BRANDFORSK
2019:1

Measuring the impact of fire on the environment.
Fire Impact Tool, version 1

Francine Amon, Jonatan Gehandler, Robert McNamee, Margaret McNamee and Azra Vilic

Brandforsk

PROJECT TECHNICAL PANEL

Christina Rönquist, MSB
Lisa Björk, Brandskyddsföreningen
Therese Göras, Skanska
Thomas Hansson, Sundsvalls fire service
Erika Wester, StorStockholm fire service
Froukje Bouius, Södertörns fire service
Helena Grimm, Storgöteborgs fire serive
Claes-Göran Öhman, Restvärdesledare
Morgan Palmquist, Resvärdesledare
Thomas Gell, Brandforsk
Kathleen Almand, NFPA
Birgitte Messerschmidt, NFPA

Keywords
environmental impact, fire modelling, environmental risk assessment, life cycle assessment, firefighting, fire protection, sprinkler systems

RISE Research Institutes of Sweden AB
RISE Report 2019:60
ISBN: 978-91-88907-87-5

This report constitutes a final working manuscript for the headlined project.

The official project report, to which reference should be made, can be found on the RISE's website.

"Measuring the impact of fire on the environment -
Fire Impact Tool, version 1"

www.ri.se

BRANDFORSK 2019:1

Measuring the impact of fire on the environment (Fire Impact Tool, version 1)

Acknowledgements:

The project team would like to thank Brandforsk and the National Fire Protection Association/Fire Protection Research Foundation for their financial support for this work. We would also like to thank each of our respective organisations for providing an extra bit of funding to help us meet the project goals.

In addition to the authors of this report Lotta Vylund, Marcus Runefors, Markus Sandvik, and Andreas Lundkvist were also a part of the project team. Their contributions helped to shape both the Fire Impact tool and the fire protection system environmental analysis and are very much appreciated.

Lastly, we would like to thank the reference group for their enthusiasm, contact networks, and expertise. It was a pleasure working with them and their guidance was extremely helpful.

Key words: environmental impact, fire modelling, environmental risk assessment, life cycle assessment, firefighting, fire protection, sprinkler systems

RISE Research Institutes of Sweden AB

RISE Report 2019:60
ISBN: 978-91-88907-87-5
Borås 2019

Contents

Sammanfattning

Räddningstjänstens agerande vid insatser har både en lokal och en global miljöpåverkan. Dock saknas i mångt och mycket en förståelse för miljökonsekvenserna av olika taktiska val vid aktiva insatser. Programmet ”Fire Impact tool” är utvecklat för att ge räddningstjänsten ett träningsverktyg för att öka förståelsen för konsekvenserna av taktiska val vid fordons- och rumsbränder. Utöver detta har också en utredning kring miljömässiga för- och nackdelar med att introducera ett brandskyddssystem utretts.

Bedömningsverktyget som tagits fram är baserat på ett tidigare verktyg, ”Enveco tool” (Amon et al., 2016a), vilket utvecklades för att bedöma miljö- och ekonomiska konsekvenser av bränder i lagerbyggnader. Det finns tre huvuddelar i programmet Fire Impact tool, brandmodellering, miljöriskanalys (ERA), samt livscykelanalys (LCA). Verktyget innehåller två brandmodeller, en för fordonsbränder samt en för rumsbränder. Skolbränder användes som inspiration för rumsbrandsmodellen där flera rum kan finnas inom en brandcell. När man analyserar de olika bränderna kan användaren definiera två olika scenarier som jämförs med ett referensfall där räddningstjänsten anländer och bara begränsar brandspridningen men inte släcker branden.

Fordonsbranden är baserad på experimentella data från (Lönnermark et al., 2006) där både innehållet i röken och släckvattnet analyserades. Rumsbranden är baserad på ekvationer från (Karlsson and Quintiere, 2000) och en testserie från (Blomqvist et al., 2004b) där röken från experimenten analyserades samt en analys av innehållet i släckvatten från (Wieczorek et al., 2010).

Miljöriskanalysen bedömmer konsekvensen vid spridningen av släckvatten till ytvatten, mark och grundvatten. Inverkan på ytvatten illustreras genom en beräkning av hur mycket spädning som behövs för att späda föroreningarna så att de inte överskrider gränsvärden för ytvatten. Inverkan i mark illustreras av en uppskattning av hur mycket kontaminerad jord som måste tas omhand efter branden. Inverkan på grundvatten representeras av avståndet från föroreningskällan som dricksvatten inte uppnår uppsatta gränsvärden.

I livscykelanalysen analyseras den globala påverkan från branden och räddningstjänstens insats. Den innehåller klimatpåverkan ifrån ersättning av släckmedel, ersättning av byggnader och innehåll i byggnader, destruktion av släckmedel, transporter till branden, utsläpp av rök samt bearbetning av kontaminerad jord.

Rapporten innehåller också en beskrivning av verktyget för två fallstudier, en fordonsbrand och en rumsbrand. I dessa fallstudier studeras skillnaderna mellan olika taktiska val för att illustrera hur verktyget kan användas. Själva verktyget är en del av arbetet och kan fås genom förfrågan hos RISE eller Brandforsk.

I utredningen av brandskyddssystem analyseras införandet av sprinkler i alla skolor i Sverige genom att jämföra miljökostnaderna av alla bränder i skolor med miljökostnaderna för att bygga sprinkler i alla skolor. Jämförelsen görs med CO_2 ekvivalenter. Resultatet redovisas som en funktion av hur mycket brand- och vattenskador som uppkommer samt sprinklersystemets förväntade livslängd. Metoden som använts kan användas för att analysera andra skyddssystem på ett liknande sätt.

Det finns en stor potential för vidareutveckling av verktyget. I kapitlet ”Future work” diskuteras hur precisionen kan förbättras och hur man kan utvidga användningsområdet för verktyget.

Summary

In Sweden the responsibility for damage to the environment when emergency responders are called to an incident is increasingly focussing on the responders. The problem is that most incident response personnel do not have the training and expertise to understand the environmental consequences of their field operations. The Fire Impact tool was developed for training responders to understand the environmental impacts resulting from their actions when responding to vehicle and enclosure fires. In addition to the Fire Impact tool a process was developed in this project by which the environmental advantages and disadvantages of fire protection systems can be analysed.

The Fire Impact tool is based on the Enveco tool (Amon et al., 2016a) which was created to analyse the environmental and economic consequences of warehouse fires. The Fire Impact tool has three interdependent main parts: the fire models, an environmental risk assessment (ERA) model, and a life cycle assessment (LCA) model. There are two fire models, one for vehicle fires and another for enclosure fires. School classrooms were used as a representation of an enclosure fire in which there are multiple rooms that form a single fire compartment. For both the vehicle fires and the enclosure fires the users can create two scenarios that are compared with a reference case in which the responders arrive at the incident and prevent the fire from spreading beyond the vehicle or fire compartment but do not suppress the fire.

The vehicle fire model is based on experimental data from (Lönnermark and Blomqvist, 2006) in which measurements of fire effluents to air and fire water run-off were performed. The enclosure fire model is based on equations from (Karlsson and Quintiere, 2000) and a series of experiments by (Blomqvist et al., 2004b) in which fire effluents from furnished rooms were measured, and an analysis of the contents of extinguishing water from (Wieczorek et al., 2010).

The ERA model uses a method developed by (Leeuwen and Hermens, 2007) to predict the impacts to local surface water, soil, and groundwater. The impact to surface water is presented in terms of the amount of clean water needed to dilute the contaminants of the fire water run-off to a level acceptable for the health of aquatic organisms. The impact to soil is presented in terms of the amount of soil that needs to be excavated to remove the contaminants. The impact to groundwater is presented in terms of the transport distance necessary to degrade the contaminants to a level acceptable for human drinking water.

The LCA model examines the global impacts of the fire response operations that are caused by replacement of suppression media, replacement of building and content materials, treatment of waste suppression media, response travel, smoke, the persistent effects of foam in water, and the treatment of excavated soil.

A detailed description of the Fire Impact tool is provided, along with two case studies, one for vehicle fires and another for enclosure fires. In each of these case studies other alternative outcomes are explored to allow readers to understand how the tool works and how to interpret the results. The tool itself is part of this work and is available from RISE Fire Research or Brandforsk upon request.

The examination of fire protection systems uses the mandatory installation of sprinkler systems in schools as its basis. The study compares the environmental impact of having more frequent and severe fires in schools with the environmental impact of installing sprinkler systems in every school in Sweden. The performance measure is kg of CO_2 equivalents. The results are given as a function of the amount of fire/water damage is acceptable. This methodology can be used to compare other fire protection systems in other target occupancies.

Despite the advances made with the Fire Impact Tool during this project, there is ample room for future improvements. Ideas for improving the accuracy of the tool and the breadth of applicability are discussed in the Future work chapter.

List of Abbreviations and Translations

Abbreviation	Full English name	Full Swedish name
3F	Fluorine Free Foam	
AFFF	Aqueous Film Forming Foam	
AR-3F	Alcohol Resistent Fluorine Free Foam	
AR-AFFF	Alcohol resistant Aqueous Film Forming Foam	
CPA	Civil Protection Act	Lagen om skydd mot olyckor
MSB*	Swedish Civil Contingencies Agency	Myndigheten för Samhällsskydd och Beredskap (MSB)
Swedish EPA	Swedish Environmental Protection Agency	Naturvårdsverket
KemI	Swedish Chemical Inspectorate	Kemikalieverket
FRS	Fire and Rescue Services	Räddningstjänst
ERA	Environmental Risk Assessment	
LCA	Life Cycle Assessment	Livscykelanalys
MKB	Environmental consequences analysis	Miljökonsekvensbeskrivning
PM	Particulate Matter	
POP	Persistent Organic Pollutant	
WTP	Water Treatment Plant	
n/a	County Administrative Board	Länsstyrelsen
n/a	County	Län
n/a	Region	Region/Landsting
n/a	Municipality	Kommun

*Swedish Civil Contingencies Agency uses the acronym MSB in English as well as Swedish.

1. Background

In Sweden, local and national authorities are responsible for responding to accidents or cases where there is imminent danger of accidents, such as fires, and to prevent or limit the damage incurred by people, property or the environment (see Civil Protection Act, CPA SFS2003:778[1]). As our society changes, and as resources become scarcer, these organisations are increasingly compelled to consider which response strategies are most effective, while minimizing the negative consequences on people, property and the environment. Responders and other stakeholders must adapt to fire safety risks that are shifting, e.g. due to the development of new materials, fire protection systems, construction codes and regulations.

One problem faced by the fire and rescue services (FRS) is that most incident response personnel do not have the training and expertise necessary to understand the environmental consequences of firefighting operations. A methodology is needed to help responders understand the potential environmental advantages and disadvantages of decisions regarding which type of response is appropriate to use for a particular fire incident. Improved understanding about whether the environmental damage incurred by a fire will be reduced, remain unchanged, or be increased by fire protection decisions made in response to any given incident, will help authorities, fire protection engineers and builders fulfil their obligations to the Civil Protection Act (CPA).

Fires contribute to contamination of air and possibly also to surface water, groundwater, sediment, and soil in the natural and built environments (Palm et al., 2002, Alaee, 2006, Lönnermark et al., 2007). In previous case studies it was found that replacement of the materials damaged by fire in warehouses had a much higher environmental impact than all other aspects of enclosure fires combined, including the fire service response (Amon et al., 2016b). This result has severe implications for the sustainability of materials used in the construction of buildings as well as the building contents. The impact of responding to fires, including tactics and use or choice of suppression media, can also have a negative effect on the environment (Noiton et al., 2001). The environmental consequences of fighting enclosure fires are related to the fire size, degree of ventilation, and burning contents, which affect the type and amount of contaminants in the fire effluent and residue. Also, the choice of suppression media and how it is applied, contained, and disposed of is a very important factor when considering the environmental impact of fires and their suppression (Kishi and Arai, 2008, Backer et al., 2004, Kärrman et al., 2011, Kärrman et al., 2016).

While much research has been devoted to characterizing the contaminants found in fire effluents (see for example (Blomqvist et al., 2004b, Blomqvist and Simonson McNamee, 2009)), very little work has been done to bring this complex body of knowledge to responsible authorities and responders in a form that enables them to understand the environmental consequences of choices made to protect people and the environment from fires.

The primary goal of this work has been to further advance the work on warehouse fires that was conducted as part of a feasibility study for the National Fire Protection Association (NFPA) (Amon et al., 2016b), and apply it to other types of fires. The expansion of the Enveco-tool developed as part of the previous study, aims to take it from the prototype stage to a level that provides useful information to stakeholders or users about risks to the environment resulting from certain types of fires and the FRS response to these fires. In this updated version, dubbed the Fire Impact Tool, the results can be used to coalesce knowledge gained from case studies to formulate "rules of thumb" for pre-planning and training so that FRS can answer questions about the environmental risks of response operations for fires. For example, when is it best to let the fire burn? What are the environmental trade-offs regarding the type of suppression media used?

---

[1] See https://www.msb.se/en/About-MSB/Legislative-areas/ for more information.

Further, a future sustainable society will benefit from knowledge about the environmental consequences of fire safety choices made in construction or products. Therefore, another goal of this work has been to develop a method of examining the environmental advantages and disadvantages of such fire protection systems. Therefore, a variation of the Fire Impact Tool has been used to investigate the environmental impact of the implementation of sprinkler systems in schools. The findings illustrate the need for a holistic approach to the evaluation of such a change, where the cost of replacement of material in the case of a fire is included, in order to obtain a realistic estimate of the environmental costs.

2. Introduction

When faced with a fire incident, emergency responders must make strategic and tactical decisions quickly to minimize loss of life and damage to property and the environment. As concern for the environment grows, new knowledge is needed to support these decisions. Not only is a large amount of accurate information about the local environment necessary to fully understand the situation, but the responders must be able to interpret the conditions, process the information, and predict the possible outcomes to arrive at the optimal response. While there are map-based support tools available[2] to inform responders of some of the critical conditions in the vicinity of a fire, such as heritage areas or sensitive habitats, these tools are not able to predict the fate and transport of smoke or contaminants from fire water run-off or potential damage to surrounding soil. These mapping tools require dedicated software and licenses for use and have therefore not been included in this version of the Fire Impact Tool.

Responders are also exposed to marketing pressure regarding suppression media. This is particularly evident with firefighting foams and other additives used in water. There are many different recipes for these suppressants, some of which are intended for specific types of fires, and the active ingredients are usually proprietary information. Claims that they are “environmentally friendly” may not be supported by publicly available, scientifically rigorous proof. High quality scientific research has been done concerning some fire suppressants (Kishi and Arai, 2008, Backer et al., 2004, Kärrman et al., 2011, Kärrman et al., 2016), but this research frequently does not reach the responders in a form that they can use.

In particular, the use of foam is of very high interest to the fire and rescue services (FRS). According to a recent recommendation concerning the use of firefighting foam, the application of foam should preferably not be used and if used, it should be collected as far as possible (MSB, 2019). Otherwise, a rescue effort should be planned based on the Environmental Code's precautionary principle, i.e. the best possible method/technique and a balance between the environmental benefit and property utilization, should be implemented.

Even without using additives in fire suppression water, the burning objects can produce toxins and pollutants in the effluents that are harmful to people and the environment. Fire effluents from burning vehicles, enclosures and various contents or furnishings have been characterized by many researchers (Amon et al., 2014). The Swedish Civil Contingencies Agency (MSB, previously the Swedish Rescue Services Agency, SRV) commissioned a large project in which fire effluents to air, soil, and water from large fires were analysed (Blomqvist et al., 2004a). These studies have provided much useful information about species such as polyaromatic hydrocarbons (PAH), flame retardants (FR), volatile organic compounds (VOC), acid gases, halogenated compounds, metals, dioxins and furans, and other toxic compounds that have short- and long-term impacts on the environment.

The behaviour of the fire itself is very uncertain, although most firefighters have a good training foundation in fire dynamics and experience in predicting fire behaviour. Characterizing the environmental toxicity of the fire effluent in terms of fire behaviour, however, is still a subject that remains mostly within the research community.

Given the complexity of predicting the environmental impacts of fire, the Fire Impact tool was developed to provide *a basic structure for training responders about the environmental consequences of fires and firefighting operations*. This tool does not attempt to provide absolute, all-inclusive, perfectly accurate predictions for every possible fire scenario; while this is a valiant goal, it is beyond the time and funding resources available for this work. The value of the Fire

---

[2] See, for example https://www.firstsupporttools.com/, https://www.incidentview.com/, https://medium.com/10-eight/4-ways-integrated-mapping-increases-productivity-for-law-enforcement-and-first-responders-572d6ac4a7db

Impact tool is its ability to create a focal point for discussion of choices made when fighting common fire scenarios, or common fire safety choices that can be made during the design and construction of buildings. This dialogue is expected to foster a holistic systems approach to dealing with similar scenarios in real events.

The tool has been constructed to be easily expanded to include more and higher quality data, as this becomes available. For example, the tool can be expanded to include electric vehicle fires when sufficient data are collected, or it can include new firefighting tactics, such as high-pressure water mist, as they come into use. In short, this tool is not a final solution. It is a framework into which increasingly improved information (both in breadth and depth) can be added over time to keep the tool current, strengthening the bridge between the scientific research and emergency responder communities, and thereby help emergency responders better understand how fire and firefighting operations impact the environment.

There are several key factors to consider when developing a training and pre-planning tool that can estimate the environmental impacts of fires. For example, who would be the users of the tool? What are their needs and expectations? Which types of fires should be included? Can results from these fires be applied to other types of fires? What is the optimal way to describe the growth, spread, and effluents of the fires? What is/are the best method(s) to quantify the environmental impacts? What are the limitations of this methodology? What is the best design format for the tool? How should the tool be implemented? What can be done, here and now, to maximize the value of the tool, and what could be done in the future?

Answers to some of these questions, dealing with the Fire Impact tool in an overall sense, are given in the following sections. Answers to the questions that apply to specific parts of the tool are included in the relevant chapters and form the basic structure of this report as shown in Figure 1. The fire models and environmental impact models that are the principal components of the Fire Impact tool are presented as separate entities in Chapter 3. A description of the tool and case studies showing how it can be used are provided in Chapters 4 and 5, respectively. The analysis of fire protections systems (mandatory sprinkler systems in schools) is presented as a parallel study in Chapter 6. Ideas for future work on the Fire Impact tool as well as the analysis of fire protection systems is are given in Chapter 7. A summary of the conclusions and important points of each major part of the project is presented in Chapter 8.

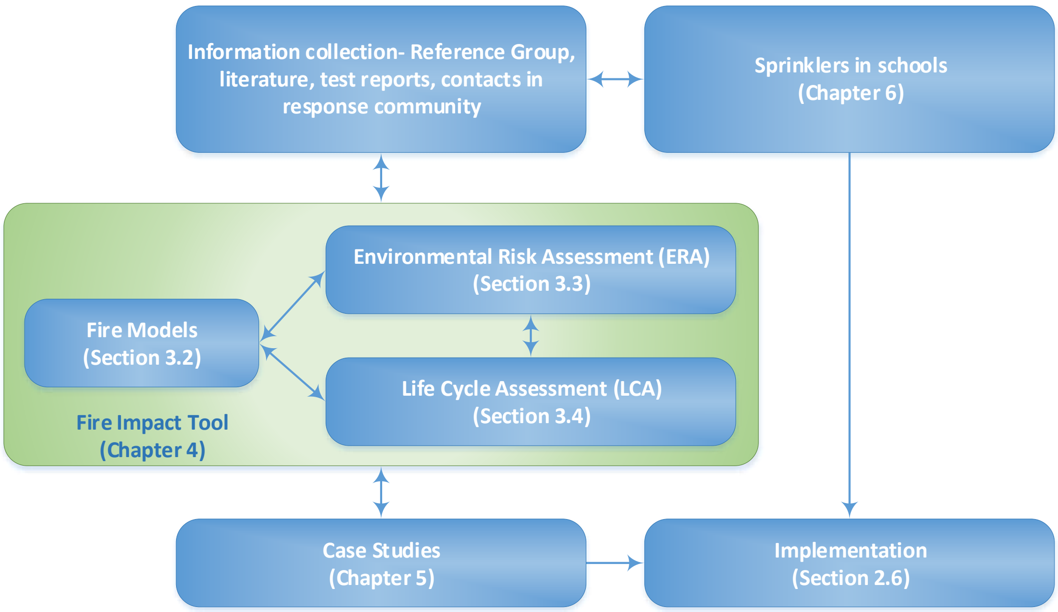

Figure 1: Schematic structure of this work.

2.1. Users of the Fire Impact tool

The intended users of the Fire Impact tool are those who respond to fires and have responsibility or provide advice or training to those with the responsibility, to make decisions concerning firefighting tactics that can affect the environment. This includes firefighters and environmental officers from the fire and rescue services (FRS), and it also includes people involved in firefighter training and pre-planning activities. There are other stakeholders that could benefit from access to the tool, e.g. environmental professionals, regional planners, policy makers, insurance companies, and authorities such as the Swedish Civil Contingencies Agency (MSB), the Swedish Environmental Protection Agency (Swedish EPA), and the Swedish Chemical Inspectorate (KemI).

The Fire Impact tool is not meant for use at a fire incident during an on-going event. It is expected that the emergency services will use the tool for training and pre-planning purposes, and that other stakeholders might use it for planning and educational purposes. As the tool is further developed, it could become increasingly useful to a larger array of users.

2.2. Types of fires

This project has been limited to the implementation of a small number of representative fire scenarios[3]. The initial fire scenario that was implemented was a vehicle fire. Vehicle fires were chosen because they are rather common and simple to deal with compared to enclosure fires, they can happen nearly anywhere, and they are generally a well-defined fire event. By addressing vehicle fires first, the consensus was that expanding the tool to include enclosure fires later would not be as difficult and time consuming as other possible strategies.

An enclosure fire scenario was adopted as the second representative scenario. An important factor to consider when deciding the type of enclosure fire, was how the regulations for fire protection in buildings affect the spread of fire. For example, in an apartment building, each apartment is a separate fire compartment and the spread of fire beyond the apartment will be influenced by the fire protection system, not only the actions of the firefighters. Another important factor is the standard operating procedure for saving lives first. The rescue service will always attempt to save lives if people are in danger and will use whatever means necessary to do so in the most effective manner. In such cases, there is (rightly) no room to debate about saving property or the environment.

The type of enclosure fire chosen as the second scenario was a school fire as school fires are relatively common events in Sweden. Therefore, there is documentation available that describes some such fires and some research is available concerning fires loads and emissions. A single fire compartment that encompasses four classrooms was chosen. This arrangement provides flexibility for users to explore the potential for fire spread between classrooms and the environmental consequences of enclosure fires, assuming that there is no danger to people. This should not be interpreted to mean that a fire compartment in a school in Sweden always contains four classrooms. The size of the fire compartments in schools varies and can include both fewer and more classrooms. This scenario was also chosen as it is easily generalized to other enclosure fires.

[3] The fire scenarios implemented in this version of the Fire Impact Tool were identified and selected by the project team together with the Reference Group (RG) that was assembled to provide guidance for this work. The RG was comprised of representatives from active fire and rescue services, MSB, an insurance company, Brandforsk, NFPA and fire consultants.

2.3. Fire models

Two simple, time-resolved fire models that predict the amount and composition of smoke and contaminants in fire water run-off were developed for the Fire Impact tool, to represent the chosen fire scenarios. The user can create two independent fire and response scenarios for comparison, which are compared against a reference case in which the fire service arrives at the incident and prevents the fire from spreading beyond the vehicle or fire compartments, but otherwise does nothing to suppress the fire.

The fire model used for the classroom fires allows users to input information about the classrooms (geometry, openings, fire load), the fire behaviour (start and end of fully developed phase), and the suppression operations used for each room. Both the vehicle fire model and the enclosure fire model have been based on data from the literature. The details of both fire models are discussed in the next chapter.

2.4. Environmental impact models

The environmental impacts of fires are caused by transport of toxic (to people) or eco-toxic (to ecology) fire effluents to local sensitive receptors, or to the world in general. For example, the fire water run-off from a vehicle fire could be transported to local surface water that is the habitat of many kinds of plants and animals that could suffer from exposure to it, depending on the concentration and type of contaminants. A well-established method for estimating the local impacts of the transport and fate of contaminants in a specific environment is Environmental (or Ecological) Risk Assessment (ERA). Time and local geology, as related to biological degradation or flow of contaminants, are important parameters within the ERA.

Not all the impacts of fire on the environment can be predicted using an ERA. Impacts that are not related directly to the local environment, such as replacement of damaged materials and fire suppressants, are better suited to a Life Cycle Assessment (LCA) methodology for analysis. LCA is typically used to evaluate the potential environmental impacts of a product, process, or activity (usually referred to as a system). It is a comprehensive method for assessing impacts across the full life cycle of a system, from materials acquisition through manufacturing, use, and end of life. A formal procedure for conducting an LCA has been standardized by the International Organization for Standardization (ISO) in ISO 14040 and ISO 14044 (Standardization, 2006a, Standardization, 2006b). In general, LCA-based environmental impact methods can be used to assess a wide range of environmental impact categories, for example: global warning, eutrophication[4], resource depletion, ecotoxicity of soil and water bodies, depending on which impact assessment method is considered important for the goals of the LCA.

