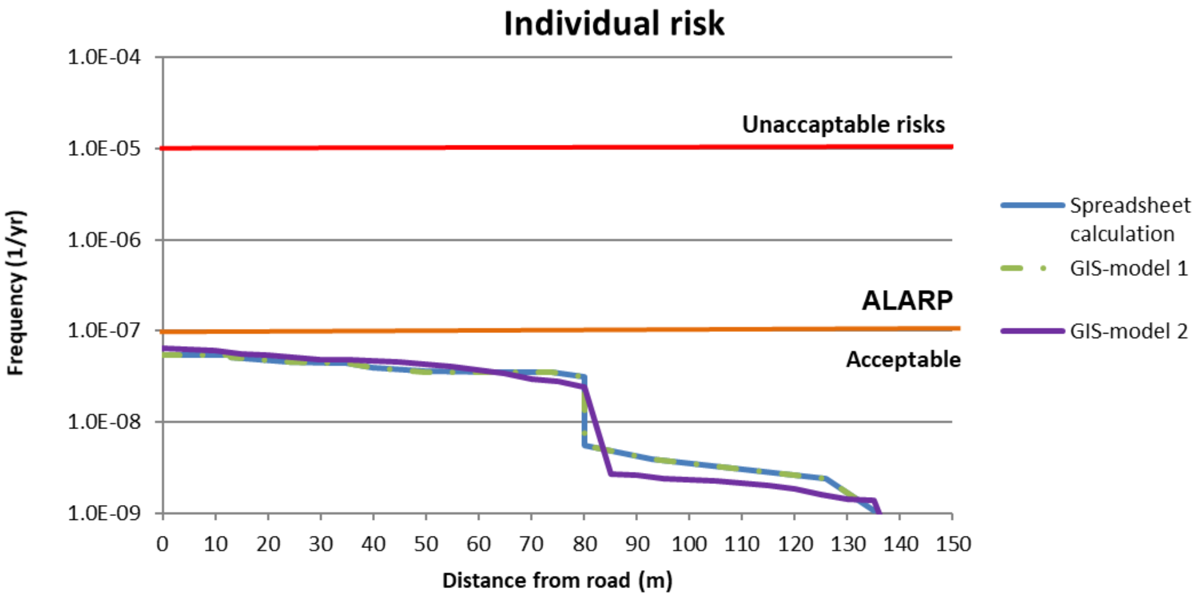
4XX, 5XX, 10XX, 11XX

$$w(x) = IF(\$x <= \text{”}max/min\text{”}\ ;\ \text{”}Radius/with\text{”}\ ;\ 0)$$

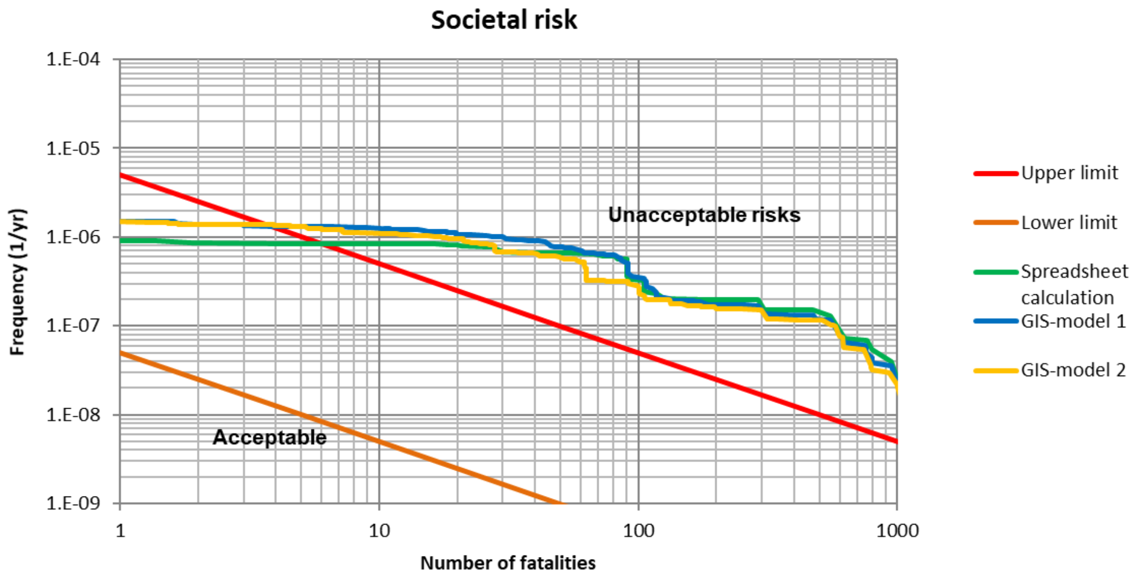
Appendix E – Result validation against spreadsheet calculation

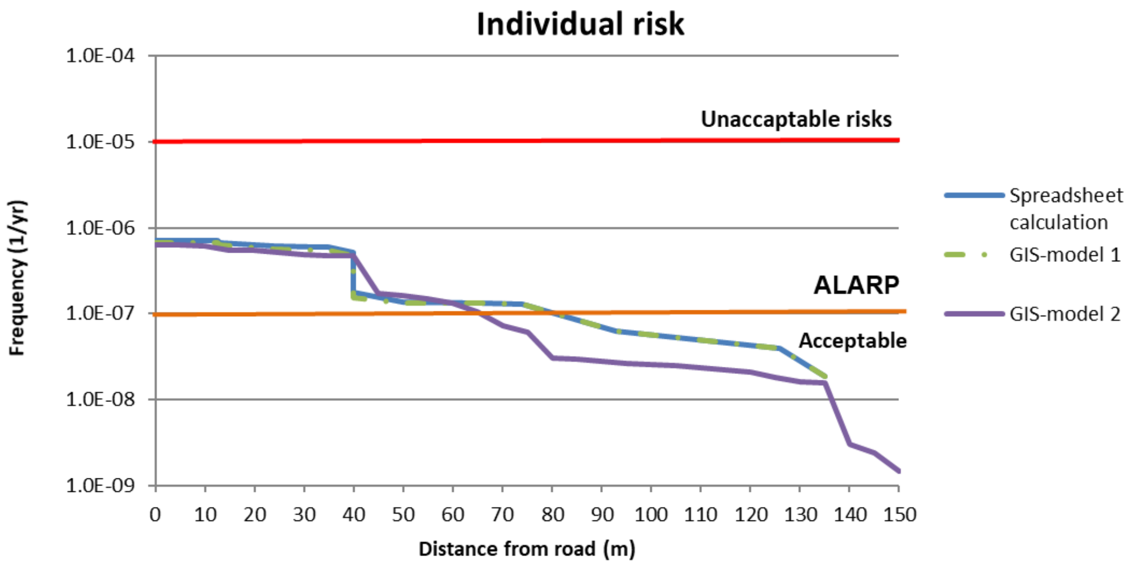
Validation 1





Validation 2





Validation 3