These two impact models, ERA and LCA, are used in a complementary way in the Fire Impact tool. The Enveco tool (Amon et al., 2016a), on which the Fire Impact tool is based, was developed for warehouse fires. The assumptions used for the Enveco tool precluded a need to address impacts to the local environment, but these assumptions do not hold for vehicle and enclosure fires in this present application, which is why the ERA model was added to the Fire Impact tool.

Details of the ERA and LCA models are found in the next chapter.

2.5. Limitations and assumptions

Given the dearth of data concerning emissions from real fires and their actual environmental impact, it is virtually impossible to validate the tool. Some comparison has been made to two

[4] Eutrophication refers to the oversupply of nutrients, most commonly nitrogen or phosphorus, which leads to overgrowth of plants and algae in aquatic ecosystems. Eutrophication can cause organisms die, bacterial degradation of their biomass results in oxygen consumption, thereby creating the state of oxygen depletion in the system.

Case studies, but the results should be read with care. Further, as the time scales of the ERA and LCA are fundamentally different, the results from the two models should be considered separately and cannot be directly compared. Specific limitations and assumptions used for each of the major tool components are listed and discussed in detail in their respective sections of Chapter 3.

2.6. Description of tool interfaces

The use of the Fire Impact tool is described in Chapter 4 and several case studies are examined using the tool in Chapter 5. These descriptions include all the parts of the tool that the user can see and interact with. There are locked or hidden parts of the tool that are used for calculations for the fire models, the ERA and the LCA. The methodology behind these calculations and the rationale behind their restricted use is discussed in their respective sections in Chapter 3.

2.7. Implementation

The Fire Impact tool has been implemented through the project Reference Group via their networks and through Brandforsk and the NFPA. At the time of writing this report the tool is available in English. A Swedish explanation will be added, together with the Swedish summary of this report. Additionally, descriptions of various aspects of the tool have been (or will be) published or presented at seminars, conferences, in Brandposten and other publications.

2.8. Future work

The work presented in this report is an extension of that which began as the Enveco tool (Amon et al., 2016a). The Fire Impact Tool provides a proof-of-concept of the ability to study tactical choices associated with fire and rescue service response to a vehicle fire or an enclosure fire (exemplified as a school). The ability to compare fire safety choices made during building design is also exemplified. The application is not universal and there are numerous potential openings for future work to improve and extend the present version of the Fire Impact Tool. Many ideas about future improvements to the tool surfaced during its development. These ideas are presented in Chapter 7.

3. Methodology

3.1. Introduction

The foundation of the Fire Impact tool is comprised of three components: the fire models, the environmental risk assessment (ERA) and the life cycle assessment (LCA).

The general idea behind the Fire Impact tool stems from the Enveco tool, although several major improvements were made to expand its functionality. The Enveco tool was designed to apply to warehouse fires, in which it was reasonable to make these simplifying assumptions:

- Human life is not threatened so there is no reason to enter the warehouse
- The fire could spread through holes in the roof
- The firefighting strategy is to prevent the fire from spreading beyond the original warehouse (defensive strategy), so the entire fire compartment of the original warehouse is lost
- The warehouse is situated in an industrial area with a dedicated drainage collection system
- The environmental impacts were limited to smoke, replacement of warehouse contents and structural materials, and fire service transit to/from the incident

The assumption that human life is not threatened has also been adopted in the Fire Impact tool. Further, fire spread beyond the vehicle or the fire compartment is not currently a possibility. Expanding the tool to apply to vehicles and (non-warehouse) enclosures removes the limitation of using a defensive firefighting strategy. In fact, one of the goals of the Fire Impact tool is to allow responders to compare the environmental consequences of a variety of possible firefighting operations. This has led to an important improvement: the Fire Impact tool uses ERA modelling to predict environmental impacts to the local surroundings from fire water run-off. Impacts that are not directly tied to the local environment are modelled using LCA, as was done with the Enveco tool.

Another major improvement for the Fire Impact tool is the use of fire models, which were not necessary given the defensive firefighting strategy assumed in the Enveco tool warehouse fires. The fire models (one for vehicle fires and one for enclosure fires) provide fire effluent data to the environmental impact models and describe the fire behaviour as it relates to suppression operations.

The environmental impacts from vehicle and enclosure fires can affect local receptors, such as organisms living in or around nearby surface water and soil. They can also negatively affect groundwater and thus the human drinking water supply. These impacts might have a temporal component, such as soil contamination, in which the volume of soil to be remediated depends on the speed of contaminant transport through the soil. ERA is used to capture the impacts of fire on the environment immediately surrounding the incident site. LCA is an accepted method of predicting impacts that are not as closely tied to the vicinity of the fire incident, such as the impacts associated with replacing materials that were consumed in the fire. LCA results can be applied globally, and in some cases regionally or nationally, but the LCA methodology is not intended to apply to a specific place such as the location of a vehicle or enclosure fire. Further, LCA results are not temporal. In Figure 2 the division of environmental impacts between ERA and LCA, as treated in the Fire Impact tool, is shown.

One contaminant fate that was not addressed in the tool is the local impacts of smoke. This is a topic of concern to the responder community. Smoke can enter homes and hospitals through windows and can be deposited on surfaces where vulnerable receptors such as the infirmed, elderly, or young people are exposed to them. A method for including the local effects of smoke is among the suggestions for future improvements to the tool.

The effects of foam in fire water run-off are handled using both ERA, for acute effects, and LCA, for persistent effects. Indefinitely persistent substances are difficult to handle in ERA because there is no limit value for them. In other words, these substances cannot be diluted or degraded to acceptable values. The LCA method allows comparisons to be made for persistent organic pollutants (POP) but does not consider their effects on the local environment. Therefore, the results from the ERA and the LCA are largely complementary.

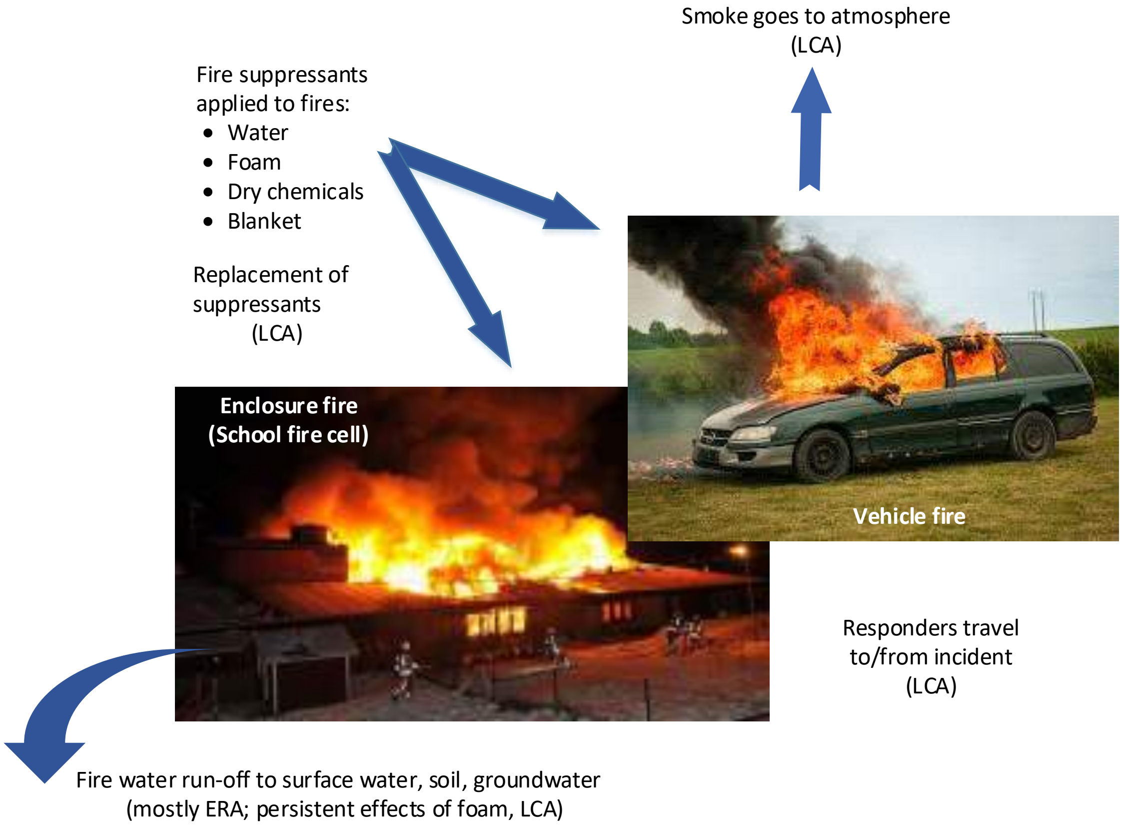

Figure 2: Division of environmental impacts between ERA and LCA models.

3.2. Fire scenarios and models for contamination of extinguishing water

Two basic fire scenarios have been included in the Fire Impact tool: a vehicle fire scenario, and a building fire scenario representing a fire in an enclosure with four sections. The focus of the vehicle fire scenario was on internal combustion engine vehicles due to the availability of data. Future applications of the model might be extended to include electric or hybrid vehicles. The enclosure fire scenario has been developed to be representative for a school where a fire compartment can include four classrooms, although it can be applied to represent other similar enclosure geometries. Note that the selection of four classrooms in the enclosure fire scenario does not imply that this is always the case in Sweden. An enclosure can contain both more or less rooms depending on the size, use and geometry according to the Swedish Building regulations (BBR).

3.2.1 Vehicle fire scenario and model for contamination of extinguishing water

The experimental data was used as a basis for developing models of emissions to air, soil and water from burning cars and was used by permission of Lönnermark and Blomqvist. This data has been presented by them previously (Lönnermark and Blomqvist, 2006), and full details of the experimental set-up are contained there. The vehicle used in the experiments was a medium class model from 1998. It was considered representative in terms of materials and size for that found in an average modern vehicle. For safety reasons, the petrol tank had been emptied, the battery, air bags, belt actuators and the hood dampers had all been removed.

The car was placed in a concrete pool, which was used to collect extinguishing water for analysis. The pool was positioned under the large fire calorimeter at RISE – Research Institutes of Sweden's fire safety facility in Borås, to allow the collection of time resolved heat release data and emissions to the air. The experiment was extinguished using water after the maximum HRR had been passed. Run-off water was collected and analysis of fire emissions to water conducted. Therefore, time resolved data was available for emissions to air while non-time resolved data was available for emissions to water. Assumptions have been made concerning emissions to the soil as described in the next section.

The experiment on the car was conducted in stages. The data used to model emissions from fires with and without fire service intervention, is comprised of measurements from the point of "ignition coupé fire 2" in Lönnermark and Blomqvist (2006). Figure 3 shows the heat release rate that was used as the basis for estimation of the environmental emissions where data prior to that point has been eliminated. As shown, there is an intervention in the original test but as this is on the descending branch of HRR, this curve was used as a reference for "no invention". This means the emissions for the "let it burn" scenario are slightly underestimated. The choice to leave the experimental data as collected was to reduce the uncertainty that would have been caused by arbitrary implementation of fire decline behaviour. This is in line with the deliberate choice to keep the models as simple and transparent as possible.

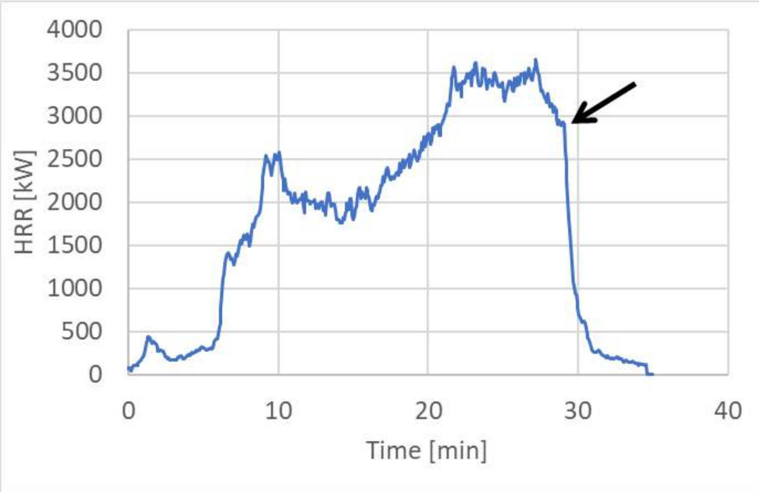

Figure 3: Heat Release Rate (HRR) as a function of time. The arrow denotes the point of extinguishment (with water) in the original experiments.

Emissions to air

Time resolved data for the car fire presented in Lönnermark and Blomqvist was available for HRR, CO_2, CO, HCN, HCl and SO_2. As a first step, all contaminant data was normalised relative to its integral and compared to ensure that the time resolved data had comparable evolution over the period of the experiment, see Figure 4. Note that CO, HCN, HCl and SO_2 all have a peak at approximately 18-20 minutes and then decrease substantially before intervention at 29 minutes. Due to this species evolution, it is expected that the underestimation of the species emissions in the "let it burn" scenario is minor. As can be seen in the figure, there appears to be a small time difference between the FTIR (emissions) data and the HRR data. No correction has been made for this discrepancy.

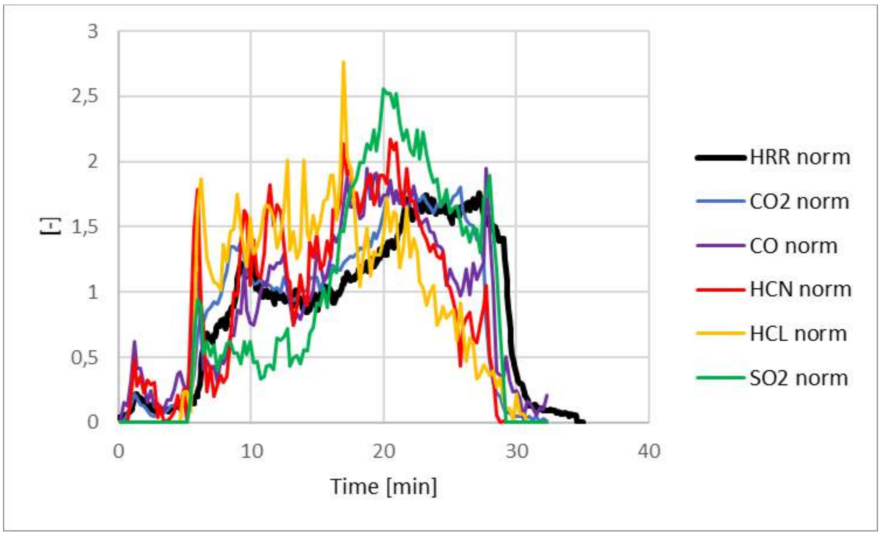

Figure 4: Normalised time resolved data for species emissions to air.

Given that the time resolved data covered essentially the same time period, it was assumed that emissions to air could be calculated by truncating the individual curves at the time of intervention using a linear decline for the period of intervention. The Fire Impact Tool allows the fire service users to choose time of intervention as the model parameters for emissions. Figure 5 contains an example of results for an intervention beginning 10 minutes after ignition, with default knock-down time of 5 minutes until the vehicle is extinguished.

Using this methodology, emissions to air were calculated as the area under the time resolved emission curve.

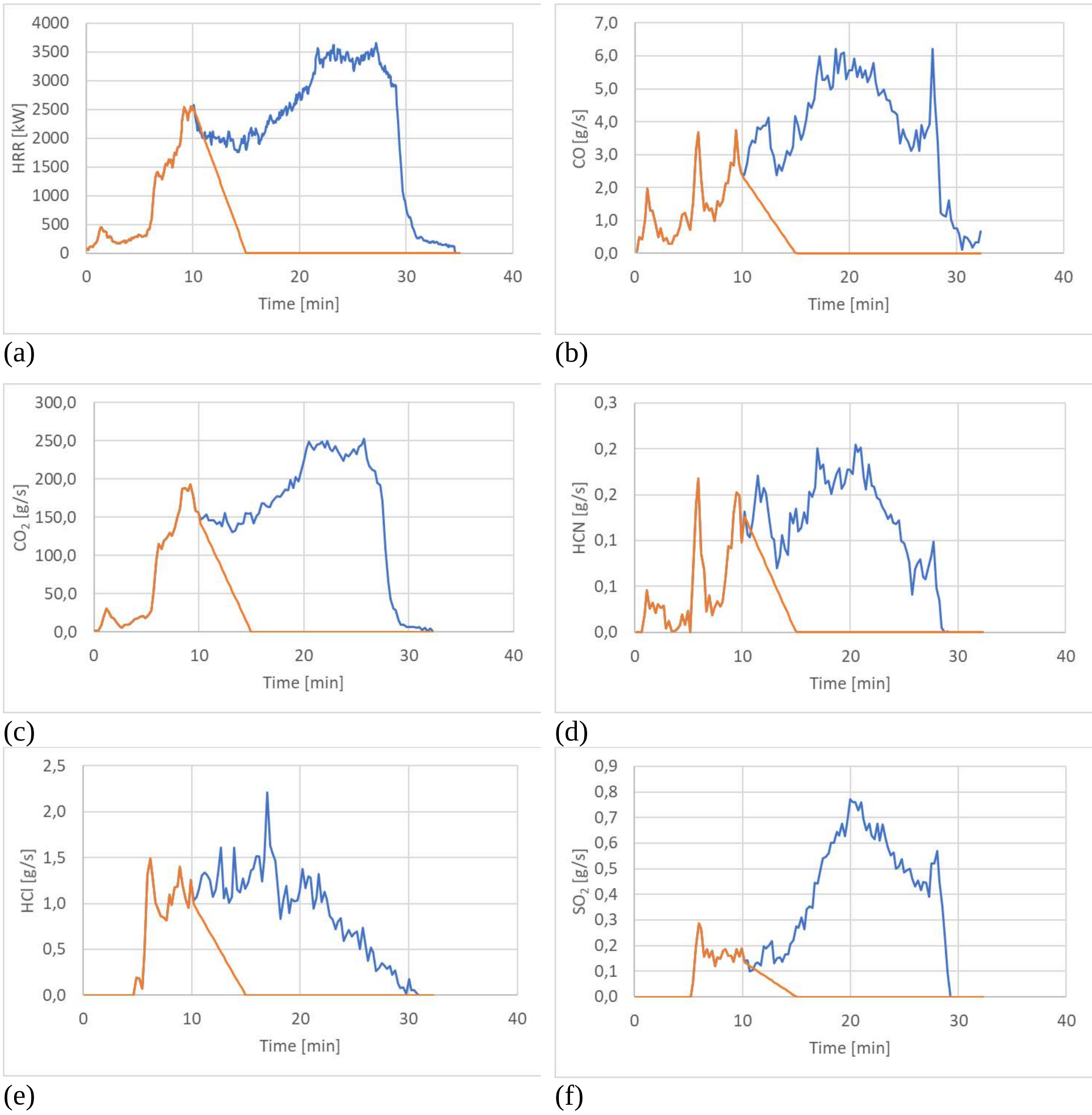

Figure 5: Car fire with and without intervention. This example assumes 10 minutes from ignition to intervention, 5 minutes from intervention to extinguishment. The panels correspond to the following data: (a) HRR, (b) CO, (c) CO_2, (d) HCN, (e) HCl, (f) SO_2.

Emissions to water

Lönnermark and Blomqvist (2006) measured emissions to run-off water from the point of extinguishment of their vehicle (see arrow in Figure 3), at approximately 29 minutes. It was estimated that 200 litres of water were applied in the test, although only 105 litres were collected. According to Lönnermark and Blomqvist (2006) some of the extinguishment water was vaporised and some fell outside the collection area which explains the difference between the amount applied and that collected. The water was applied for a very short period of time and it can be assumed that the run-off water contains both quenched fire species and components of soot washed off surfaces in the burning vehicle.

The tabulated run-off water species summarised in Lönnermark and Blomqvist, were used as the starting point for estimation of the run-off water for the scenario model. This means that the data was scaled relative to the HRR at the point of extinguishment in the actual experiments. In the case presented in Figure 5, the HRR at the point of intervention (10 minutes) was 87% of that at the point of intervention in the actual experiments. Therefore, the emissions in the run-off water were scaled by 0.87 compared to the actual experimental values. This was assumed to be a reasonable approximation to ensure that early extinguishment translates into lower emissions to water.

The emissions to water were used in both the LCA and ERA aspects of the Fire Impact tool. To facilitate this analysis, the fire service can choose to define how much water is used to extinguish the fire (0 litres is an option), what type of additive is used (to be selected from a short list of options, no additive is also an option), whether a hand-held extinguisher is used, whether a blanket is used, whether the water is sent to a municipal treatment facility, is released to the environment (a body of water or soil), or collected and destroyed.

Emissions to soil

It was assumed that unless the run-off water was collected, the contaminants in the water would eventually become available to the soil. The Fire Impact tool calculates the impact on the local environment for three different types of soil. The risk for contamination is based on calculations using transport models recommended by the Swedish EPA (Berggren Kleja et al., 2006, Naturvårdsverket, 2009, Naturvårdsverket, 2016). More details can be found in the next section on the Environmental Risk Assessment (ERA).

3.2.2 Enclosure fire scenario and model for contamination of extinguishing water

In the Fire Impact tool, the enclosure fire scenario is divided into four separate rooms, as illustrated in Figure 6. In the model each room is independent of the other rooms. The following parameters can be input by the user for each room: size of room and openings in the room, fuel load, start and end of fully developed fire (although the fire will stop before the user-defined end time if all available fuel has been consumed), whether active suppression is used and what volume of water has been applied. With this approach the environmental consequences of different tactical choices can be compared theoretically.

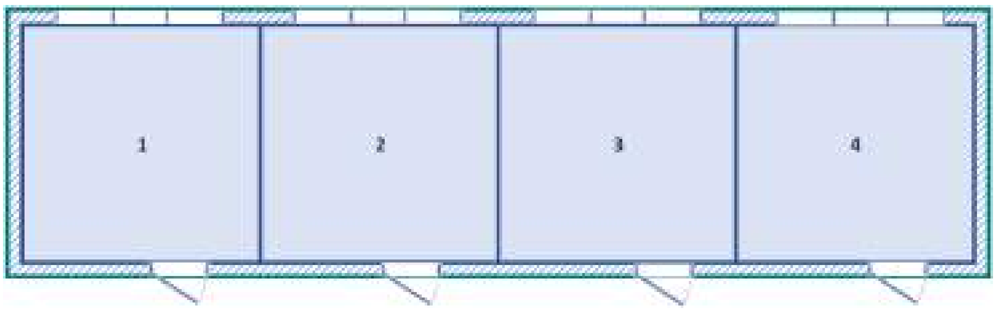

Figure 6: Enclosure fire scenario with four independent roles. Each room can have independent input values.

In Table 1, the input parameters for defining the fire scenario are shown. To keep the model simple in this first edition of the tool, only fully developed ventilation-controlled fires are included in the model. The structure with its prescribed openings is assumed to remain intact through the whole fire scenario, although it is considered to be damaged and in need of replacement with respect to the impact of the fire on the environment.

If the option active suppression is selected, a module for estimating the contamination of extinguishing water is activated.

Table 1: Input parameters for defining the enclosure fire scenario. In this case, room one is not actively extinguished.

Fire Compartment Model Input					**Defaults**
Room number	1	2	3	4	
Opening average height dimension [m]	1.2	1.2	1.2	1.2	1.2
Opening area [m^2]	10	10	10	10	10
Room size [m^2]	60	60	60	60	60
Fuel load [MJ/m^2]*	450	450	450	450	250 - 450
Comparison scenario 1:					
Start of full developed fire [min]	5	30	60	5	5
End of full developed fire [min]	5	40	100	120	30
Active suppression used? (Select No if start time<=end time)	No	Yes	Yes	Yes	Yes
Comparison scenario 2:					
Start of full developed fire [min]	5	30	0	0	5
End of full developed fire [min]	30	40	0	0	30
Active suppression used? (Select No if start time<=end time)	Yes	Yes	No	No	Yes
*Note that the fire will burn out when the fuel load is consumed					

In this application of the model, the heat release rate in the fire model is based on the ventilation factor, assuming that all available oxygen is used for combustion following the formulation (Karlsson and Quintiere, 2000):

$$HRR = 1.518 * A_0\sqrt{H_0} \tag{1}$$

Where *HRR* is the heat release rate [MW], A_0 is the opening area [m^2], and H_0 is the average opening height [m].

In fully developed fires, some part of the fire gases also typically burn outside the apartment, giving external flames. This factor is usually characterized by the fuel excess factor giving the ratio between what is burning inside and what is burning outside the enclosure. This factor is included in the tool but to keep the tool simple for the user in the first edition it is set to 1 as a default and hidden. Future versions of the tool could include this factor as a user option.

Using the given ventilation factor, a time stepping procedure is included in EXCEL to calculate how much energy is released from the fire. If the user prescribes a fuel load that is too low to maintain the fire for the time prescribed, the fire will stop burning when the fuel is consumed. No extra additional energy from combustion of the structure or installations is added in the model, so the fuel load inserted by the user is the total fuel load used in the model.

The air pollution in the smoke in the model is from an experimental study performed at RISE (Blomqvist et al., 2004b). In this study, three tests were performed with furnished rooms of size 4 x 4 x 2.5 m^3 with an opening of height 2 m and width 1.2 m. The contents in the rooms are shown in Table 2.

Table 2: Contents of the rooms in the reference scenario for smoke emission from a room fire (Blomqvist et al., 2004b) .

Item	***#***	***Weight [kg]***	***Main combustible material***
Sofa	1	72	Wood, PUR, cotton
Armchair	2	19 X 2 = 38	Wood, leather, filling
Corner bookshelf	1	52	Particleboard, veneer
Bookshelf	3	30 X 3 = 90	Particleboard, veneer
Coffee table	1	26	Wood
Carpet	2 x 2 m	Approx. 20	Wood, synthetic
Curtains	10 m	5	Cotton
Books Exp 1	-	219	Paper
Books Exp 2	-	216	Paper
Books Exp 3	-	No data	Paper
EU TV, Exp 1 and 3	1	31.4	Polystyrene
US TV, Exp 2	1	33.6	Polystyrene with flame retardants

During the experiments, the concentration of the following species was analysed in the combustion gases:

- Inorganic combustion products including CO_2, CO, HBr, HCl, HCN, NO_x and Sb
- Small to medium sized hydrocarbon species (VOC), including e.g. styrene, benzene, etc.
- Polycyclic aromatic hydrocarbons (PAH)
- Polychlorinated dibenzodioxins/furans (PCDD, PCDF)
- Polybrominated dibenzodioxins/furans (PBDD, PBDF)
- Survival fractions of the brominated flame retardant compounds deca-BDE and TBBP-A.

The amount of the air emissions used in the model is based on the average from the three experiments and is directly scaled with the total energy of the fire, i.e. if the energy in the tool is twice the energy of the experiment it is assumed to release twice as much pollutants as in the experiments.

If the option of active suppression is selected, the amount of different species in the water is based on an experimental study performed at FM Global (Wieczorek et al., 2010, Wieczorek et al., 2011). In this study, two fire scenarios were investigated. One scenario where the fire was kept under control by a sprinkler system, and one scenario without sprinklers. Both fires were extinguished by firefighters after 10.5 minutes. In this model, the contaminated water from the non-sprinkler scenario was used as a reference.

The size of the room in the experiments was 4.6 x 6.1 x 2.4 m^3 with an opening of 1.2 x 2 m^2. The room also had four windows and an exterior door, with a window that was closed during the start of the fire. The size of the windows was 0.9 x 1.47 m^2 and the window in the exterior door was 0.51 x 0.9 m^2. All the windows fell out between 4 and 6 minutes from the ignition of the fire. The main combustible content in the room is shown in Table 3.

Table 3: Contents of the rooms in the reference scenario for contamination of extinguishment water.

Item	***Weight [kg]***	***Main combustible material***
Recliner	44.5	Urethane foam, wood frame
Sofa	69.9	Polyuethane foam, wood frame
Loveseat	56.9	Polyuethane foam, wood frame
Coffee table	15.1	Rubberwood
Console table	15.6	Rubberwood
End table	8.3	Rubberwood
TV stand with shelves	21.2	Laminated composite wood
Bookcase	18.5	Laminated composite wood
37-inch LCD TV	16.7	Unexpanded plastic

Following the experiment, analysis of the extinguishment water included general chemistry parameters (e.g. pH, BOD/COD and conductivity), heavy metals, cyanide, VOC, and semi-VOC. The amount of the species released to the fire water run-off in the experiments is scaled according to the floor area of the fire. The values per m^2 are used as input to the emissions in the Fire Impact tool. Therefore, if the floor area in the tool is twice the size of the floor area in the experiment it is assumed that we have twice as much pollutants in the water. The user inputs how much water is used as a basis for the calculation of the concentrations.

3.2.1. Assumptions and Limitations

Well-characterized fire experiments with measurements of the contamination of air and extinguishment water are not very common in the open literature. Initially the aim was to develop a model based on average values from the literature, but this proved not to be feasible due to the lack of comparable detailed data. Instead, the tool was based on emissions to the air and contamination of water from reference cases shown in Table 4. This approach of building the models without averaging between different experimental studies also allows the user to read the references and understand the complete experimental background. Future versions of the tool can be updated to include averages or numerous alternative experimental sources as these become available.

Table 4: Fire Scenarios for the fire model.

Fire Scenarios	***Data source***		
	Fire Development	***Air pollution***	***Contamination of extinguishment water***
Vehicle fire	Scaled based on study by Lönnermark & Blomqvist (2006).	Scaled based on study by Lönnermark & Blomqvist (2006).	Scaled based on study by Lönnermark & Blomqvist (2006).
Enclosure fire	Heat release rate calculated based on ventilation factor (only fully developed under-ventilated fires) (Karlsson and Quintiere, 2000).	Scaled based on study by Blomqvist, Rosell & Simonson (2004b)	Scaled based on study by Wieczorek et al. (2010, 2011)

3.3. Environmental Risk Assessment (ERA)

An environmental risk assessment (ERA) aims to provide scientific evidence concerning potential adverse effects imposed on the environment by analysing available scientific data (Leeuwen and Hermens, 2007). The assessment consists of four steps, as shown in Figure 7.

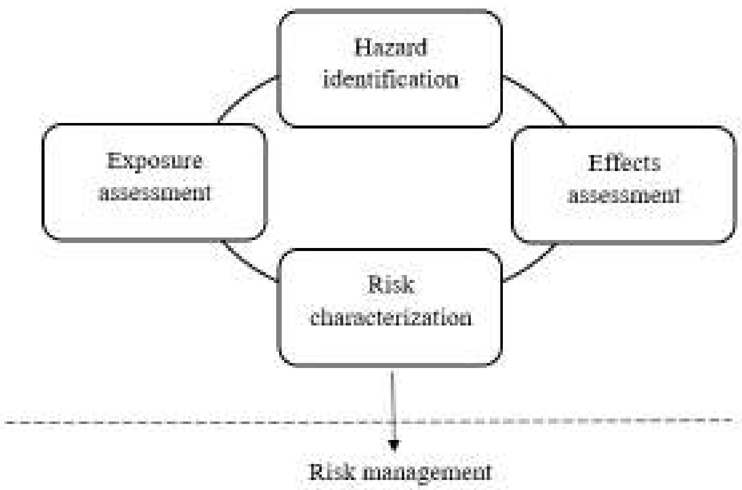

Figure 7: The four main steps of the environmental risk assessment framework. Adapted from Leeuwen and Hermens (2007).

Hazard identification is the first step of the process, which consists of acquiring knowledge about harmful substances that may cause adverse effects to the endpoints (Leeuwen and Hermens, 2007). The exposure assessment describes the circumstances in terms of contact between stressor and endpoint, by analysing pathways and concentrations of harmful substances (Leeuwen and Hermens, 2007). Effects assessment is the step in the framework that is used to relate the dose of a substance to the severity of the adverse effect that can be observed in the endpoint (Leeuwen and Hermens, 2007). Lastly, the risk characterization is composed of the preceding three steps, and is used to evaluate the likelihood and severity of adverse effects on the endpoint (Leeuwen and Hermens, 2007).

Environmental risk assessment has a considerable role in environmental management, both in policy and regulatory practices, as well as in industry (Fairman, 2008). It is a common basis for decision-making and it enables efficient communication about risks between different actors (Fairman, 2008).

In this project, the ERA acts as a basis for the development of the Fire Impact tool by providing the quantitative values that are required to assess the environmental impacts resulting from fire water run-off. It aims to quantitatively analyse three environmental impacts, i.e.:

- *How much soil is estimated to require excavation due to fire extinguishment?*
- *How does the choice of fire extinguishment approach affect the amount of water required to dilute fire water run-off to reach surface water guideline values?*
- *Within which distance from a vehicle fire may groundwater wells be contaminated?*

The environmental risk assessment focuses on the risks associated with fire water run-off from a fire. It is used to assess acute adverse effects on the local environment in close proximity to the fire. As in the ERA framework described by Leeuwen and Hermans (2007) in *Figure 7*, potential hazards with fire water run-off are identified by assessing the possible toxicants that may be present in fire water run-off. For vehicle fires, a previous study by RISE (Lönnermark & Blomqvist, 2006), where fire water run-off was collected during a vehicle fire experiment, is used as a basis of contaminant concentrations in the run-off. Similarly for enclosure fires, a study by FM Global (Wieczorek et al., 2011, Wieczorek et al., 2010), where fire water run-off was collected from enclosure fires, is used. Considering the harmful chemicals present in fire water run-off, suitable ecological endpoints are selected.

Pathways from the fire to the endpoints are assessed, and their environmental risks are specified quantitatively using mathematical models proposed by the Swedish EPA (Berggren Kleja et al., 2006, Naturvårdsverket, 2009, Naturvårdsverket, 2016). Furthermore, a conceptual model describing the pathways and endpoints considered in the ERA is constructed.

3.3.1. Hazard identification

The adverse effects that may be inflicted on the endpoints are due to exposure of stressors. An environmental stressor is a chemical, physical or biological agent that may potentially cause harmful effects on the environment (Linkov and Palma-Oliveira, 2001).

For fire water run-off, the stressors may stem from either the fire itself, or from a potential additive used to extinguish the fire. The stressors in the run-off water that stem from the fire consist of a range of chemicals, many of them metals and PAHs. Benzo(a)pyrene is a PAH that is commonly used as an indicator species for PAHs (Avino et al., 2017), and therefore guidelines values for Benzo(a)pyrene have been used to represent the value for total PAH if no explicit total PAH guideline value is available. Many additives, such as firefighting foams, may contain toxic and non-degradable substances. Additives contain a range of chemicals, although PFAS is one of major concern due to its toxic and persistent qualities.

3.3.2. Selection of endpoints

In the context of environmental risk assessment, an endpoint is an ecological entity that is sought to be protected (Suter, 2010). Due to an infinite number of ecological entities, the selection of endpoints is affected by the attributes that an ecological entity holds and how valuable it is perceived to be (Suter, 2010).

Three endpoints are considered for the ERA: the soil ecosystem, aquatic life in nearby surface waters, and drinking water quality in groundwater wells. These endpoints were selected due to their large potential exposure to the fire water run-off. The soil surrounding the fire, due to its direct contact with the chemicals of the run-off, may need to be excavated which can be a costly operation (Karlstadsregionen, 2018). The soil quality may also change due to replacement of soil

(IADC, 2016). Aquatic life in surface waters is chosen as an endpoint because of the intrinsic value of the species that may be threatened, as well as possible impacts that contaminated fish can have on human health following ingestion (Eriksson, 2008). The quality of human drinking water is considered an important endpoint due to the potential harm that a vehicle fire may impose on local communities and their health. Naturally, the choice of endpoint and limit values are affected by whether the area is already contaminated. Natural environments that are already contaminated may be even more sensitive to further contamination. At the same time, contaminated areas may be less important from an environmental point of view, e.g. industrial sites or large roads. These factors are not included in the ERA Fire Impact tool but may be considered in the future and should be kept in mind while using the information from the tool.

3.3.3. Conceptual model

The emissions that are considered in the ERA consist of the fire water run-off pathways adjacent to a fire site. To gather information regarding the potential transport of fire water run-off to waste water treatment plants (WWTPs), communication with a WWTP operative in Borås, Sweden was established. Since contaminated fire water run-off may contain toxicants that can damage the biological purification process in a WWTP, a general policy is that contaminated fire water run-off is not sent to WWTPs. Therefore, the pathways included in the ERA do not consider fire water run-off being sent to WWTPs. In Figure 8, a conceptual model visualizes the flows of run-off polluting the soil, surface water and groundwater wells. The model also depicts the inputs and outputs that are used in the Fire Impact tool, with units used in the tool in square parentheses.

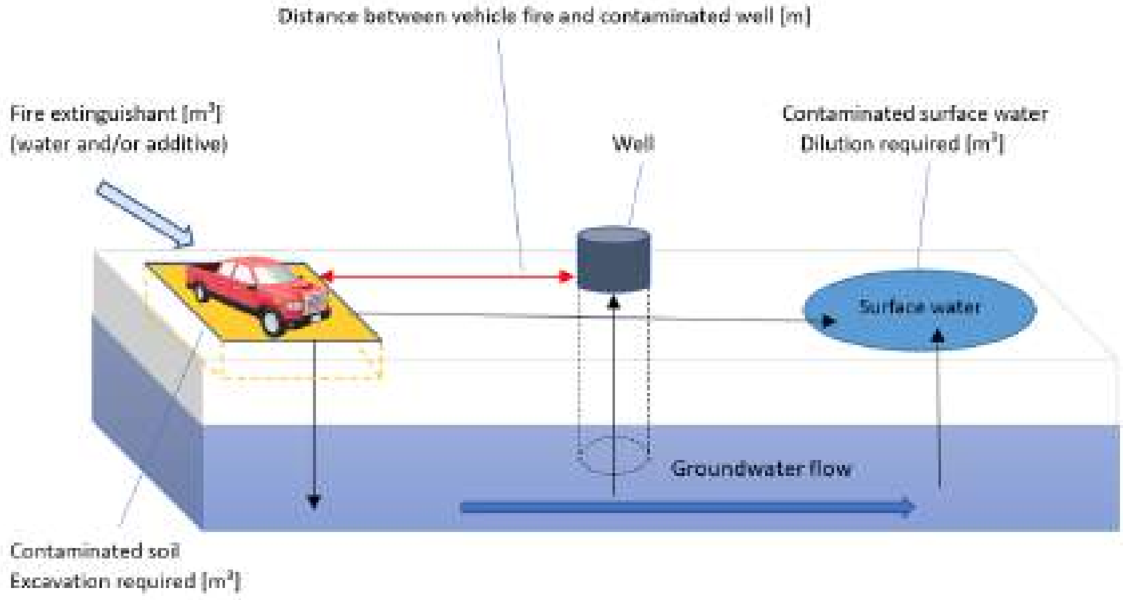

Figure 8: A conceptual model of the pathways of fire water run-off considered in the ERA. In this schematic the fire is represented as a vehicle.

The black arrows represent flows of fire water run-off, going from a fire site, in this case a vehicle fire, through the soil and travelling to surface water and groundwater. The red arrow shows the distance between the vehicle fire and a well, which could be exposed to contamination from the fire water run-off. The blue arrow shows the groundwater flow and visualizes how the contaminants in the run-off water are transported with the groundwater and may end up in surface water or in groundwater wells.

Fractions of the run-off water end up in each endpoint, depending on factors such as firefighting tactics, soil characteristics and surface steepness (Cornell, 2014). Soil data are needed to perform a quantitative analysis of both the soil ecosystem and the groundwater transport. Due to a variation of data based on soil type, three soil types are considered in this study: moraine, sand and clay. Moraine soil is the most common soil type, covering around 75 % of the Swedish surface area (SGU, n.d.). Sand and clay are likewise chosen due to their being common soil types in Sweden (SGI, 2019), which also represent upper and lower bounds for many soil parameters.

3.3.4. Exposure assessment

To establish the number of stressors that exist in fire water run-off, a previous study was used where fire experiments were conducted on a vehicle and the run-off water was collected and analysed. The study analysed a volume of 105 litres of run-off water and presents the mass of each stressor in the run-off (Lönnermark and Blomqvist, 2006). The vehicle used in the experiment is a medium class model built in 1998. The study established that the fraction between BOD/COD (the biological oxygen depletion divided by the chemical oxygen depletion) was approximately 0.6. A BOD/COD higher than 0.43 means that the run-off is perceived as persistent (Lind et al., 2009).

The mass of contaminants in the run-off water is scaled according to how developed the fire is before it is extinguished. It is assumed that the masses of stressors from the vehicle fire are limited and may reach maximum values. The mass of each stressor in the fire water run-off is divided with the volume of run-off water to calculate concentrations.

However, for small volumes of run-off water, it is assumed that the stressors' masses have not yet reached maximum values. For these smaller volumes, it is assumed that the concentrations of stressors are constant. As an example, in the vehicle scenario a constant concentration is applied on scenarios where the volume of run-off water is 105 litres or less. The choice of 105 litres as the cut-off point was based on the application from Lönnermark and Blomqvist (2006). This represents an approximation that could be developed in future versions of the tool.

For the enclosure fire, a study from FM Global (Wieczorek et al., 2011, Wieczorek et al., 2010) was used for emissions details. Information concerning additives used in firefighting, and their compositions, are taken from available industrial product data. The chemicals that additives contain are listed and their compositions are used to calculate their corresponding concentrations in the fire water run-off. In the FM Global study, benzene, antimony, pH, cyanide, ammonium and phosphorous, were among the most critical pollutants compared to water limit standards.

Equations for each endpoint are presented in the following sub-sections.

Soil ecosystem

The soil beneath the fire is subjected to infiltration of run-off water that contains harmful chemicals. It is assumed that the entire wetted volume of soil is contaminated and therefore required to be excavated. For vehicle fires, it is assumed that the area of wetted soil is the same as a larger Swedish parking lot, which has an area of 5 x 5 meters (Holgersson et al., 2013). For enclosure fires, the user specifies the wetted area. The depth of contaminated soil is related to its retention capacity (Blomqvist and Tistad, 1998) and is derived from equation (2):

$$D = \frac{V_{Runoff}}{A \cdot R_C} \qquad (2)$$

where D is the depth of contamination [m], $V_{Run\text{-}off}$ is the volume of run-off water [m^3], A is the area of contamination [m^2], and R_C is the retention capacity [m^3/m^3] of the soil. The fire water run-off is approximated as water and therefore the soil's field capacity is used as a value for the retention capacity. Field capacity is a measurement of the water content in the soil after it has been completely wetted with water and free drainage has been reduced to insignificant values (Wu et al., 2018). The volume of soil that is excavated is calculated using equation (3):

$$V_E = D \cdot A \qquad (3)$$

where V_E is the volume of excavated soil [m^3], D and A are as defined for equation (2).

It is assumed that the distance from the soil surface to the groundwater is 3 meters, which is a value used in a model by the Swedish EPA (Naturvårdsverket, 2009). Therefore, the depth of contaminated soil has a maximum value of 3 meters. The time until contamination reaches groundwater depth is shown with equation (4) (Blomqvist and Tistad, 1998):

$$t = \frac{D_{gw} \cdot n_e}{k_v} \quad (4)$$

where t is the time until the run-off water reaches groundwater levels [m], D_{gw} is the distance from the soil surface to the groundwater surface [m], n_e is the effective porosity of the soil [m^3/m^3], and k_v is the hydraulic conductivity of the soil in vertical direction [m/s].

Surface water

The concentrations of stressors are compared with guideline values for aquatic life in surface water. It is important to add that the concentrations of stressors are analysed in the fire water run-off itself, and not after it ends up in surface waters. The concentration of contaminants in the run-off is directly dependent on the volume of extinguishant that is applied to the fire. The volume of water required to dilute the contaminated run-off water to reach guidelines values for aquatic life is expressed in litres and is calculated using equation (5):

$$Volume_{Dilution} = \frac{C_{Contaminant} \cdot V_{Runoff-sw}}{C_{Guideline-sw}} - V_{Runoff-sw} \quad (5)$$

where $C_{Contaminant}$ [mg/L] is the concentration of contaminant in the fire water run-off, $V_{Run\text{-}off\text{-}sw}$ [L] is the volume of run-off that goes to surface water, and $C_{Guideline}$ [mg/L] is the concentration that represents the guideline values of aquatic life in surface waters. The volume required to dilute the stressors to reach guideline values is not a proposed mitigation measure. It is used to compare and communicate the extensiveness of how much the concentration of stressors in run-off water deviates from the proposed guideline values, while also gives a sense of how large a polluted body of surface water may be.

Groundwater wells

Fire water run-off seeps through to groundwater through the soil and is transported to nearby water wells. Groundwater wells within a certain distance from a fire may be contaminated by the run-off, which presumably happens if the concentration of stressors in the water is above guideline values for human drinking water quality.

It is assumed that the change in concentration of contaminants in the groundwater flow is only affected by dilution taking place in the groundwater flow. The distance to a contaminated well is correlated to the dilution factor ($DF_{gw\text{-}well}$) of the groundwater well (Naturvårdsverket, 2016). This correlation is provided by the Swedish EPA and is shown in equation (6). An overview of the groundwater transport model is shown in *Figure 9*.

$$DF_{gw-well} = \frac{L \cdot I_r \cdot W}{k \cdot i \cdot d_{mix-well} \cdot (2 \cdot y_{mix-well} + W) + (W + y_{mix-well}) \cdot (L + x_{well}) \cdot I_r} \quad (6)$$

where L is the length of the contaminated area in the direction of the groundwater flow [m], I_r is the groundwater recharge [m/year], W is the width of the contaminated area in perpendicular direction of the groundwater flow [m], k is the hydraulic conductivity of soil [m/year], i is the hydraulic gradient [m/m], $d_{mix\text{-}well}$ is the thickness of the mixing zone in the aquifer [m], $y_{mix\text{-}well}$ is the spread of the mixing zone [m] and x_{well} is the distance to the well [m].

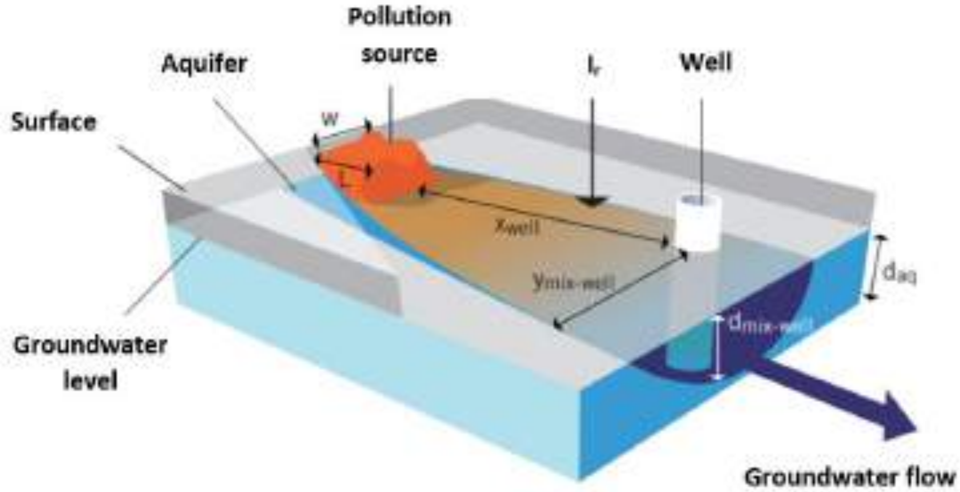

Figure 9: A conceptual model of the flows and parameters of the groundwater transport model. Adapted from (Naturvårdsverket, 2016).

The parameters $d_{mix\text{-}well}$ and $y_{mix\text{-}well}$ may be calculated with equation (7) and (8) respectively:

$$d_{mix-well} = \sqrt{0{,}0112 \cdot (L + x_{well})^2} + d_{aq} \cdot \left[1 - exp\left(-\frac{(L+x_{well})\cdot I_r}{k \cdot i \cdot d_{aq}}\right)\right] \quad (7)$$

where d_{aq} is the aquifer's thickness [m]. $d_{mix\text{-}well}$ may be approximated as d_{aq}, if $d_{mix\text{-}well} > d_{aq}$.

$$y_{mix-well} = \sqrt{0{,}0112 \cdot (L + x_{well})^2} \quad (8)$$

The dilution factor, $DF_{gw\text{-}well}$, is a dimensionless number that is the quotient of the concentration in the groundwater well and the concentration of the mobile contaminant in the ground, as seen in equation (9):

$$DF_{gw-well} = \frac{1}{\left(\frac{C_{well}}{C_{contaminant}}\right)} \quad (9)$$

where in this case, C_{well} [mg/L] is the guideline concentration for drinking water quality and $C_{contaminant}$ is the concentration of contaminants in the run-off water.

In the ERA Fire Impact tool, the width, *W* and length, *L* of the contaminated site is assumed to be 5 m x 5 m.

3.3.5. Effects assessment

Several stressors found in fire water run-off do not have established surface water guideline values or drinking water guideline values. Contaminants present in the fire water run-off that do have available guideline values are presented in Table 5 and Table 6.

Table 5 presents available surface water guideline values, obtained by the US EPA's recommended aquatic life criteria (EPA, n.d.), the Canadian council of Ministers of the Environment (CCME) (CCME, n.d.), as well as the Swedish Agency for Marine and Water Management (HVMFS, 2018).

Table 5: List of contaminants in fire water run-off and their respective guideline values corresponding to aquatic life criteria.

Stressor	**USEPA Guideline value [mg/L]**	**CCME Guideline value [mg/L]**	**HVMFS Guideline value [mg/L]**
PAH (total)		0,000015	

Cadmium (Cd)	0,0018		
Lead (Pb)	0,065		
Arsenic (As)	0,34		
Chromium (Cr)	0,016		
Copper (Cu)	0,0048		
Zinc (Zn)	0,12		
Nickel (Ni)	0,47		
Mercury (Hg)	0,0014		
Glycols		192	
Mixture of fluorosurfactants (PFAS)			0,036

Table 6 presents available drinking water guideline values, obtained by National Food Agency of Sweden (Livsmedelsverket, 2015).

Table 6: Stressors in fire water run-off and their respective guideline values corresponding to drinking water quality.

Stressor	**National Food Agency of Sweden Guideline value [mg/L]**
PAH (total)	0,0001
Cadmium (Cd)	0,005
Lead (Pb)	0,01
Arsenic (As)	0,01
Antimony (Sb)	0,005
Chromium (Cr)	0,05
Copper (Cu)	2
Nickel (Ni)	0,02
Mercury (Hg)	0,001
Mixture of fluorosurfactants (PFAS)	0,00009

3.3.6. Model uncertainty, sensitivity and validation

Sensitivity analysis

The results of the ERA are largely dependent on guideline values. In some cases, guideline values are still debated and uncertain. For instance, the proposed drinking water guideline value for PFAS is described as an "action threshold" rather than a guideline value (Livsmedelsverket, 2018). A sensitivity analysis has been performed on guideline values for the most vital stressors to gain an understanding of how the results may vary due to variations in guideline values. The most critical stressors that provide the results in the Fire Impact tool for required dilution in surface waters are metals, PAH and PFAS.

Surface water guideline values

In Figure 10, comparison scenario 2 represents results after a lowering of guideline values for PAH and PFAS for aquatic life in surface by a factor of 100, which means that the guidelines are stricter. Comparison scenario 1 represents the unchanged surface water guideline values.

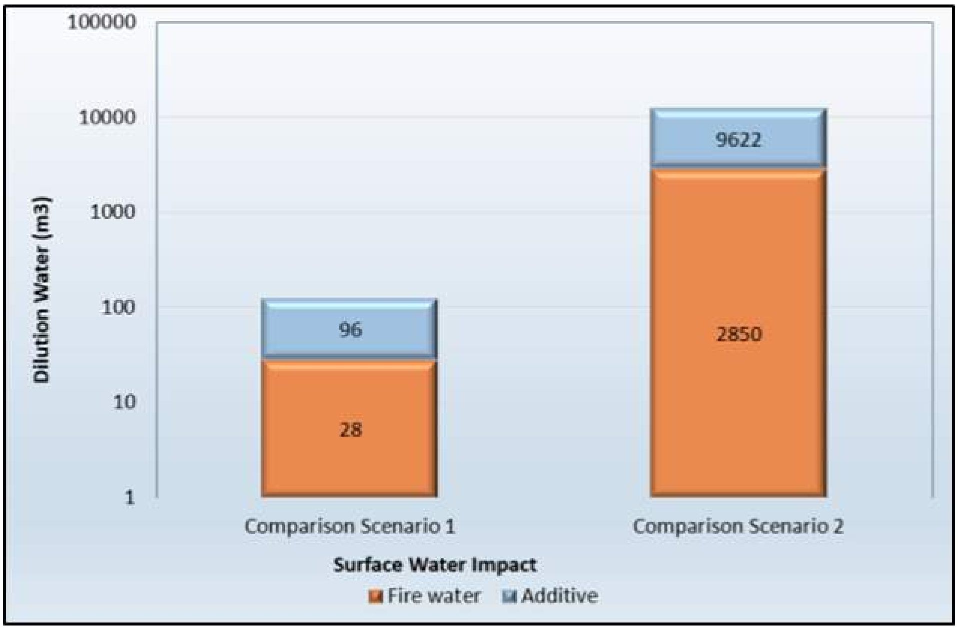

Figure 10: Volume of water required to dilute run-off water to guideline values after surface water guideline values for PAHs and PFAS are lowered with a factor 100.

Figure 10 shows that stricter guideline values for aquatic life in surface water leads to a higher requirement for dilution to reach guideline values, i.e. the lowering of guideline values for PAHs and PFAS by a factor of 100 leads to a hundredfold increase in required dilution. To further understand how trends regarding required dilution differ with variations in guideline values, the guideline values were increased by a factor of 100 as shown in Figure 11.

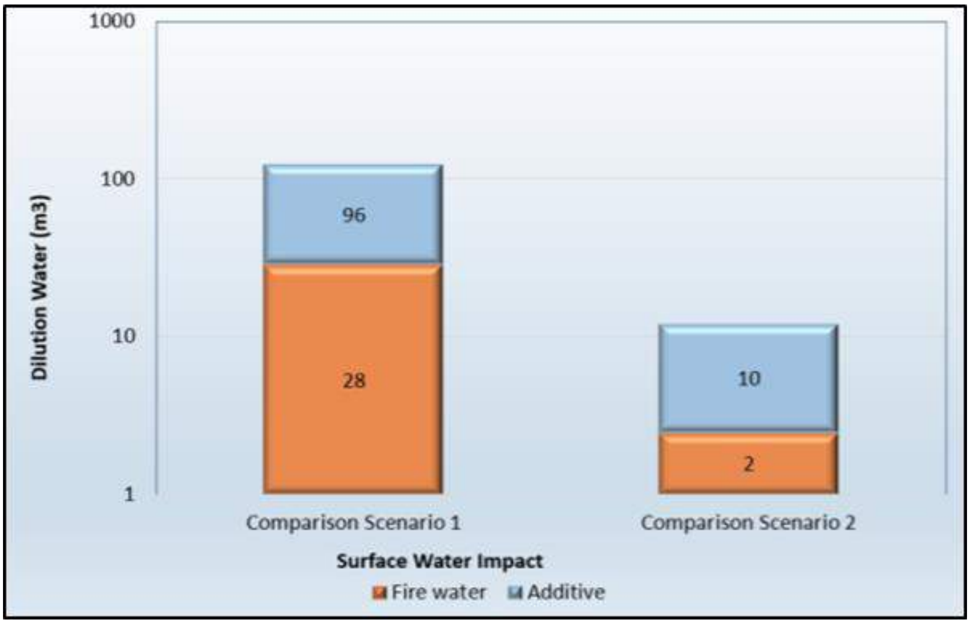

Figure 11: Volume of water required to dilute fire water run-off to reach surface water guideline values after they have been increased with a factor 100.

Figure 11 shows that increasing the guideline values for PAH and PFAS by a factor of 100 entails less strict guidelines, and therefore the required dilution volume lowers significantly. As seen in equation 8, guideline values are directly related to the amount of water required to dilute fire water run-off to reach guideline values. Therefore, an increase in guideline values by a factor 100 leads to a lowering of the required dilution with a factor 100. Comparing Figure 10 and Figure 11 demonstrates that guideline values largely impact the results of this study.

Uncertainties in surface water guideline values, and future changes to them, may alter the estimated impact significantly.

Uncertainty analysis

The environmental risks with fire water run-off on aquatic life in surface waters, as well as drinking water quality in groundwater wells, are heavily dependent on guideline values. Results are based on the stressor that contributes to the highest value of required dilution, which is a relationship between the concentration of the stressor in the runoff water and the guideline value for that specific stressor. However, guideline values for all stressors are not available. Due to the lack of guideline values, there are stressors whose contributions to environmental risks that are not analysed. In addition, some guidelines values that exist have values that are still debated and are uncertain. As shown in the sensitivity analysis in this report, guideline values have a large impact on the results.

Furthermore, contributions to required dilution to reach surface water guidelines are measured from concentrations observed in the fire water run-off itself, and not from concentrations in surface waters. In reality, the concentrations of chemicals will have changed during the runoff's path from the vehicle fire to nearby surface waters.

Considering groundwater transport, a simplification is made where the stressors are merely diluted with the groundwater flow. In reality, a complex process takes place where the chemicals may spread as the runoff water moves or react with other chemicals in the groundwater flow. These aspects are not considered in this project due to a large range of stressors that all may react differently and be subjected to different chemical reactions respectively. In addition, an assumption that the groundwater level is 3 meters below the soil surface is applied. In reality, the groundwater level differs across the country and may also change with the season.

Moreover, fire water run-off is approximated as water when used in calculations, though it is a mixture of many different substances which affects the runoff's fluid characteristics. Furthermore, it is assumed that the entire volume of wetted soil due to fire extinguishment is contaminated and requires excavation. It is difficult to predict the exact volume requiring excavation due to different soils having different levels of sensitivity, as well as different field capacities. Calculations in this study assume that the entire field capacity for a soil is available, which means that a maximum amount of water is retained in the soil. Moreover, the Fire Imp tool provides a point estimation regarding the expected requirement for soil excavation. It is likely that a higher volume than the one suggested by the tool should be excavated, to ensure that all contamination is removed. Furthermore, it is assumed that fire water run-off only infiltrates the soil vertically. It is uncertain how the expected volume of excavated soil may change due to horizontal movement of runoff water in the soil.

Model validation

The exposure of stressors to the endpoints considered in the ERA are analysed with mathematical models connecting the emissions of contaminants in fire water run-off to the environmental impacts surrounding a vehicle fire. The mathematical models are based on dispersion models that describe how fire water run-off and its contents infiltrate the environment.

The dispersion models used in the ERA in this study are simplifications of the complex movements and reactions that take place in reality. To accurately validate the models and establish their precision, case scenario studies with experiments in known conditions are required. However, such experiments were not available for this work.

The dispersion models used for calculating an estimation of required soil excavation, as well as the distances between a vehicle fire and contaminated groundwater wells, are adapted from previous reports. The dispersion model used for the analysis of required soil excavation stems from a report published in 1998 by the Swedish Transport Administration and the Swedish Rescue Services Agency (part of MSB). Moreover, distances between a vehicle fire and contaminated groundwater wells was analysed using a dispersion model provided by the Swedish Environmental Protection Agency. It is important to note that the dispersion models were taken from previous studies and adapted to fit the context of this report.

The equations used in the assessment of the volume of water required to dilute fire water run-off to reach surface water guideline values, are based on a previous study performed at RISE that established the mass of contaminants present in fire water run-off, as well as assumptions regarding the concentrations of stressors in the run-off water. The calculations of required dilution are not based on dispersion models from other reports, as they are comparisons of concentrations of stressors in fire water run-off and surface water guideline values.

3.3.7. Conclusions

The environmental risks associated with fire water run-off are dependent on many factors such as firefighting tactics and the environment in the vicinity of the fire. Fire water run-off contains chemicals that are toxic to soils, aquatic life in surface water, and human drinking water.

The tool provides quantitative values regarding how firefighting tactics and fire effluents impact expected soil excavation, volume of water required to dilute fire water run-off to reach surface water guideline values, and the distance between the fire incident and contaminated groundwater wells.

Users of the Fire Impact tool may experiment with input data and analyse how the environmental impacts are affected by firefighting tactics to make informed decisions about fire extinguishment before a fire occurs. The results provided by the Fire Impact tool show that environmental impacts due to fire water run-off are largely affected by the volume and type of extinguishant used and how developed a fire is before intervention begins. Results may vary significantly depending on which soil type that is subjected to fire water run-off.

The ERA used to develop the Fire Impact tool is limited to environmental impacts due to fire water run-off on three endpoints. It does not include all possible environmental impacts that can arise due to fires. Fire Impact is most efficiently utilized with knowledge regarding its assumptions and limitations as well as how fire surroundings and other variables may influence the tool’s results.

3.4. Life Cycle Assessment (LCA)

LCA is a methodology that is used to predict the environmental impacts associated with the whole or partial life of a product, process or activity; the subject of the assessment is usually referred to as a “system” (Finkbeiner et al., 2010). An LCA can be conducted in compliance with the procedures specified in the International Organization for Standardization (ISO) standards ISO 14040 and ISO 14044 (Standardization, 2006a, Standardization, 2006b), or non-standardized life cycle *thinking* can be applied to virtually any situation.

LCA is a method capable of assessing impacts across the full life cycle of a product or system, from materials acquisition through manufacturing, use, and end of life. Depending on the application, it is possible to examine the impact of only part of the life cycle, for example from cradle to gate, where the gate is some point in the life of the system being studied beyond which the life cycle has no further bearing. As depicted in Figure 12, a standard LCA study is structured to have four major components: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation of results. The development of an LCA is typically an iterative process in which each of these components is revised as new information from other components is acquired.

Figure 12: Components in an LCA analysis of a system.

The life cycle phases of a product or a system are assessed with respect to their impact on the environment (both good and bad) within this structure. The life cycle phases depend on the product or system but, for products, generally follow this pattern:

- Production (includes materials and manufacturing processes),
- Use (includes energy requirements, maintenance, during service life), and
- End of life (includes landfill, incineration, recycling).

The product or system being assessed could be nearly anything, for example, an LCA can be applied to the production of a warehouse (all or just part of it), or it could be used by politicians to examine the environmental consequences of policies and regulations, or it could be applied to internal industrial systems to, for example, optimize waste streams within a manufacturing facility. In this work life cycle thinking has been used to predict the environmental impacts caused by decisions made during two main situations: (1) tactical choices concerning fire and rescue service response to vehicle and enclosure fires, and (2) design choices concerning the instalment of a fixed-firefighting system in a school.

3.4.1. Goal and Scope

This LCA model provides support for including global environmental consequences when considering the most appropriate course of action in response to a fire. It is understood that there are many factors that affect decisions made in response to fires, and that environmental impact may not always be the most important factor; however, it is not possible to balance environmental considerations against other factors without knowledge of their nature and magnitude. The goal of the Fire Impact tool is to make this knowledge available to responders during their training and pre-planning activities so that they can make informed decisions during fire incidents.

The boundaries of the system used in this model include the burning object, global and local surroundings that are affected by the fire and its effluents, including any storm drain systems and subsequent treatment of run-off water or suppression agents. The system also includes fire suppression operations, replacement of fire suppressants, travel to/from the incident and restoration operations. Since this is a comparative tool, the focus is on the differences between the results for a reference case and two user-created scenarios:

1. A reference scenario where it is assumed that the fire and rescue service responds to the fire but does not attempt to extinguish the fire. This is the “let it burn” scenario.
2. Fire Response scenario 1 where one set of extinguishment tactics is created by the user.

3. Fire Response scenario 2 where another set of extinguishment tactics is created by the user.

The system boundaries for the vehicle fires includes the fire, the vehicle, the response, and treatment of the used suppression media. The effluents to air from smoke and the persistent effects of the fire water run-off are included. Since the fire occurs and destroys the vehicle in every scenario and is not allowed to spread beyond the burning vehicle, it is not necessary to consider the impacts of replacing the vehicle in the LCA. The user can change the response input, such as the number and type of vehicles responding, the average distance driven, and the tactics used to extinguish the fire so all of these factors are included in the system.

The system boundaries for the enclosure fires includes the fire, replacing the enclosure and its

contents, the response, and treatment of contaminated soil and used suppression media. As with the vehicle fires, the effluents to air from smoke and the persistent effects of the fire water run-off are included. Replacing the enclosure and its contents is included because there could be differing amounts of material to replace depending on the spread of the fire to other rooms within the fire compartment. The response is the same as for vehicle fires.

The functional unit of the LCA models is one response to a vehicle or enclosure fire.

3.4.2. Inventory Analysis

Quite a lot of information (inventory data) is needed in order to assess the environmental impact of a fire. The quality of the LCA model depends heavily on the accuracy and completeness of the inventory data, which can be difficult to obtain. The majority of inventory information has been obtained from open source data, the literature, test reports, and communication with a manufacturer. In all cases, basic units of the inventory data, such as 1 kg of a material or 1 piece of a school structure, were analysed using LCA software and the results were exported to the Fire Impact tool and scaled according to the user input.

The inventory data includes:

- Fire effluents as produced by the fire models described in Section 3.2
- Replacement of suppressants (water, blanket, handheld fire extinguisher, additive)
- Replacement of structural materials as described below
- Replacement of the contents of the enclosure as described in Section 3.2
- Transport using heavy and light vehicles (for example fire engines and ambulances, respectively) and passenger cars
- Soil restoration, which includes transport of the excavated soil to a storage facility (landfill)
- Treatment of used suppression media, such as water at a water treatment plant or fire water run-off that is transported to a hazardous materials treatment facility

The fire effluents were either components of smoke or fire water run-off. The local effects of the fire water run-off on surface water, soil, and groundwater are part of the ERA; the only parts of the fire water run-off included in the LCA are the global impacts of the foam additive and replacement and treatment of suppressants.

Replacement of structural materials was accomplished by using the Athena Building Impact Estimator (ABIE) (Athena, 2019) to produces a bill of materials for a school structure. The building has a concrete slab floor, wooden joists and beams, wooden exterior cladding, triple glazed windows, painted gypsum interior walls, and a tile roof. The building consists of 4 rooms having an area of 60 m^2. The ABIE also predicts the energy needed to construct the building. The output from the ABIE was used as input to LCA software to predict the impacts of replacing the structural materials lost in the fire.

The fate of the fire water run-off is included in the LCA models if the fire water run-off is collected and disposed of, meaning that it is either sent to an incinerator or a hazardous materials treatment facility, or if the run-off drains to a water treatment plant.

Inventory data regarding the firefighting foam came from communication with a foam manufacturer and is proprietary information.

The output from the LCA software is allocated in several different ways in the Fire Impact tool, especially for the enclosure fires, using input from the user. The allocation is described below:

- The smoke is allocated according to the timing of the response for vehicle fires and according to the total energy produced by the fire per room for enclosure fires, and whether or not a fire occurs in the room
- Replacing the suppressant additive is allocated by the total energy produced by the fire per room for enclosure fires, and whether or not active suppression occurs in the room
- Replacing the structural materials is allocated according to the area of the room, normalized to the 240 m^2 building used in the ABIE
- Replacing the contents of the enclosure is allocated according to the fuel load, and whether or not a fire occurs in the room
- Treatment of the used suppression media is allocated according to the fuel load, and whether or not active suppression occurs in the room
- All other inventory data, especially for the vehicle fires, is allocated directly by user input to the Fire Impact tool

3.4.3. Impact Assessment

The initial plan for the Fire Impact tool was to use the same impact assessment method used by the Enveco tool (Amon et al., 2016a), which was the "Tool for Reduction and Assessment of Chemical and Other Environmental Impacts" (TRACI) impact assessment method (Bare et al., 2003). Unfortunately, the TRACI method does not have the characterisation factors needed to predict the impacts of firefighting foam so the impact assessment method was switched to the Eco-Scarcity 2013 method (Frischknecht and Busser Knöpfel, 2013), which can predict some of the impacts for firefighting foams. The impact categories used in the Eco-Scarcity method are described in Table 7.

Table 7: Impact categories from the Eco-Scarcity impact assessment method (Frischknecht and Busser Knöpfel, 2013). Note that all units are in UBP, "Eco-points".

Impact Category	Comments/description
Global warming	Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to changes in global climate patterns.
Main air pollutants and PM	Sulphur dioxide (SO_2), Nitrogen oxides (NO_X), Non-methane volatile organic compounds (NMVOCs), ammonia (NH_3), Particulate matter (PM_{10} and $PM_{2.5}$)
Water pollutants	Nitrogen, nitrate, phosphorus, CODs, AOXs, chloroform, PAHs, endocrine disruptors
POP into water	Persistent organic pollutants
Energy resources	Non-renewable: natural gas, crude oil, raw lignite, raw hard coal. Uranium Renewable: harvested quantities of wood, solar radiation, kinetic energy (wind energy) potential energy (water power), geothermal energy

3.4.4. Interpretation

The interpretation step in LCA involves analysis of the completeness and accuracy of the modelling process as well as analysis of the results. Conclusions and recommendations are made only after the model and results have been examined and the strengths and weaknesses identified. Sensitivity and uncertainty analyses are presented in the following section.

The primary strength of the LCA component of the Fire Impact tool is that non-environmental experts can use it for training and pre-planning purpose to estimate the environmental impacts of a limited number of vehicle and enclosure fires, comparing scenarios that the users create against a reference case. Another strength is that this tool can be expanded as new inventory data and firefighting tactics become available.

The main weakness of this tool is its dependency on high quality inventory data. Trade-offs in model accuracy are necessary when simplifying a complicated assessment process such as LCA. By scientific and engineering standards, LCA has a relatively high level of uncertainty that can be exacerbated by simplifications and assumptions, thus making the results less meaningful.

Details of how the LCA thinking has been developed for this project and its application in the Fire Impact Tool are given in the next chapter.

3.4.5. Sensitivity and Uncertainty Analyses

A sensitivity analysis was performed on the user inputs for the response and the fire compartment model. The sensitivity is defined as the absolute value of the percentage change in model output divided by the percentage change in model input; larger numbers shown the results in Table 8 indicate higher sensitivity. The percentage change in model input was 200 % in most cases.

Table 8: Sensitivity analysis of Fire Impact tool input effects on LCA results.

		Range of input values		Results = (% change output)/(% change input)				
Input- Response	**Unit**	**default**	**200 % change**	**Global warming**	**Air Pollution**	**Water Pollution**	**POP into Water**	**Energy Resources**
Time of response (vehicles)	min	15	30	**0.24**	0.08	0.00	0.00	0.00
Water used	litres	200	400	0.16	0.16	0.02	0.06	0.15
Additive used	litres	0	4	0.01	0.01	0.04	**7539**	0.03
Additive type	-	none	unknown					
Handheld fire extinguisher (vehicl	yes/no	yes	no	0.04	0.08	**0.34**	0.07	0.10
Blanket (vehicles)	yes/no	no	yes	0.11	0.05	0.04	0.03	0.07
Response travel- vehicles	-	2, 1, 1	4, 2, 2	0.12	0.15	0.14	**0.36**	**0.25**
Response travel- distance	km	15	30	0.12	0.15	0.14	**0.36**	**0.25**
Fire water run-off to WTP	%	25	50	**0.53**	0.00	0.04	0.00	0.00
Fire water run-off collected	%	25	50	0.11	0.05	0.04	0.03	0.06
Input- Enclosure Fire Model								
Openings height dimension	m	1.2	2.4	0.00	0.00	0.00	0.00	0.00
Openings area	m^2	10	20	0.00	0.00	0.00	0.00	0.00
Room size	m^2	60	120	**0.48**	**0.49**	**0.49**	**0.46**	**0.47**
Fuel load	MJ/m^2	350	700	0.16	0.12	0.01	0.01	0.01
Fire burning time	min	25	50	0.00	0.00	0.00	0.00	0.00
Active suppression	yes/no	yes	no	0.00	0.00	0.00	0.02	0.00

Most of the sensitivity results are between 0 and about 0.2, meaning that a global environmental impact will change by up to about 20 % for a 100 % change in an input value. The most notable exception is that the use of foam has an extreme effect on the POP into Water impact. Other, much less extreme results are:

- All impact categories are sensitive to the size of the rooms, which determines the amount of structural material that must be replaced.
- Global Warming is somewhat sensitive to the amount of smoke generated by a vehicle fire and by fire water run-off to a water treatment plant.
- Water Pollution is sensitive to the use of handheld fire extinguishers.

- POP into Water and Energy Resources are sensitive to the number of vehicles responding to a fire incident as well as the distance they travel.

The LCA software has a built-in uncertainty analysis procedure that uses a Monte Carlo method. In this analysis 1 000 iterations and a 95 % confidence interval were used. The quantities evaluated were smoke, foam into water, replacing the suppressants, treating the suppressant waste, treating the soil, and replacing the structure materials and contents. The results are shown in Figure 13 in terms of error bars for each impact category.

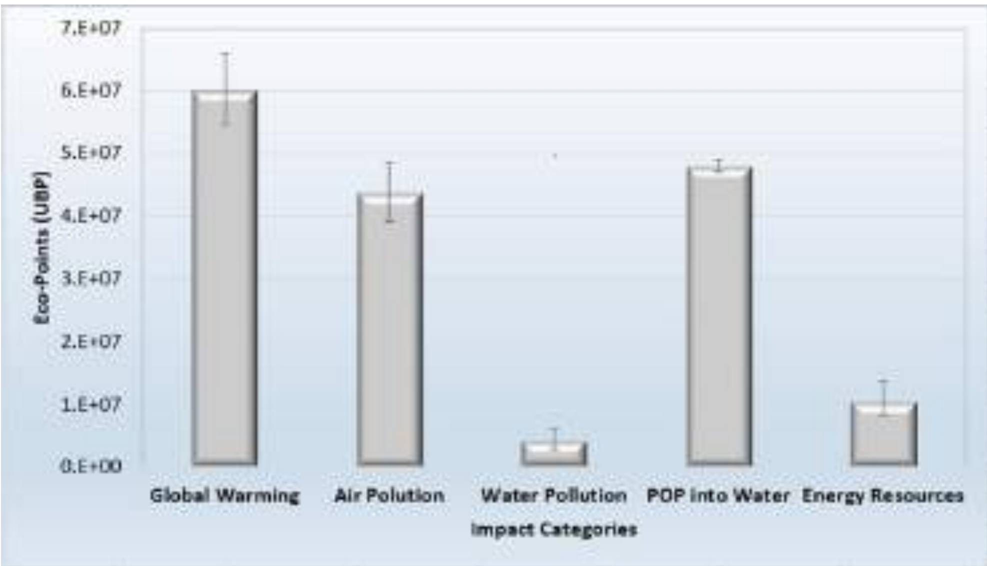

Figure 13: Uncertainty analysis of the LCA model used in the Fire Impact tool.

The most uncertain categories are Water Pollution and Energy resources, with coefficients of variation of 19 % and 13 %, respectively. This information, when considered in conjunction with the results of the sensitivity analysis indicate that the response vehicles and the handheld fire extinguisher are both relatively sensitive and uncertain. Fortunately, both these user inputs are usually recorded in fire response reports and are therefore usually verifiable.

4. Description of the Fire Impact tool

The Fire Impact tool is described in detail in this chapter. The platform is an Excel® spreadsheet, which was chosen because most end users are familiar with spreadsheets, have access to the program suite and because it is desirable to keep the tool as simple as possible. At some point in the future, the complexity of the tool may make it necessary to adopt a more complicated platform. In the following sections, each worksheet available to the end users is described, along with general descriptions of the worksheets that are hidden. The calculations used in the fire and environmental impact assessment models are described in detail in their respective sections.

4.1. Instructions worksheet

The goal of the *Instructions worksheet* is to orient the user to the setup of the tool and explain what it does and how it is used. It describes the difference between non-specific effects (global environmental impacts predicted by LCA) and specific effects (local impacts predicted by ERA). Users are directed to the examples worksheet and given a brief explanation of how the results are presented.

This worksheet also introduces the input sheets for vehicle and enclosure fires and the results found both on the input worksheets and the detailed analysis worksheets. It explains the need to prevent certain cells from being changed by the users to protect calculations. Users are encouraged to provide feedback (contact information is given) about any changes they would like to see and report possible bugs.

4.2. Examples worksheet

Two examples are provided, one for vehicle fires and another for enclosure fires. In each case a screenshot of the input for two user-created scenarios is shown and screenshots of the results, in which the two scenarios are compared together with a reference case in which the responders arrive at the fire incident and prevent the fire from spreading but do not attempt to suppress the fire.

Explanations of the input are given- what is being compared and why. An interpretation of the results is also given. There may be more than one way to interpret the results, but the intent of the examples worksheet is to guide the users so that they become comfortable using the tool and can come to their own conclusions regarding the results.

4.3. VEHICLES Input worksheet

The VEHICLES Input worksheet is where the users provide their input for two vehicle fire comparison scenarios. The input cells are green and all the other cells are locked. The vehicle fire input area is shown in Table 9 below. There is a brief description of the input in the column to the left of the green input cells and the column to the right of the input cells contains default values that the user can consider using if the input is unknown or uncertain. When the user clicks on an input cell additional information pops up that gives further guidance.

Table 9: Example of user input area for vehicle fires showing two comparison scenarios.

VEHICLE Fire Input	Comparison Scenario 1	Comparison Scenario 2	Defaults
Start of intervention (min)	15	25	15
Water used (liters)	1000	200	200
Additive concentrate used (liters)	0	0.5	2
Type of additive used (select from dropdown list at right)	AFFF	3F	Unknown
Handheld fire extinguisher used?	No	N[illegible]	[illegible]
Blanket used?	No	N[illegible]	[illegible]
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2	[illegible]	[illegible]
Number of light vehicles responding (like an ambulance)	1	[illegible]	[illegible]
Number of passenger vehicles responding (car, SUV)	1	[illegible]	[illegible]
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) that goes to the environment	40%	40%	50
% of fire water run-off that goes to water treatment plant (WTP)	25%	25%	<< 25 % each
% of fire water run-off collected & destroyed	25%	25%	
% of fire water run-off that goes to soil	25%	25%	
% of fire water run-off that goes to surface water	25%	25%	

Allowable input
Currently, only foam is allowed as input. This will change as more information on other additives becomes available. Click on the little arrow on the side to change type.

Users can compare the times when intervention starts, the types of suppression media used (choosing from water, a selection of five foam additives, a handheld dry chemical extinguisher, and a blanket to smother the fire), the amount and type of vehicles used in the response and the distance they travel, and the fate of the fire water run-off. If more than two comparison scenarios are desired the user can save the file with a different name and run it again as many times as needed. The reference case is always “let it burn”, in which responders arrive but do not suppress the fire. In this case there is no fire water run-off so there are no local effects to show in the ERA results; however, the LCA results capture the global impacts of the comparison scenarios along with the reference case. Note that if an additive is used in a scenario, there must also be water used in that scenario.

A diagram of the transport mechanisms for contaminants in surface water, soil, and groundwater is located to the right of the user input area, see Figure 14. This diagram helps explain the reasoning behind the ERA results.

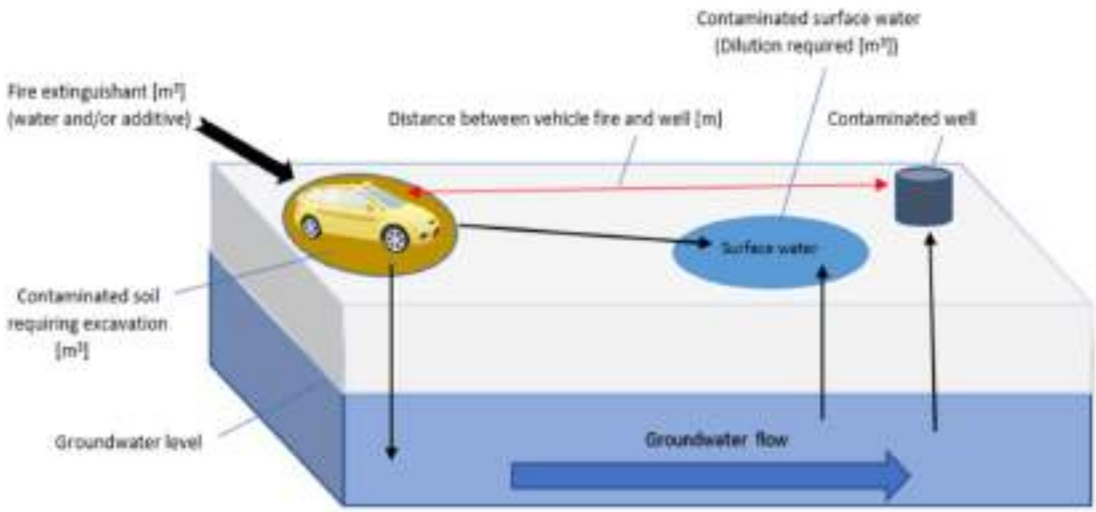

Figure 14: Diagram of contaminant transport mechanisms through surface water, soil and groundwater.

A list of assumptions and comments is located to the right of the diagram in the tool and listed below:

- Fire does not spread to local surroundings
- Fire does not spread to another vehicle

- "Contamination" implies pollutant concentrations above acceptable levels
- Note: UBP = ECO-Point, a unit of environmental impact
- % of suppression media collected and destroyed is the same for all media (foam + water)
- Notify water treatment plant (WTP) if any fire water run-off is going there
- Disposal site for used blanket, foam, water, and soil is 100 km from incident
- Reference case for non-specific effects is to let the vehicle burn
- Reference case uses default response vehicle numbers

Interactive plots of the results, that change when the input data change, are located below the user input area. These results show overall comparisons; the detailed analysis worksheet is available if the user is interested in seeing more detailed results. An example of global results, from the LCA models, is shown in Figure 15, where the results have been normalized to the scenario having the highest impact in each category. The results, which are based on the input shown in Table 9 above, show that comparison scenario 1 has the highest (worst) impact in all categories. The reason for this is that much more water is used is scenario 1 than in scenario 2, even though scenario 2 uses 0.5 litre of 3F foam concentrate. The reference case "Let it Burn" has the lowest impact in all categories except Global Warming.

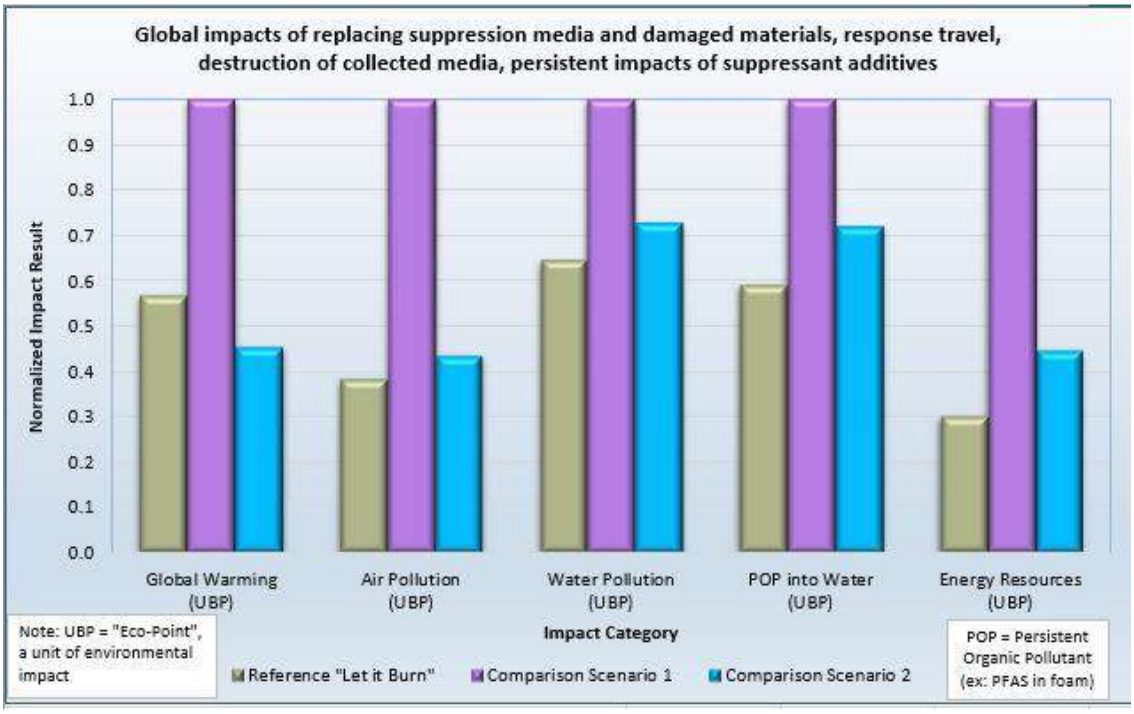

Figure 15: Example of global environmental impact results plotted in the VEHICLES Input worksheet.

Examples of the local impacts resulting from the input in Table 9 are shown in Figure 16 below. As mentioned above, the "Let it Burn" reference case does not apply to the local impacts because there is no fire water run-off. The surface water impact indicates the volume of clean water needed to dilute the contaminants in the fire water run-off to an acceptable concentration. The soil impact indicates the volume of soil that must be excavated and sent to a treatment facility, for two possible types of soil. The groundwater impact indicates the distance needed for the contaminants to travel in the soil and thus be degraded by organisms to an acceptable level, assuming the soil type is moraine. In this example much more water is used in scenario 1, and it requires the excavation of much more soil, but it also dilutes the concentration of contaminants. The amount of clean surface water needed to dilute the contaminants in the fire water run-off is not significantly higher for scenario 1 than for scenario 2 due to this dilution effect. This is also true for groundwater contamination, where the degradation distance is lower for scenario 1, even though there is much more fire water run-off. The presence of 3F foam in the fire water run-off is evident in the surface water and groundwater results but has no effect on the amount of soil to be excavated.

It is important to note that the results shown in Figure 15 and Figure 16 are related to the input shown in Table 9. Using different input data in the user-created scenarios will result in different outcomes.

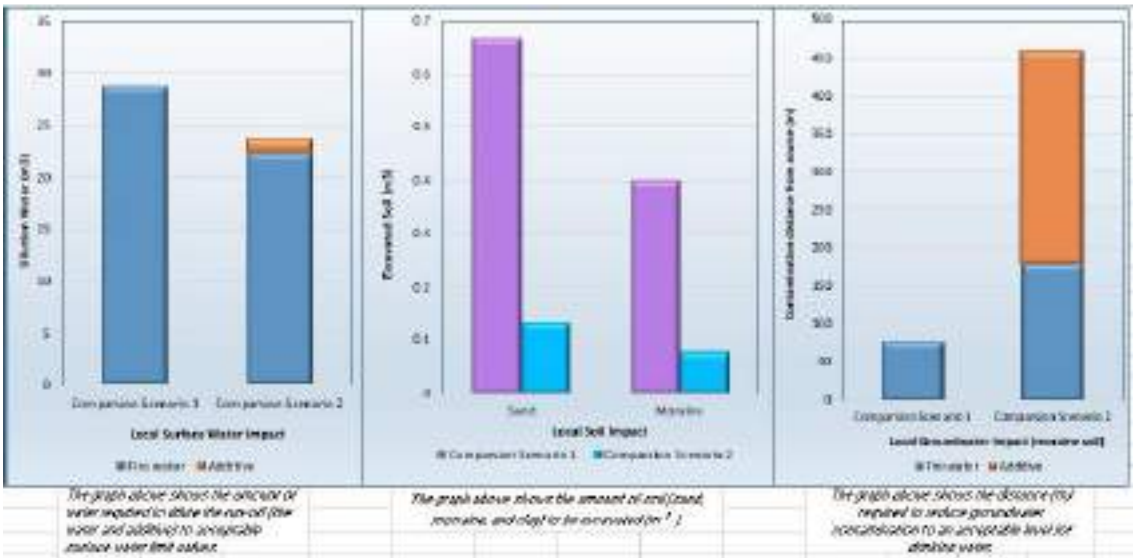

Figure 16: Example of local environmental impact results plotted in the VEHICLES Input worksheet.

4.4. VEHICLES Detailed Analysis worksheet

The results shown in the *VEHICLES Detailed Analysis* worksheet change when the input data change. The input data itself can only be changed in the *VEHICLES Input* worksheet and a copy of it is shown "greyed-out" in the *VEHICLES Detailed Analysis* worksheet to indicate that it cannot be changed in this worksheet.

The detailed global impacts are located to the right of the grey user input area, beginning with the same plot shown in Figure 15 above. To the right of this plot is a breakdown of the contributions made by the smoke, replacing the suppressants, response travel, and fate (treatment) of the suppression media, shown in Figure 17 below. To the right of this plot is a further breakdown of the fate of the suppression media, shown in absolute UBP (ECO-point) values. These impacts represent how much fire water run-off goes to a waste treatment plant (WTP), is destroyed in an incinerator, how much soil needs to be treated, and how much persistent organic pollutant (POP) is released to water.

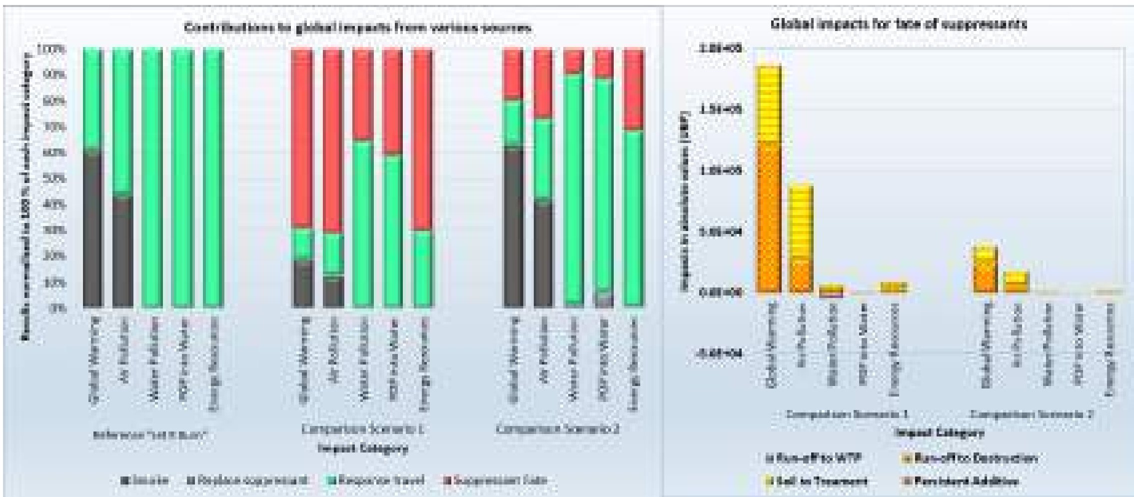

Figure 17: Example of detailed global environmental impacts plotted in the VEHICLES Detailed Analysis worksheet.

For this example, based on the input shown in Table 9, the contributions for global impacts from various sources are normalized to 100 % in each category so that the relative impacts of the contributors can be seen easily. Since the reference case includes only the response travel and smoke from the burning vehicle, one can see that smoke has impacts in the Global Warming and Air Pollution categories and travel to/from the incident site account for the rest of the impacts. In scenarios 1 and 2, there is suppressant that must be taken to a treatment facility. In scenario 2, a small contribution to Water Pollution and POP into Water can be seen, but it comes from sources other than the 3F foam and is also present as a smaller percentage of the impacts in the reference case and scenario 1.

Looking more closely at the fate of the suppressants, when fire water run-off is cleaned in a water treatment plant it becomes clean and useful again. This shows up as a negative impact as plotted in Figure 17 because environmental impacts are customarily shown as positive values in LCA results. For this example, the larger amount of water used in scenario 1 creates higher impacts across all the categories.

The detailed local environmental impacts for vehicle fires are presented, both in tabular and graphic form. An example of the tabular results is given in Table 10.

Table 10: Example of detailed local environmental impacts tabulated in the VEHICLES Detailed Analysis worksheet.

Surface water	***Vol (m³)***	***Critical Species***
Comparsion Scenario 1- Total run-off released (water + additive)	0.10	
Comparison Scenario 1- Required dilution for fire water	29	PAH
Comparison Scenario 1- Required dilution for additive	0	
Comparsion Scenario 2- Total run-off released (water + additive)	0.02	
Comparison Scenario 2- Required dilution for fire water	22	PAH
Comparison Scenario 2- Required dilution for additive	1	Magnesium salts
Soil	***Vol (m³)***	***Time to reach volume (h)***
Comparison Scenario 1- Volume of Sand* to Excavate	0.7	1.48E-03
Comparsison Scenario 1- Volume of Moraine* to Excavate	0.4	3.56E-01
Comparison Scenario 2- Volume of Sand* to Excavate	0.1	2.97E-04
Comparison Scenario 2- Volume of Moraine* to Excavate	0.1	7.13E-02
**Note: Assume that the soil is completely of one type (Sand or Morraine)*		
Groundwater	***Distance (m)***	***Critical Species***
Comparison Scenario 1- Distance fire water travels in groundwater (sand)	10	Sb
Comparison Scenario 1- Distance additive travels in groundwater (sand)	0	
Comparison Scenario 1- Distance fire water travels in groundwater (moraine)	79	Sb
Comparison Scenario 1- Distance additive travels in groundwater (moraine)	0	
Comparison Scenario 2- Distance fire water travels in groundwater (sand)	36	Sb
Comparison Scenario 2- Distance additive travels in groundwater (sand)	77	Glycols
Comparison Scenario 2- Distance fire water travels in groundwater (moraine)	179	Sb
Comparison Scenario 2- Distance additive travels in groundwater (moraine)	282	Glycols
Note: Assume contaminant concentration is not diluted in groundwater		

The remaining results provided in the *VEHICLES Detailed Analysis* worksheet are a plot of the time required for fire water run-off to travel through sand, moraine and clay and a plot of distances needed to degrade the fire water run-off to acceptable levels in sand, moraine and clay for the two comparison scenarios. These plots are shown below in *Figure 18*.

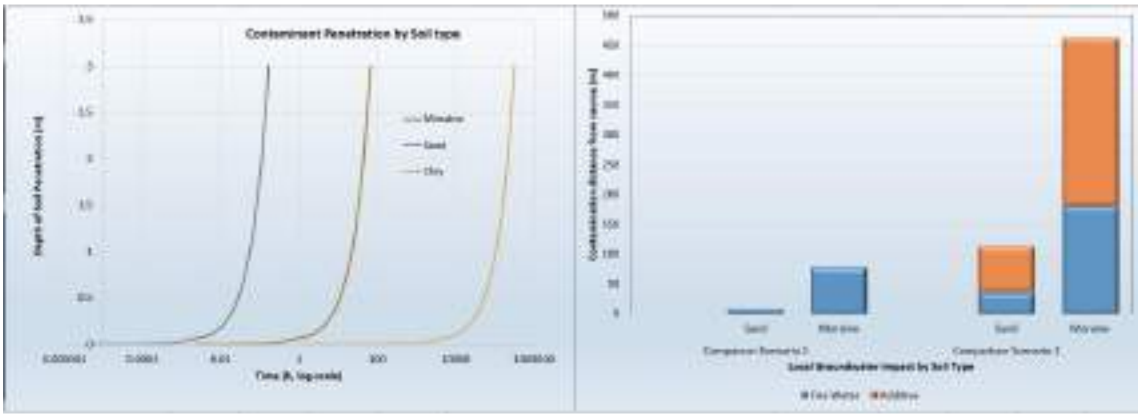

Figure 18: Example of local environmental impact results plotted in the VEHICLES Detailed Analysis worksheet.

The time required for fire water run-off to travel through sand, moraine and clay shown in Figure 18 is not specific to a particular scenario; it is included as an illustration of the importance of soil type when estimating contaminant transport. The local effects of fire water run-off on groundwater in different types of soil are shown in the right part of Figure 18.

4.5. ENCLOSURE Input worksheet

The *ENCLOSURE Input* worksheet is where the users provide their input for two enclosure fire comparison scenarios. The user input area for enclosure fires has two parts, one for the fire(s) and another for the response to the fire(s). The input cells are green and all the other cells are locked. There is a brief description of the input in the column to the left of the green input cells and the column to the right of the input cells contains default values that the user can consider using if the input is unknown or uncertain. As with the vehicle fires, when the user clicks on an input cell additional information pops up that gives further guidance.

The fire input area is shown in Table 11. The user can input information about the openings to the rooms, room sizes, and fuel loads for up to four rooms. The user can also input the start, end, and whether active suppression was used in each of the rooms for each of two comparison scenarios. If zeros are entered as input for all the cells in any given room in the input table, and if “No” active suppression is selected, that room will not be included in the calculations. If the fire start and end times are the same for a room, there will be no fire in that room.

Table 11: Example of user input area for enclosure fire model.

Fire Compartment Model Input					Defaults
Room number	1	2	3	4	
Opening average height dimension [m]	1.2	1.2	1.5	0	1.2
Opening area [m²]	10	15	10	10	10
Room size [m²]	60	60	40	60	60
Fuel load [MJ/m²]*	450	600	450	400	250 - 450
Comparison scenario 1:					
Start of full developed fire [min]	5	5	10	0	5
End of full developed fire [min]	10	5	60	15	30
Active suppression used? (Select No if start time=end time)	Yes	No	Yes	Yes	Yes
Comparison scenario 2:					
Start of full developed fire [min]	5	5	10	0	5
End of full developed fire [min]	40	20	50	0	30
Active suppression used? (Select No if start time=end time)	Yes	Yes	Yes	No	Yes
*Note that the fire will burn out when the fuel load is consumed.					

A cartoon diagram to the right of the fire model user input area shows graphically whether a fire occurs and whether active suppression is assigned to a room to help the user confirm that the input is accurate for the scenarios being studied. This diagram is shown below in Figure 19.

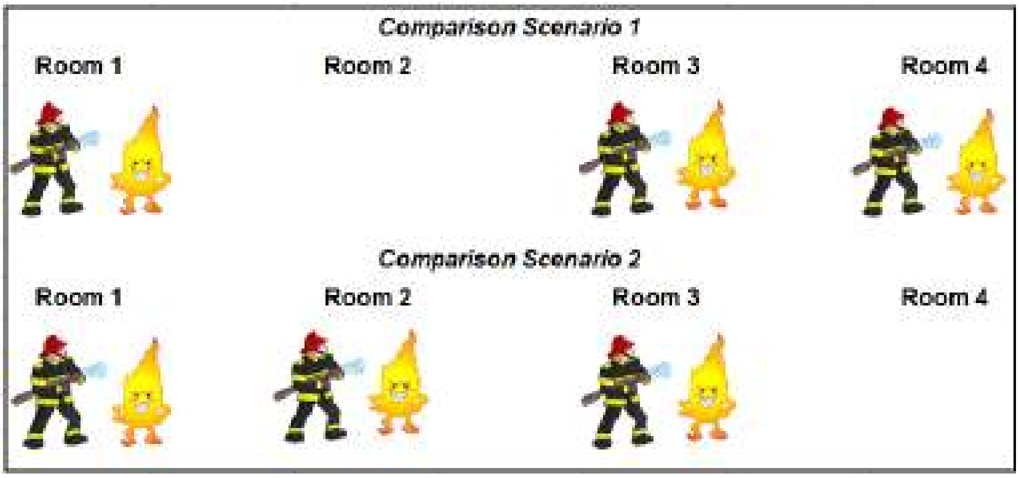

Figure 19: Cartoon diagram indicating whether a fire occurs in a room and if active suppression is used.

The input data for enclosure fires was initially designed for multiple rooms in a fire compartment, but the model can be used for other enclosures as well. School classrooms are used as a representative application throughout this report.

A list of assumptions and comments is located to the right of the cartoon diagram in the tool and listed below:

- Fire does not spread beyond fire compartment
- "Contamination" implies pollutant concentrations above acceptable levels
- % of suppression media collected and destroyed is the same for all media (foam + water)
- Disposal site for collected suppressant and soil is 100 km from incident
- The fire service responds and prevents fire spread beyond fire compartment
- All openings are open with fully developed fire
- A fully developed fire means all building and content materials are damaged

The assumptions and comments for the reference case- in which the entire fire compartment burns, defensive firefighting operations only (to prevent spread outside fire compartment) are:

- Scenarios: 1, 2, or 3 rooms can be "saved"
- Openings, room sizes, and fuel loads can be varied
- Fire can occur in any room at user defined times and durations
- The fire will burn out if the fuel load is exceeded
- Offensive firefighting operations can occur in any scenario except the reference case
- All 4 rooms can be lost with active suppression
- Reference case uses default response vehicle numbers

For enclosure fires, the user input area for the fire response is located directly below the input area for the fire(s). This area is shown in Table 12 and is very similar to the input for the vehicle fires, with the exception that handheld fire extinguishers and blankets are not suppression options, the area of wetted soil is added, and the timing of the fire(s) has been moved to the fire input for enclosures.

Table 12: Example of user input area for the response to enclosure fire(s) in the ENCLOSURE Input worksheet.

Other Input	Comparison Scenario 1	Comparison Scenario 2	Defaults
Water used (liters)	10000	500	1000
Additive used (liters) Enter both type and amount	0	1	0
Type of additive used (select from dropdown list at right)	AFFF	AFFF	Unknown
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	5	[illegible]	[illegible]
Number of light vehicles responding (like an ambulance)	1	[illegible]	
Number of passenger vehicles responding (car, SUV)	2	[illegible]	
Average 1-way distance vehicles travel (km)	15	[illegible]	[illegible]
% of suppressant (water + additive) that goes to the environment	15%	[illegible]	[illegible]
% of fire water run-off that goes to water treatment plant (WTP)	0%	0%	<< 25 % each
% of fire water run-off collected & destroyed	25%	25%	
% of fire water run-off that goes to soil	50%	50%	
% of fire water run-off that goes to surface water	25%	25%	
Area of wetted soil (m^2)	40	40	40

Allowable input
Currently, only foam is allowed as input. This will change as more information on other additives becomes available.

As with vehicle fires, users can compare the types of suppression media used (choosing from water and a selection of five foam additives), the amount and type of vehicles used in the response and the distance they travel, and the fate of the fire water run-off. If more than two comparison scenarios are desired the user can save the file with a different name and run it again as many times as needed. The reference case is always “let it burn”, in which responders arrive but do not suppress the fire.

An important difference between the *VEHICLES Input* worksheet and the *ENCLOSURE Input* worksheet is the addition of the active suppression user input for the enclosure fire model. This input must be coordinated with the response input. If active suppression is used on any room in a scenario then there must be water used in that scenario as well. If an additive is used in a scenario, there must also be water used in that scenario.

Interactive plots of the results, that change when the input data change, are located below the user input area. These results show overall comparisons; the detailed analysis worksheet is available if the user is interested in seeing more detailed results. An example of global results from the LCA models, is shown in *Figure 20*, where the results have been normalized to the scenario having the highest impact in each category. *Figure 20* shows results from the user input shown in *Table 11* and *Table 12*. The reference case "Let it Burn" has the highest impacts in all categories except POP into Water, in which case scenario 2 has the highest impact due to the use of AFFF. For this example, except for the POP into Water category, the two comparison scenario results are similar for Global Warming and Air Pollution but scenario 1 is higher than scenario 2 for Water Pollution and Energy Resources mainly because of the differences in fire durations.

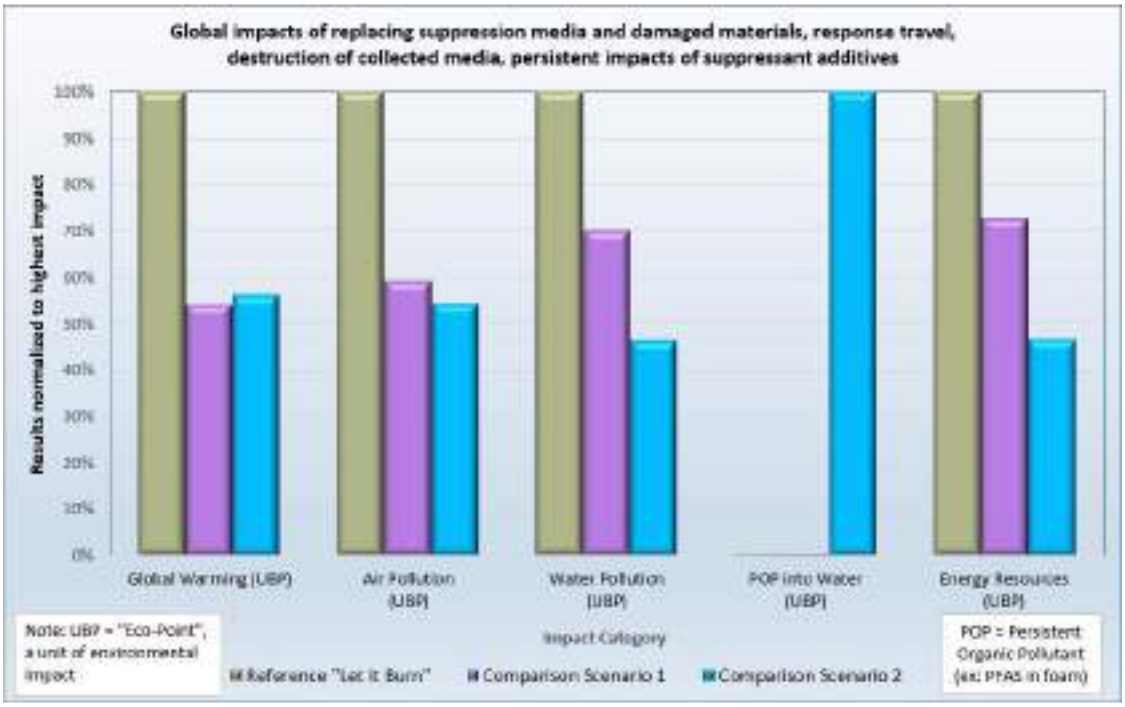

Figure 20: Example of global environmental impact results plotted in the ENCLOSURE Input worksheet.

Examples of the local impacts are shown in Figure 21 below. As mentioned above, the "Let it Burn" reference case does not apply to the local impacts because there is no fire water run-off. As with the vehicle fire results, the surface water impact indicates the volume of clean water needed to dilute the contaminants in the fire water run-off to an acceptable concentration. The soil impact indicates the volume of soil that must be excavated and sent to a treatment facility, for two possible types of soil. The groundwater impact indicates the distance needed for the contaminants to travel and be degraded by organisms in the soil to an acceptable level, assuming the soil type is moraine. In this example the presence of AFFF in the fire water run-off is evident in the surface water and groundwater results but the large amount of water used in scenario 1 requires more soil excavation than in scenario 2.

It is important to note that the results shown in Figure 20 and Figure 21 are related to the input shown in Table 11 and Table 12. Using different input data in the user-created scenarios will result in different outcomes.

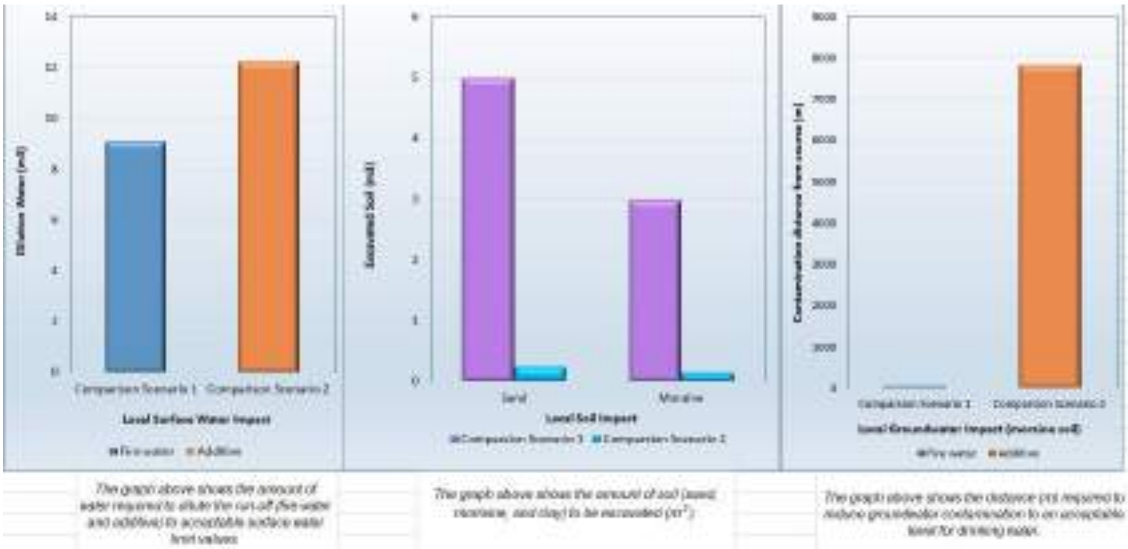

Figure 21: Example of local environmental impact results plotted in the ENCLOSURE Input worksheet.

4.6. ENCLOSURE Detailed Analysis worksheet

The results shown in the *ENCLOSURE Detailed Analysis* worksheet change when the input data change. The input data itself can only be changed in the *ENCLOSURE Input* worksheet and a copy of it is shown "greyed-out" in the *ENCLOSURE Detailed Analysis* worksheet to indicate that it cannot be changed in this worksheet.

The detailed global impacts are located to the right of the grey user input area, beginning with the same general plot of global impacts shown in Figure 20 above. To the right of this plot are five plots, one for each impact category, that show the contributions of each room in each scenario, compared with the "Let it Burn" reference case. These plots are shown in Figure 22 below.

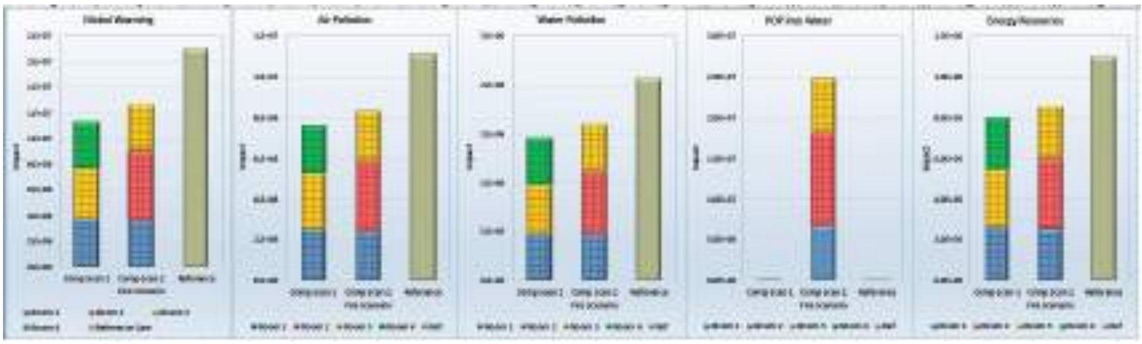

Figure 22: Example of global impact contributions from rooms for two user-created scenarios and the "Let it Burn" reference case.

Both scenarios share the same room configurations, for example their room sizes and fire loads are the same. The fires can burn for different amounts of time and may or may not have active suppression, depending on the user input. The burned rooms share a portion of the impacts related to replacing the structure (based on their area) and replacing the contents (based on their fire load). The response travel is also shared among the rooms in which a fire burns.

For the conditions shown in this simple example, there is no fire or active suppression in room 2 of scenario 1 and room 4 of scenario 2. The impacts for each room vary depending on the user input for the room configurations and for the response.

Below these plots is a breakdown of the global contributions for each scenario made by the smoke, replacing the structure, contents, and suppressants, response travel, and the treatment of the suppression media, shown for scenario 1 and scenario 2 in Figure 23 and Figure 24, respectively. In these plots, each bar is normalized to 100 % of the impact so that the contributions from the sources can be more easily seen. To understand what the total impact for a room in a category is, users should refer to *Figure 22* above, which provides results in absolute numbers for each category.

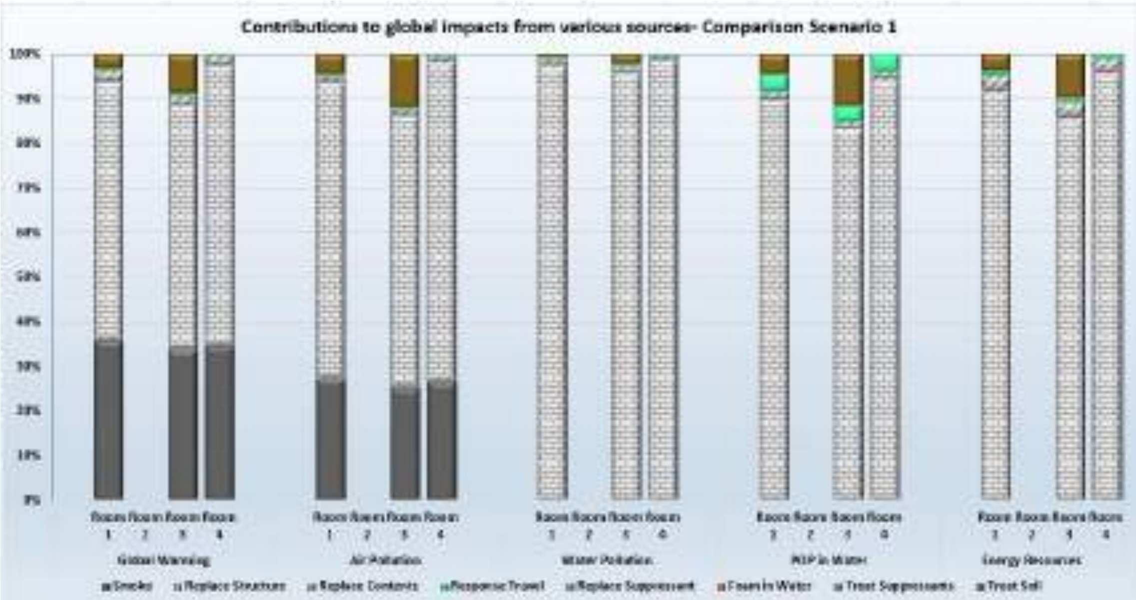

Figure 23: Breakdown of global contributions to impacts to each category per room for scenario 1.

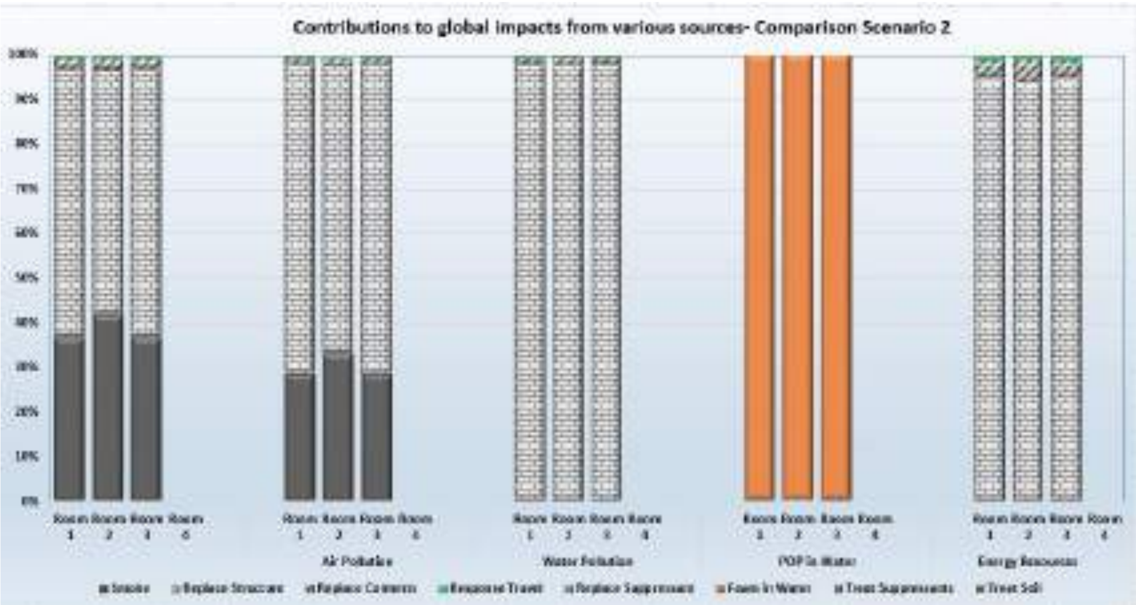

Figure 24: Breakdown of global contributions to impacts to each category per room for scenario 2.

A significant observation that can be made from Figure 23 and Figure 24 is that replacing the structure materials has a very high impact compared with the other sources. The use of foam in scenario 2 also clearly has a major impact in the POP in Water category. Smoke has a noticeable impact in the Global Warming and Air Pollution categories in both scenarios, while the other sources are relatively small contributors for the conditions in this example.

The ERA results are provided in the ENCLOSURE Detailed Analysis worksheet only as tabular data, shown in Table 13. This table is located below the reference user input cells.

Table 13: Example of detailed local impacts for enclosure fires.

Surface water	**Vol (m^3)**	**Critical Species**
Comparsion Scenario 1- Total run-off released (water + additive)	1.50	
Comparison Scenario 1- Required dilution for fire water	9	Zinc
Comparison Scenario 1- Required dilution for additive	0	
Comparsion Scenario 2- Total run-off released (water + additive)	0.08	
Comparison Scenario 2- Required dilution for fire water	0	Solids (total dissolved)
Comparison Scenario 2- Required dilution for additive	120	
Soil	**Vol (m^3)**	**Time to reach volume (h)**
Comparison Scenario 1- Volume of Sand* to Excavate	5.00	6.94E-03
Comparsison Scenario 1- Volume of Moraine* to Excavate	3.00	1.67E+00
Comparison Scenario 2- Volume of Sand* to Excavate	0.25	3.47E-04
Comparison Scenario 2- Volume of Moraine* to Excavate	0.15	8.33E-02
**Note: Assume that the soil is completely of one type (Sand, Moraine, or Clay)*		
Groundwater	**Distance (m)**	**Critical Species**
Comparison Scenario 1- Distance fire water travels in groundwater (moraine	56	Lead
Comparison Scenario 1- Distance additive travels in groundwater (morraine)	0	
Comparison Scenario 2- Distance fire water travels in groundwater (moraine	56	Cyanide, Total
Comparison Scenario 2- Distance additive travels in groundwater (moraine)	24604	Cocoamidopropyl betaine
Note: Assume contaminant concentration is not diluted in groundwater		

4.7. Worksheets unavailable to the users

There are many worksheets in the Fire Impact tool that are hidden from the end users. They include worksheets for calculating the ERA and LCA results, worksheets with data from experimental and modelling software results used to develop the fire and LCA models, worksheets used to facilitate the user interface, and worksheets for sensitivity analysis. The details of these worksheets, with the exception of protected data, are available from RISE upon request.

Many of the cells in the worksheets that the users can see are locked so that the calculations that might be attached to the cells are protected.

5. Case Studies

In this chapter the Fire Impact tool will be used to predict the impacts from two case studies, one for a vehicle fire and the other for a school fire. In both cases the analyses will start with an approximation of the actual event using data taken from reports, then the tool will be used to explore other possible conditions to illustrate how the tool works and how it can be used for training and pre-planning purposes.

5.1. Vehicle fire analysis

The following analysis is based on the vehicle fire reported by (Palmqvist, 2018) in which a farm tractor burned in July during a dry time period in an agricultural field located in a sensitive area. There is an aquifer in sandy/gravelly soil under the field that supplies drinking water to several towns in the Karlstad municipality. The fire had consumed the tractor so there was no property to protect, there was also no risk of fire spread, see Figure 25. The tractor's fuel tank had ruptured and about 300 litres of diesel fuel either burned or soaked into the soil. The first responders extinguished the fire using about 3000 litres of water, which mixed with the diesel fuel and other fire effluents. No fire water run-off was collected, all of it went into the soil.

The fire occurred in the morning, in the afternoon of the same day soil samples were tested for oil and polyaromatic hydrocarbons (PAH). There was a noticeable oily smell in the soil. That day 176 tonnes (132 m^3) of soil were excavated from the site and sent to a landfill. The next day another 24 tonnes (18 m^3) were excavated due to a continuing oily smell, for a total of 150 m^3 of soil.

The environmental investigator concluded that 15-25 tonnes (11 – 19 m^3) of soil would have had to be excavated if a different extinguishing choice had been made.

Figure 25: Tractor in sensitive area after fire was extinguished.

5.1.1. Fire Impact tool set-up

The Fire Impact tool uses a passenger car in the fire and LCA models so the results are be somewhat different than if these models were based on a farm tractor. The input to the *VEHICLES Input* worksheet is listed below:

- The report does not state the time that the responders arrived after the fire started, but it does state that the fire was well developed so 25 minutes will be used.
- No additive, handheld fire extinguisher, or blanket was reported.
- The number and type of vehicles were not explicitly stated so the default values will be used.

- Assuming the responders came from Karlstad, the average one-way distance is 15 km according to Google Maps ®.
- There is no information about the amount of fire water run-off that goes into the environment so the default of 50 % will be used.
- All of the fire water run-off that goes into the environment soaks into the soil.

Since there is no scenario 2 in this initial analysis of the response to the tractor fire, it is set to be the same conditions as the reference case ”Let it Burn”. The results are shown in Figure 26 and Figure 28, where it is very clear that letting the tractor burn has much less impact on both the global and local environments than using 3000 litres of water to extinguish it.

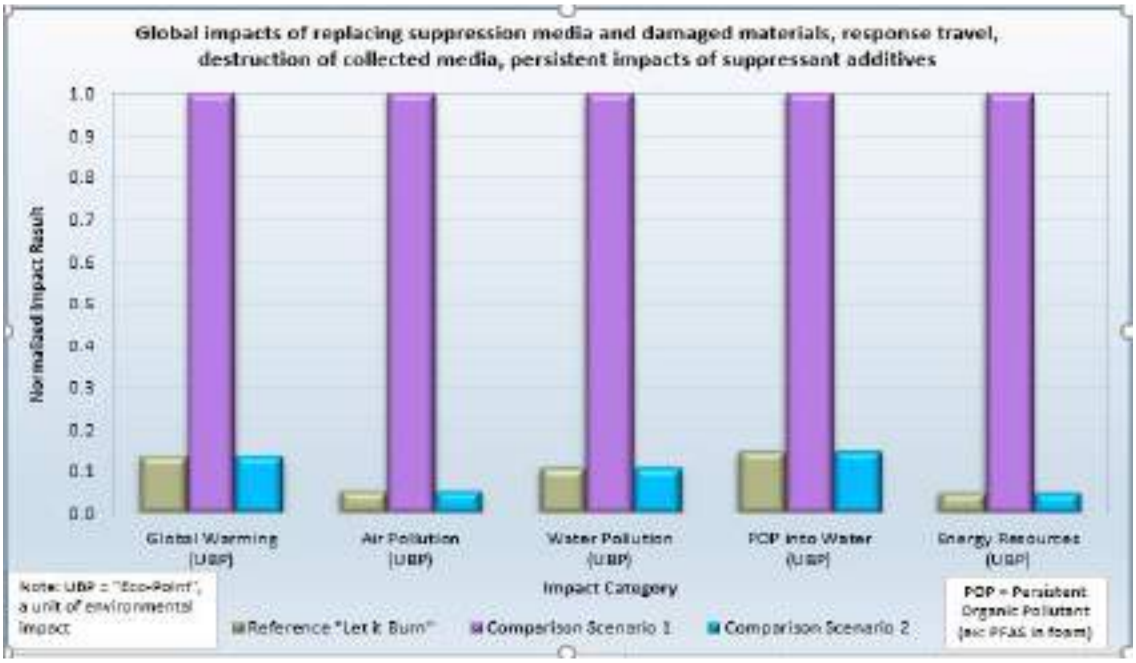

Figure 26: Global results of the initial analysis of a tractor fire in a sensitive area

Comparing the ”Let it Burn” reference case with scenario 1, the highest impacts in all categories are attributed to scenario 1. Although no foam was used in the extinguishing effort, a small amount of persistent contaminants are released into the environment due to the response travel and treating the soil (because the soil is transported to a landfill), and a very small amount is associated with replacing the water used.

A closer look at the distribution of the sources of the impacts shows, in Figure 27, that the main sources of contamination for the ”Let it Burn” case are smoke and response travel. The main source in scenario 1, across all categories, is treating the suppressant, which in this case means excavating the soil and transporting it to a landfill.

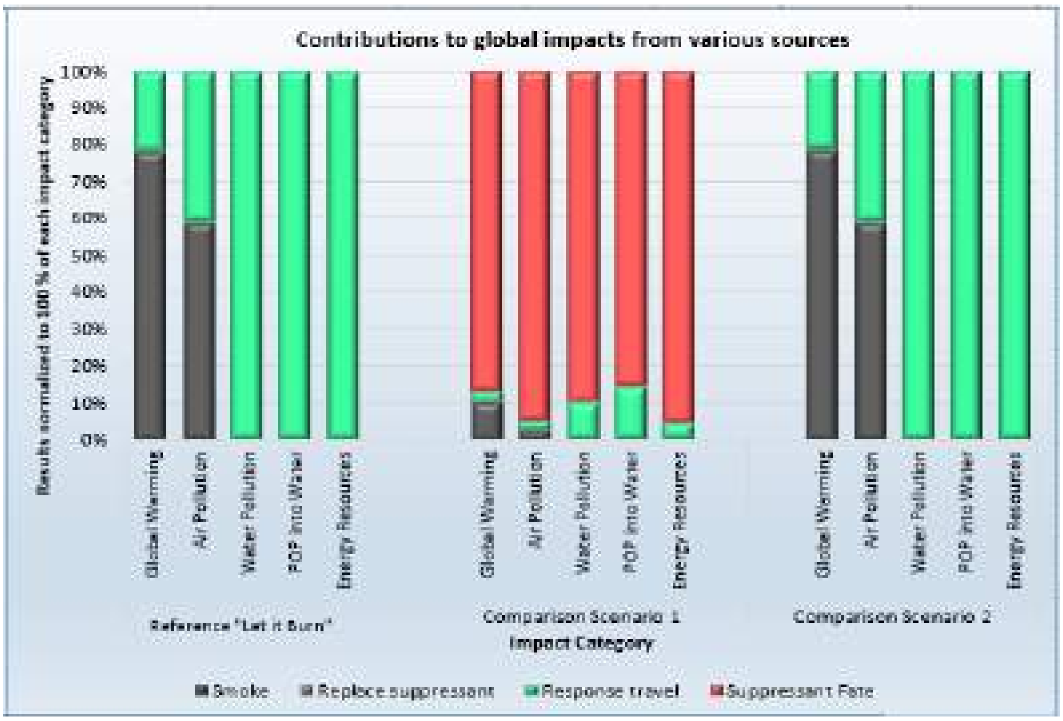

Figure 27: Sources of contamination of tractor fire initial analysis.

The local effects of the tractor fire are shown in Figure 28 below. Recall that scenario 2 is not used in this initial analysis.

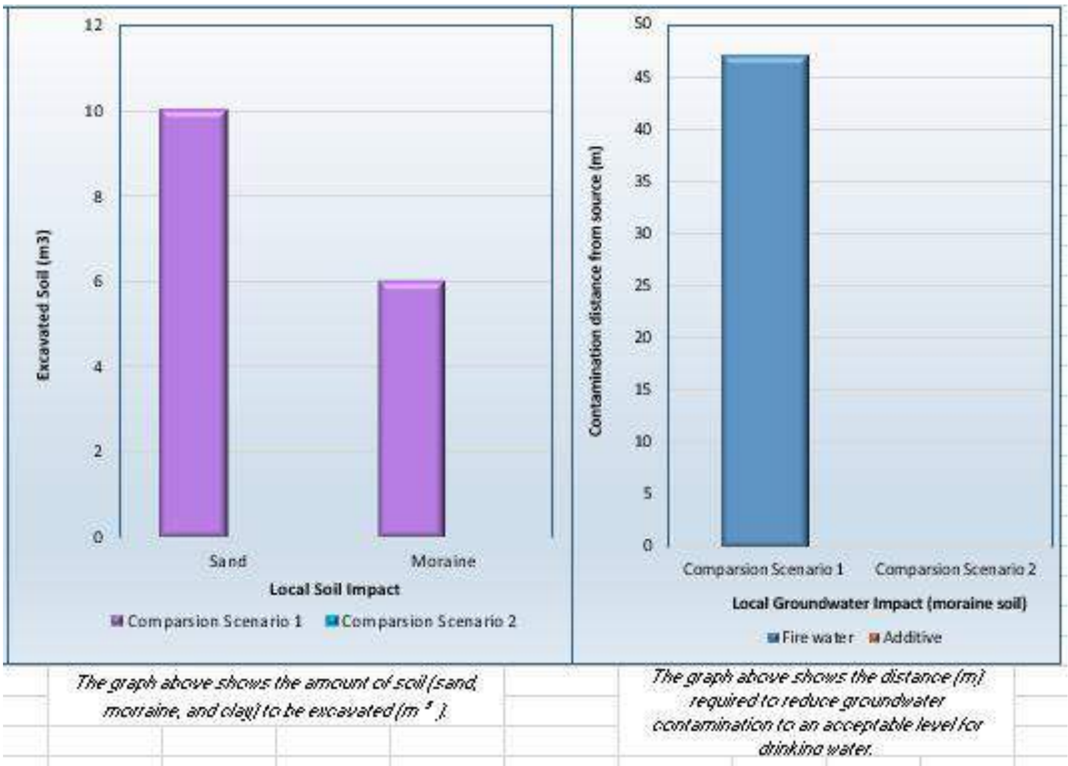

Figure 28: Local results of the initial analysis of tractor fire in a sensitive area.

According to the report, the fire happened during a dry period in July and the soil type is probably a sand/gravel mix. Both these facts partially explain why the Fire Impact tool results for soil excavation are lower than the amount of soil that was actually excavated. There could be other, unknown, reasons related to the exact conditions at the incident site that influenced the amount of soil removed as well. The plot on the right side of Figure 28 shows that wells located within roughly 47 m of the incident could be contaminated by fire water run-off, assuming the soil is moraine. The detailed analysis indicates that this distance is reduced to about 5 m for sand.

5.1.2. Alternative outcome 1

This section considers the case where the responders had chosen different tactics. For example, consider if foam and less water had been used? If 500 litres of water and 5 litres of AFFF is used in scenario 1 and 500 litres of water and 5 litres of 3F is used in scenario 2, with everything else remaining the same, what would the results look like? In Figure 29 the global results show that letting the vehicle burn is still the choice having the least impacts on the environment.

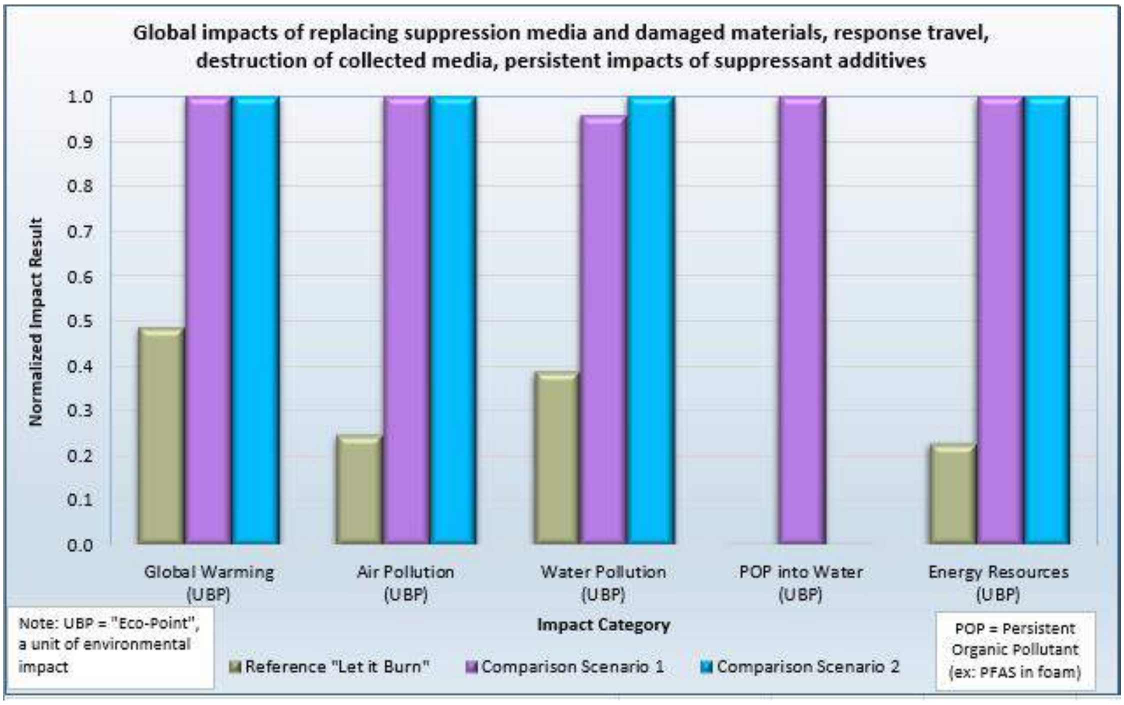

Figure 29: Global results for vehicle fire with two types of foam.

The ”Let it Burn” case still has the lowest impacts in all categories. In most of the impact categories there is not a significant difference between the AFFF and the 3F foams. The exception is the POP into Water category, in which the AFFF used in scenario 1 dominates the category.

A closer inspection of the sources of global impacts shows, in Figure 30, that excavating the soil is still a major contributor to the impacts, but replacing the foam has a noticeable impact for scenario 2. This result may seem puzzling because there appears to be a much bigger impact in the POP into Water and Water Pollution categories for scenario 2, in which 3F foam is used, compared to scenario 1, in which AFFF is used. There are two explanations for this: first, replacing the AFFF in scenario 1 has a smaller percentage of the total impacts from all sources, so if one or more of the other impacts (in this case Suppressant Fate) are larger in scenario 1 than in scenario 2 it will cause the impact of replacing the AFFF to look smaller than replacing the 3F. The second reason is that replacing the suppressants accounts for collecting the raw materials, transporting them to a manufacturer, and processing them into suppression media, in this case foam concentrate. The effects of all these manufacturing-related activities includes releasing some amount of POP into Water and causing some amount of Water Pollution. It is not the same situation as releasing the foam concentrate into the environment in fire water run-off.

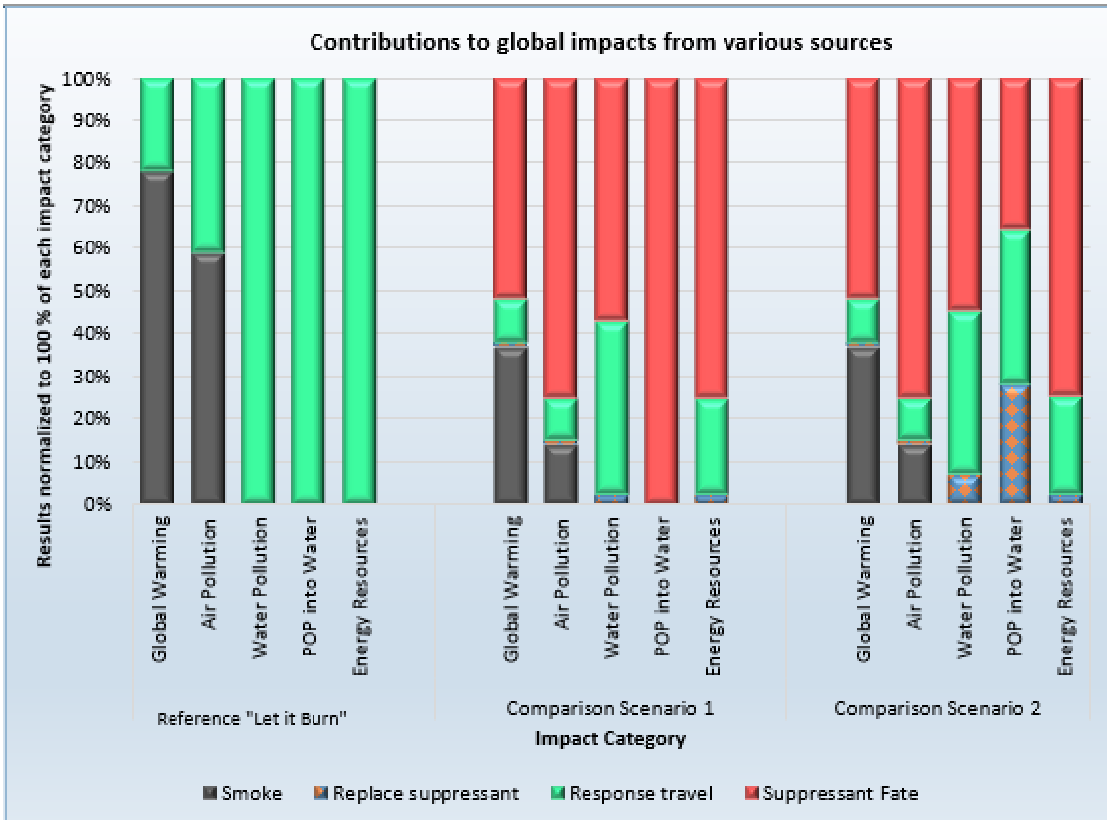

Figure 30: Comparison of two types of foam.

For the local impacts shown in Figure 31, the AFFF used in scenario 1 could contaminate wells within about 17 – 18 km while the 3F used in scenario 2 reduces this distance to under 1 km.

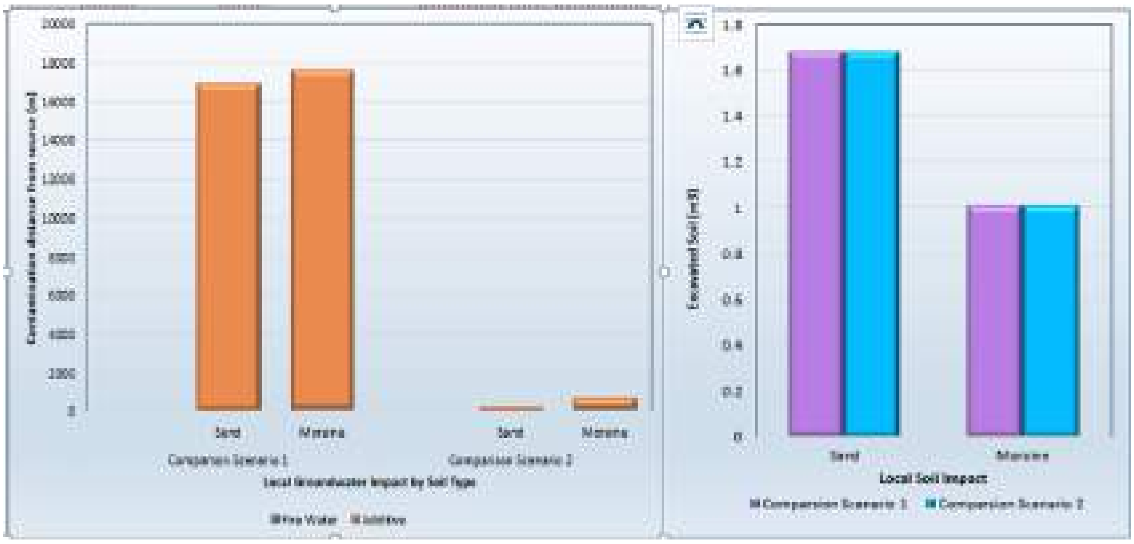

Figure 31: Comparing the local effects of two types of foam

There is no difference between the scenarios in the amount of soil to be excavated because the soil contamination model is based on the amount of wetted soil, not on the contaminants in the fire water run-off. This is an area for future improvement of the Fire Impact tool.

5.1.3. Alternative outcome 2

Another interesting situation to consider is what would happen if the tractor fire had occurred near a lake or other body of surface water. To investigate this, the fire water run-off fate is changed so that half the run-off goes to surface water and half goes to soil. The other input remains the same as in the Alternative outcome 1 section.

The global results show in Figure 32 that the ”Let it Burn” case still has the lowest impacts in all categories. The distribution of contributions from the various sources shown in Figure 33 is very similar to the Alternative outcome 1 comparison as well; even though there is less transport of soil involved, there is no significant difference in the global impacts.

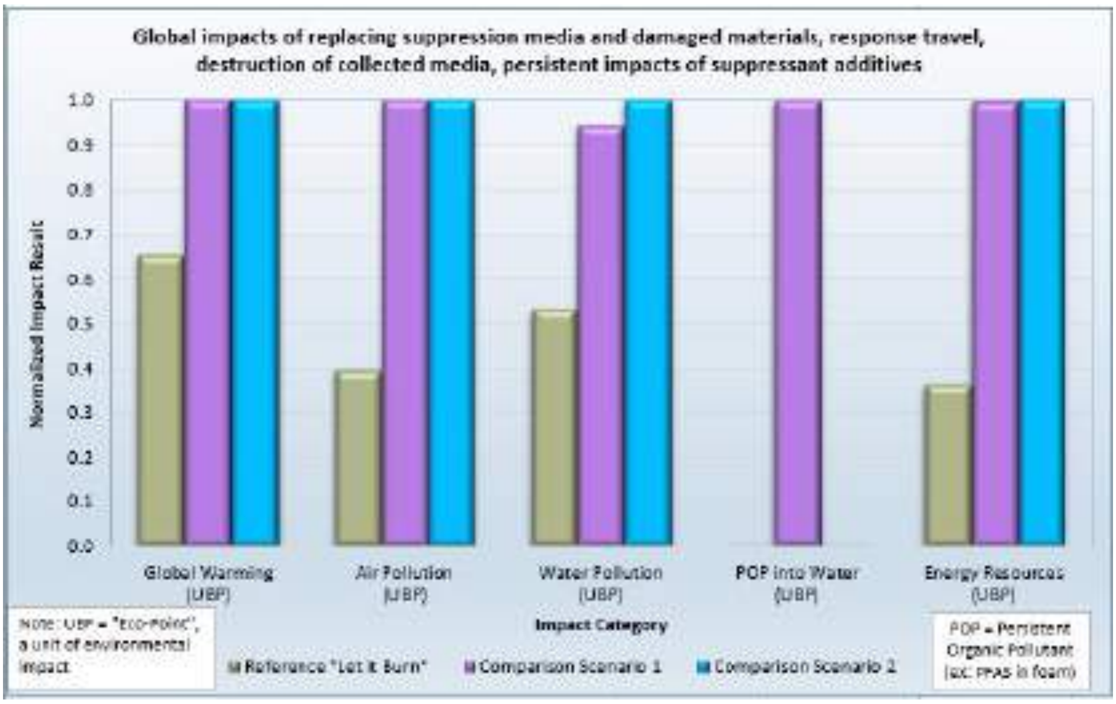

Figure 32: Fire water run-off goes to surface water and soil.

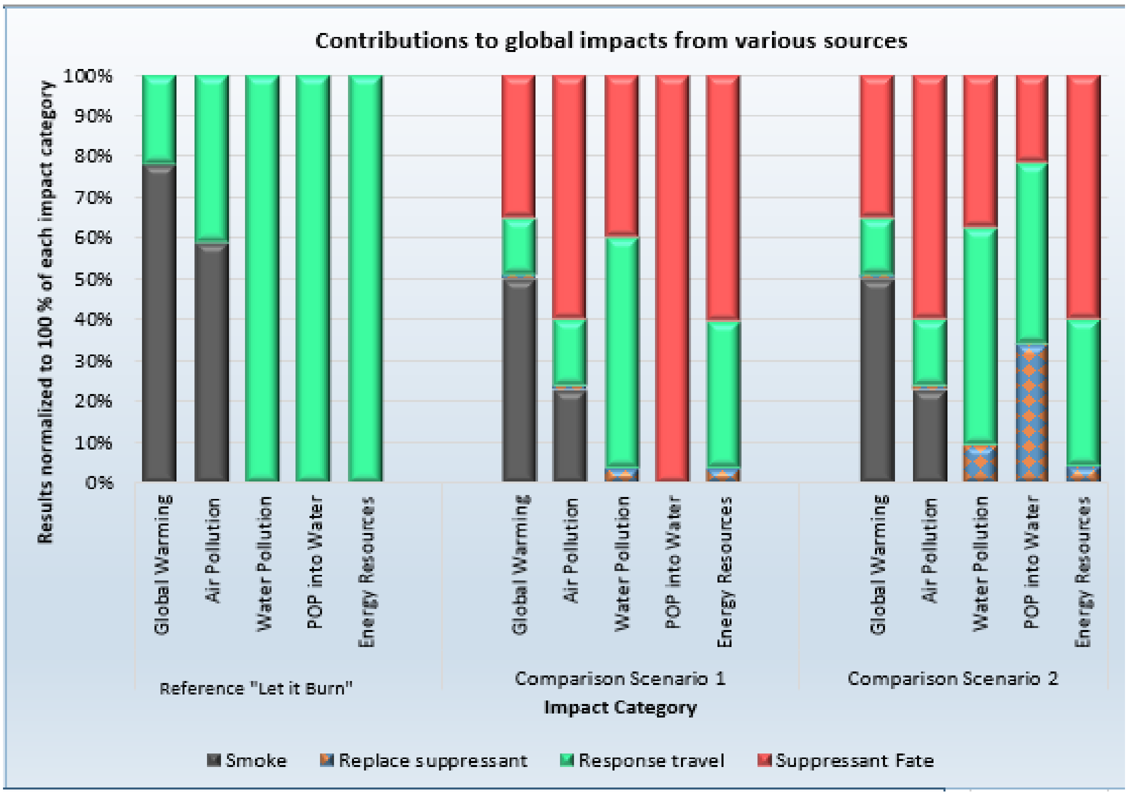

Figure 33: Comparison of contaminant sources for half the run-off water going to surface water and half to soil

There is, however, a difference in the local impacts for this comparison, as shown in Figure 34. Half of the fire water run-off goes to surface water, requiring more than 500 m^3 of clean water to dilute it to an acceptable level for aquatic life for scenario 1, mostly due to the AFFF used. This is compared with about 150 m^3 of clean dilution water for scenario 2, in which 3F was used.

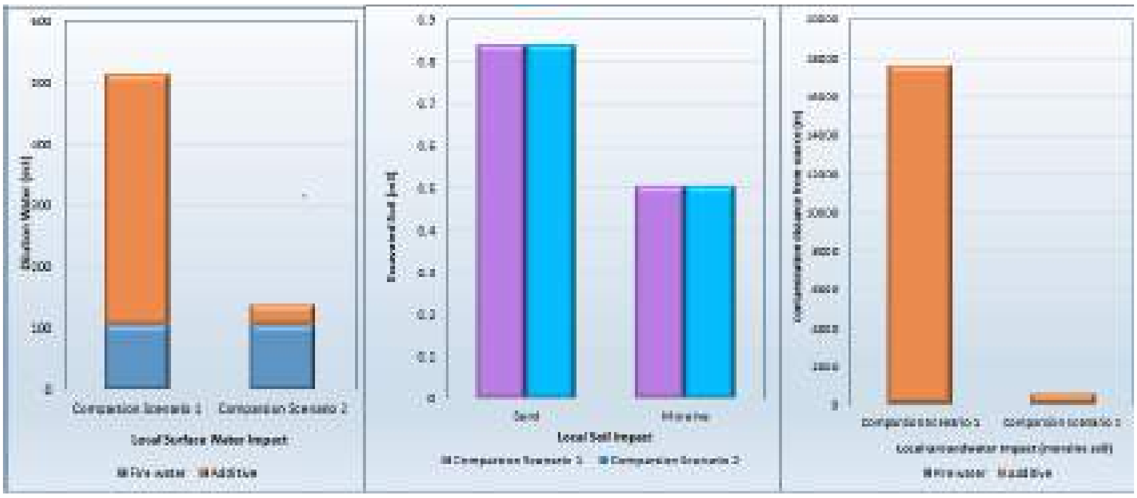

Figure 34: Comparison of local effects when half the fire water run-off goes to surface water and half goes to soil.

As one might expect, the amount of soil to be excavated is half of the amount predicted in Alternative outcome 1, since half of the fire water run-off experienced a different fate. The distance needed to protect drinking water wells is the same in both outcomes because the groundwater model used in the ERA does not consider dilution of the contaminants in the fire water run-off as it flows toward a well, it only considers degradation due to soil-based organisms. This is an area for future improvement to the Fire Impact tool.

5.2. School fire analysis

The following analysis is based on the Grillby school fire reported by (Gustafsson, 2014) in which a fire started, probably in a cloakroom, and spread into two parts of the school: a “pavilion” and an “expedition”, which are part of the same fire compartment. The school was evacuated quickly with no injuries, removing life safety as a strategic priority. Police established an incident perimeter prior to the arrival of the rescue services.

The rescue service strategy was to limit the fire spread to the pavilion if possible, then limit it to the expedition, and then the library, as fall-back positions if necessary. A diagram of the affected school building is shown in Figure 35.

Firefighters used a compressed air foam system (CAFS) and water, along with ventilation, a cutting nozzle, and a backhoe to extinguish the fire. The report does not specify the amount of foam and water used, or the type of foam. At the height of the response there were 32 people, 2 engines, 5 basic vehicles, 3 tankers, 1 ladder truck, 1 smoke safety container, and at least 1 passenger car at the incident site.

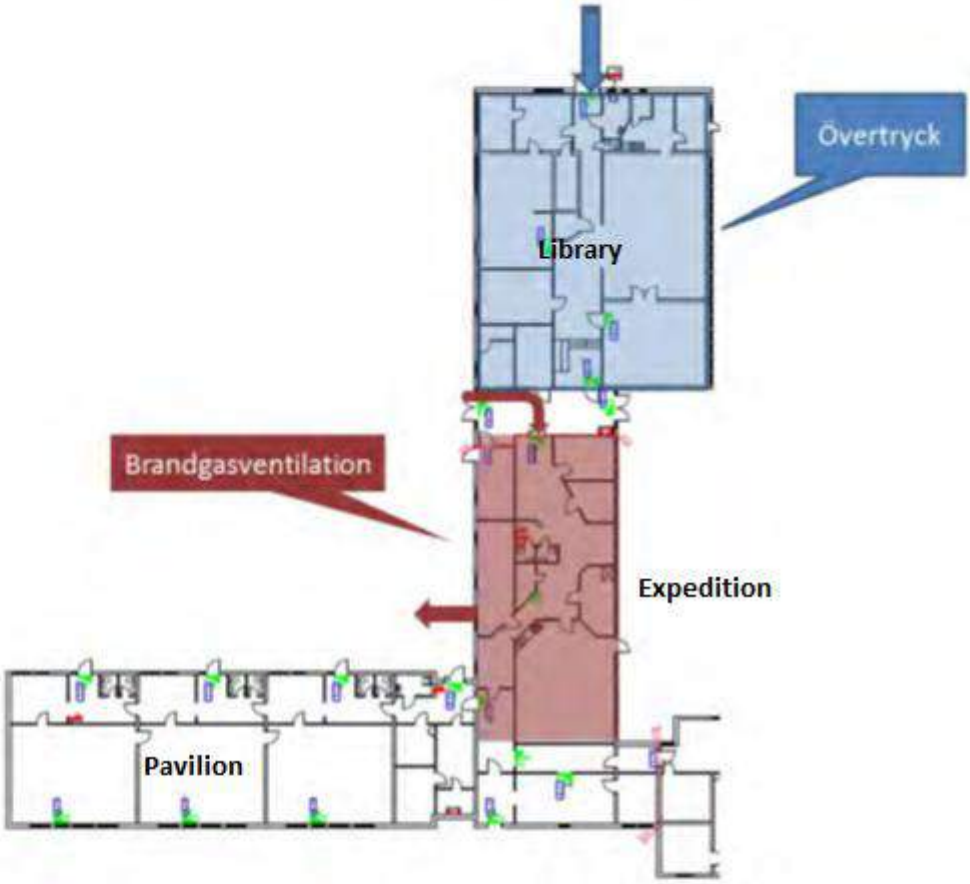

Figure 35: Grillby school fire configuration. Fire started in Pavilion and spread to Expedition, but not to Library

5.2.1. Fire Impact tool setup

Since there is not a large amount of information available about the school and the response to the fire some simplifying assumptions will be made for the purpose of demonstrating the use of the Fire Impact tool. The first step is to set up the fire compartment model. Three large rooms in the fire compartment will represent the affected areas: the pavilion (Room 1), the expedition (Room 2), and the library (Room 3).

- The default of 1.2 m for the average opening height dimension will be used.
- The opening area will be 100 m^2, based on the default ratio of opening area to room area used for smaller classrooms.
- The rooms are approximately the same size according to Figure 35, and they are much bigger than a standard classroom so 600 m^2 is chosen.
- A fuel load of 350 MJ/m^2 is used for the pavilion and expedition, which is in the centre of the default range. The library is given a higher fuel load of 450 MJ/m^2 due to the extra load of books.
- The fire started in the pavilion and burned for several minutes before reaching the fully developed phase so 5 minutes is chosen as the start time.
- The response was finished within about 4 hours of the initial alarm so 240 minutes will be used for the end time of the fire in the pavilion.
- It is not clear when the fire spread to the expedition, so an estimate of 30 minutes is chosen.
- It is also not clear when the fire ended in the expedition, so an estimate of 60 minutes is chosen.
- The fire did not spread to the library.

- Active suppression was used on all three rooms. It was used as a preventative measure for the library.

Comparison scenario 2 is removed from both the fire and response models for the initial setup. Scenario 1 will represent the actual response for this part of the analysis. The fire model input is shown in Table 14 and the response input is listed below and shown in Table 15:

- The amount of water used was not mentioned in the report so 10000 litres is chosen.
- The amount of foam concentrate was not reported. Assuming a 3 % concentrate/water mix and that 1/4 of the total water used in the response was mixed with foam concentrate gives an estimate of 75 litres of foam concentrate.
- The type of foam was not reported so ”Unknown mixture” is chosen.
- According to the report there were at least 2 engines, 5 basic vehicles, 3 tankers, 1 ladder truck, and 1 smoke safety container responding to the incident, which totals at least 12 heavy vehicles.
- According to the report there was at least 1 ambulance (light vehicle) responding to the incident.
- According to the report there was at least 1 passenger car responding to the incident.
- There was a traffic issue due to parents coming to the school to pick up their children, so the response vehicles had to use a slightly longer route. An estimate of 15 km average one-way response travel distance is used per Google Maps ®.
- There was no mention of the fate of the suppression media, therefore default values are used for the percentage of fire water run-off going into the environment and its fate.

Table 14: Fire compartment model input for the initial analysis of the Grillby school fire.

Fire Compartment Model Input					Defaults
Room number	**1**	**2**	**3**	**4**	
Opening average height dimension [m]	1.2	1.2	1.5	0	1.2
Opening area [m²]	100	100	100	0	10
Room size [m²]	600	900	600	0	60
Fuel load [MJ/m²]*	350	350	450	0	250 - 450
Comparison scenario 1:					
Start of full developed fire [min]	5	30	0	0	5
End of full developed fire [min]	240	60	0	0	30
Active suppression used? **(Select No if start time>=end time)**	Yes	Yes	Yes	No	Yes
Comparison scenario 2:					
Start of full developed fire [min]	0	0	0	0	5
End of full developed fire [min]	0	0	0	0	30
Active suppression used? **(Select No if start time>=end time)**	No	No	No	No	Yes
*Note that the fire will burn out when the fuel load is consumed					

Table 15: Response model for the initial analysis of the Grillby school fire.

Response Input	Comparison Scenario 1	Comparison Scenario 2	Defaults
Water used (liters)	10000	0	1000
Additive used (liters) Enter both type and amount	75	0	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture	Unknown
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	12	0	5
Number of light vehicles responding (like an ambulance)	1	0	1
Number of passenger vehicles responding (car, SUV)	1	0	2
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	25%	25%	<< 25 % each
% of fire water run-off collected & destroyed	25%	25%	
% of fire water run-off that goes to soil	25%	25%	
% of fire water run-off that goes to surface water	25%	25%	
Area of wetted soil (m^2)	40	0	40

For the initial analysis the global impacts presented in Figure 36 show that the ”Let it Burn” case is worse than scenario 1 in all categories except POP into Water. The impacts in scenario 1 are split roughly equally between the pavilion and the expedition in all categories (not shown here).

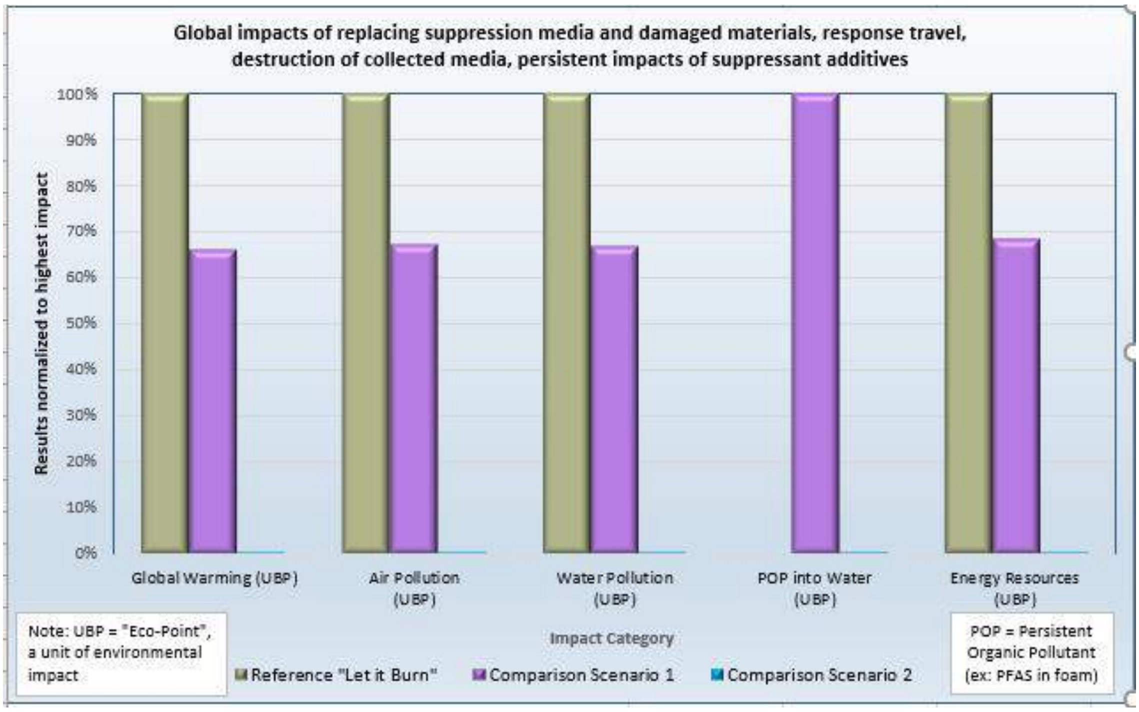

Figure 36: Global results for initial analysis of the Grillby school fire

The distribution of global impacts according to their sources is shown in Figure 37, where it is clear that most of the impacts come from replacing the building materials. A portion of response travel is assigned to Room 3 (library) because active suppression was used to prevent the fire from spreading into it. The same portion of active suppression is also assigned to Room 1 (pavilion) and Room 2 (expedition), but contributions from other sources obscure the relatively small contribution from response travel for Room 1 and Room 2.

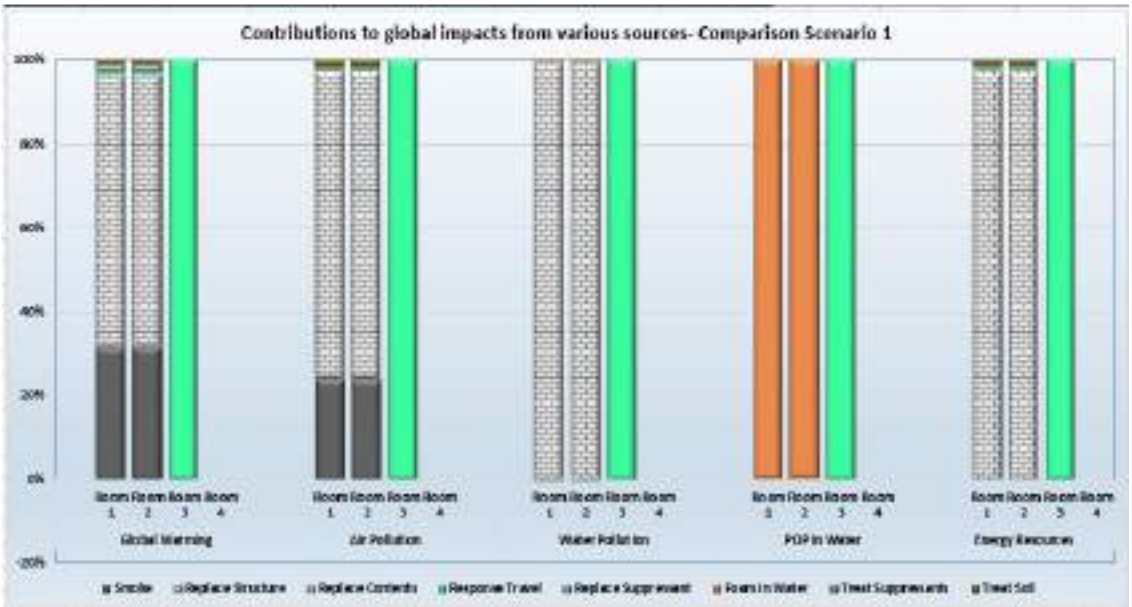

Figure 37: Distribution of global impacts by their source for the initial analysis of the Grillby school fire.

When using the Fire Impact tool for training, it is advisable to *first* look at the surroundings of the incident and make estimates of the amount of surface water, potentially exposed soil and possible distances to the nearest drinking water well(s). These impacts are usually considered acute and could impose negative consequences on the well-being of the community if not given suitable priority.

For this initial analysis the local effects show, in Figure 38, that about 5800 m^3 of clean dilution water would be necessary to lower the concentration of contaminants in the foam to an acceptable level for aquatic life if 25 % of the fire water run-off went to surface water. Looking at Google Maps® it does not appear that there are any large surface water bodies near the Grillby school but it is possible that the fire water run-off could be captured in a ditch or other drainage collection system and make its way to surface water that exists some distance away from the incident. This type of information is helpful when setting up a training exercise.

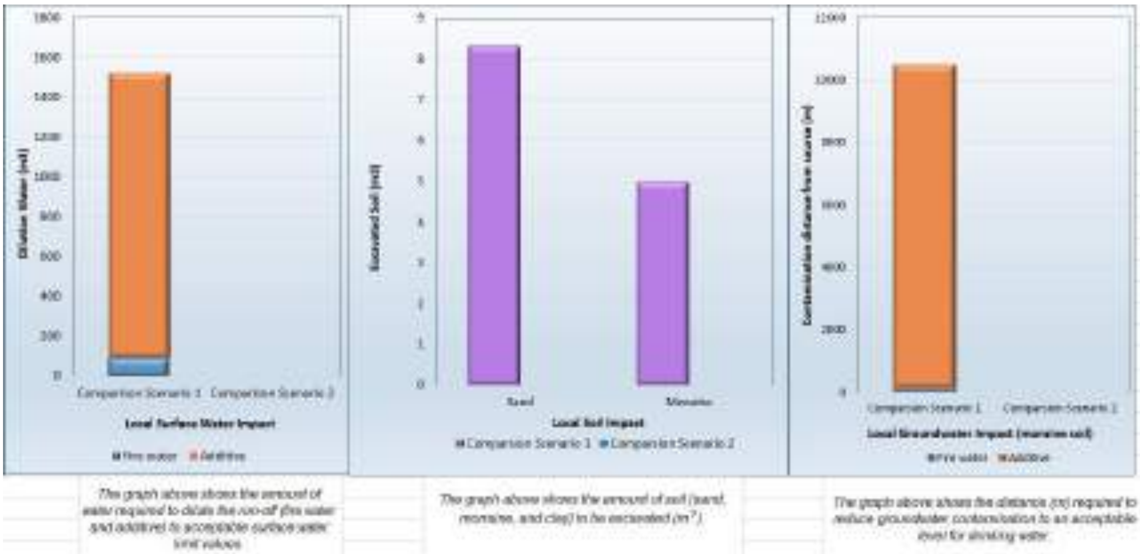
Figure 38: Local effects of initial analysis of the Grillby school fire.

Figure 38 also shows the expected amount of soil that would need to be excavated if 25 % of the fire water run-off went into the soil (around 8 m^3 for sand or 5 m^3 for moraine) and the distance needed to degrade the foam in the run-off to a level acceptable for drinking water (10 km).

5.2.2. Alternative outcome

This alternative outcome will be used to investigate the consequences if the responders were not able to prevent the fire from spreading to the library. The amount of suppression media will be increased only slightly (10 %) because active suppression was already being used to protect the library. The fire model input for this alternative outcome is shown in Table 16.

Table 16: Fire compartment input comparing the initial analysis (scenario 1) with a scenario in which the library burns (scenario 2).

Fire Compartment Model Input					Defaults
Room number	1	2	3	4	
Opening average height dimension [m]	1.2	1.2	1.5	0	1.2
Opening area [m²]	100	180	100	0	10
Room size [m²]	600	600	600	0	60
Fuel load [MJ/m²]*	350	350	450	0	250 - 450
Comparison scenario 1:					
Start of full developed fire [min]	5	30	0	0	5
End of full developed fire [min]	240	60	0	0	30
Active suppression used? (Select No if start time>=end time)	Yes	Yes	Yes	No	Yes
Comparison scenario 2:					
Start of full developed fire [min]	5	30	40	0	5
End of full developed fire [min]	240	60	100	0	30
Active suppression used? (Select No if start time>=end time)	Yes	Yes	Yes	No	Yes
*Note that the fire will burn out when the fuel load is consumed					

The response input is the same as the initial analysis for scenario 1, shown in *Table 17*, and 10 % more suppression media used for scenario 2. All other inputs are equal.

Table 17: Response input comparing the initial analysis (scenario 1) with a scenario in which the library burns (scenario 2).

Response Input	Comparison Scenario 1	Comparison Scenario 2	Defaults
Water used (liters)	10000	11000	1000
Additive used (liters) Enter both type and amount	75	82.5	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture	Unknown
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	12	12	5
Number of light vehicles responding (like an ambulance)	1	1	1
Number of passenger vehicles responding (car, SUV)	1	1	2
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	25%	25%	<< 25 % each
% of fire water run-off collected & destroyed	25%	25%	
% of fire water run-off that goes to soil	25%	25%	
% of fire water run-off that goes to surface water	25%	25%	
Area of wetted soil (m^2)	40	40	40

The global results shown in *Figure 39* show higher impacts for scenario 2 in three categories and virtually no change in two categories. The Water Pollution and Energy Resources categories are not sensitive to the changes in the water and foam used for fire suppression in scenario 2, although differences in these impacts are seen in the local results.

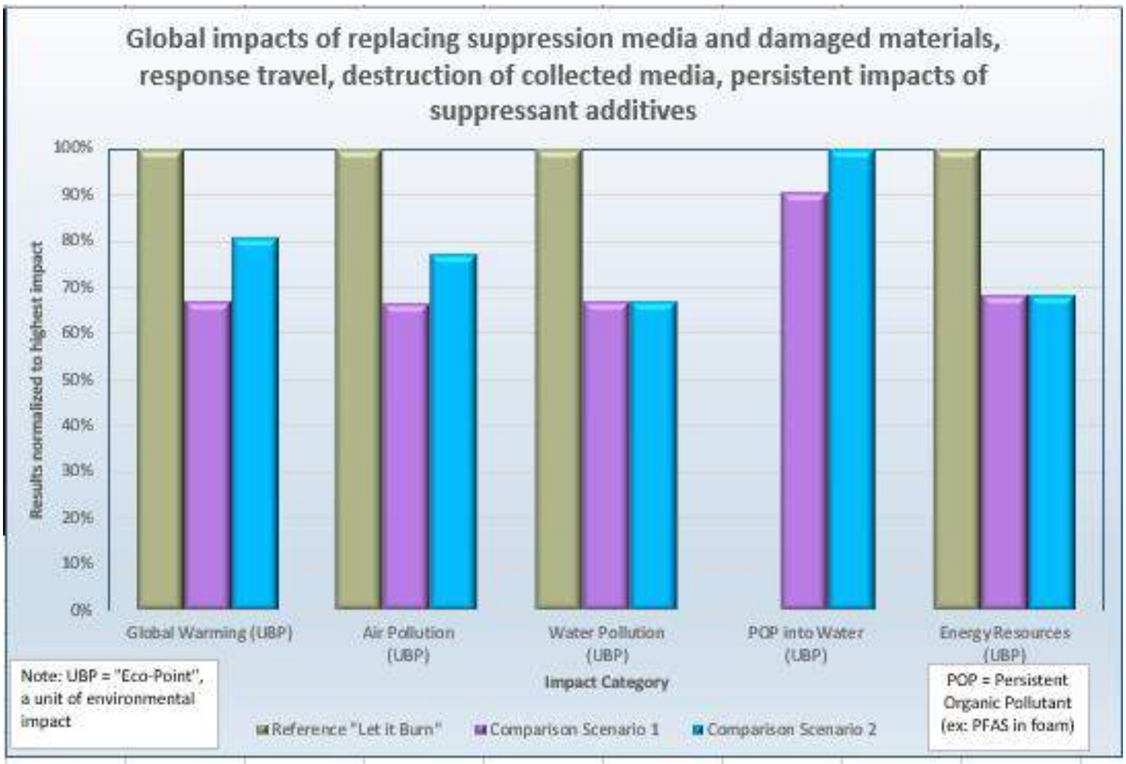

Figure 39: Global impact results comparing the initial analysis (scenario 1) with the fire spreading to the library (scenario 2)

In Figure 40 the contributions to global impacts by their source are presented for scenario 2 and can be compared with the results shown in Figure 37 for scenario 1. Since the fire has spread to the library in scenario 2 the response travel is no longer the only contributor to global impacts for Room 3. The results for Room 3 now look very much like the results for Room 1 and Room 2, in which replacing the building materials is the dominant contributor in all categories.

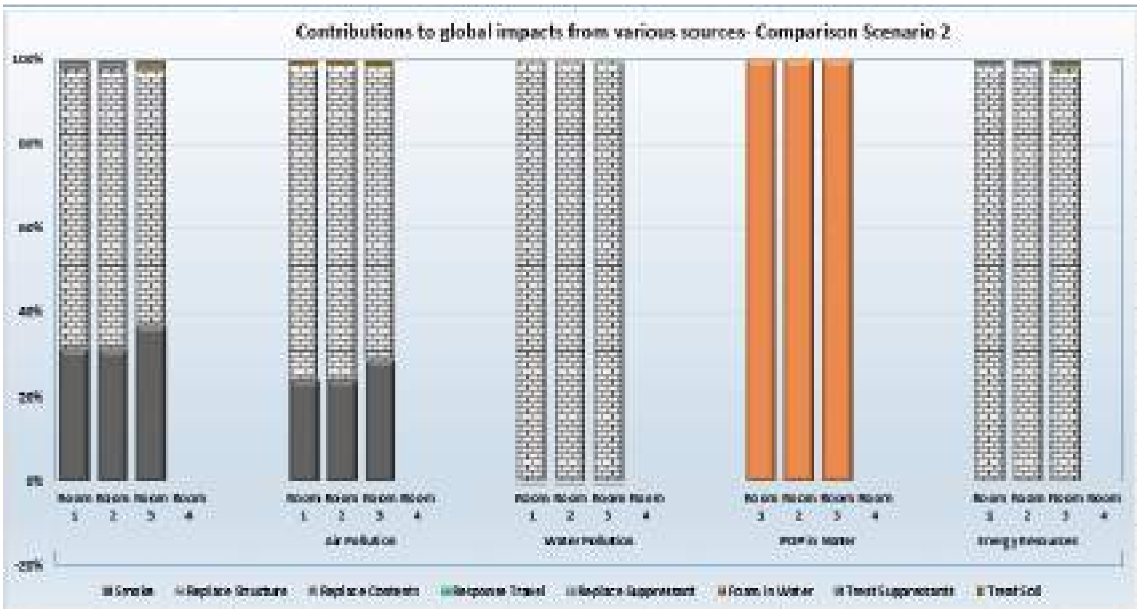

Figure 40: Distribution of global impacts by their source for the alternative outcome that the fire spreads to the Grillby school library.

The breakdown of global impacts by room and impact category is shown in *Figure 41*. The additional impacts from the fire spreading to the library, which has a higher fuel load than the other two rooms, cause the total impacts per category slightly higher (except for the POP into

Water category) than the "Let it Burn" reference case. This is because of the impacts associated with the suppression media. Note that the difference in magnitude between scenario 2 and the reference case is insignificant when uncertainties in the model results are considered.

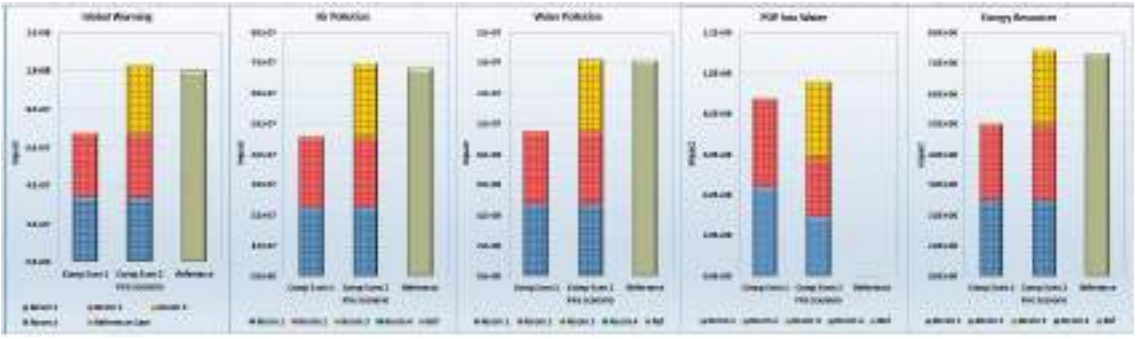

Figure 41: Breakdown of global impacts by room and impact.

The local impacts are shown in Figure 42, where scenario 2 has slightly higher impacts than scenario 1 due to the 10 % increase in water and foam used. There is no difference in the groundwater results because the concentration of the fire water run-off is the same in both scenarios.

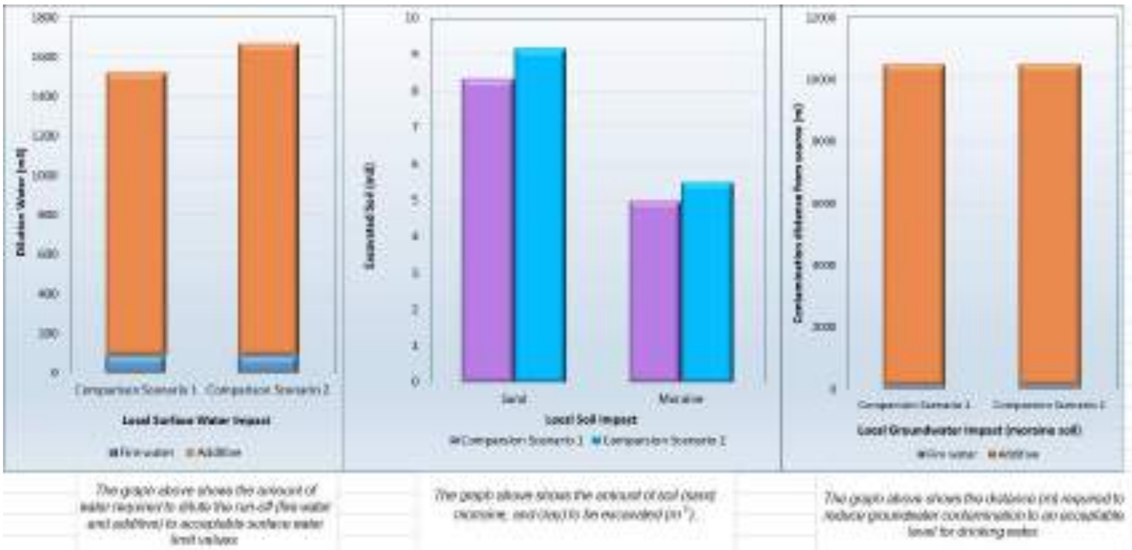

Figure 42: Local impacts comparing initial analysis (scenario 1) with the fire spreading into the library (scenario 2).

The two case studies and their alternative outcomes highlight the possibilities of using the tool for training and pre-planning to investigate the environmental consequences of different strategic and tactical decisions made during a response to a vehicle or enclosure fire. The results are useful for capturing trends and making comparisons among different scenarios, however, the Fire Impact tool is not intended to produce highly accurate predictions of environmental impacts. A balance was sought in the development of the tool between the amount of user input required and the accuracy of the results.

6. Sprinkler systems in schools

6.1 Introduction

A special study on the environmental effects from introducing sprinklers in all schools in Sweden, has been performed. By comparing fire statistics defining the amount of fires during the lifetime of a typical sprinkler system, and the environmental cost for building sprinkler systems in all schools we can make an estimate of the differences in CO_2-equivalent between the two choices. The idea behind the study is summarized in Figure 43.

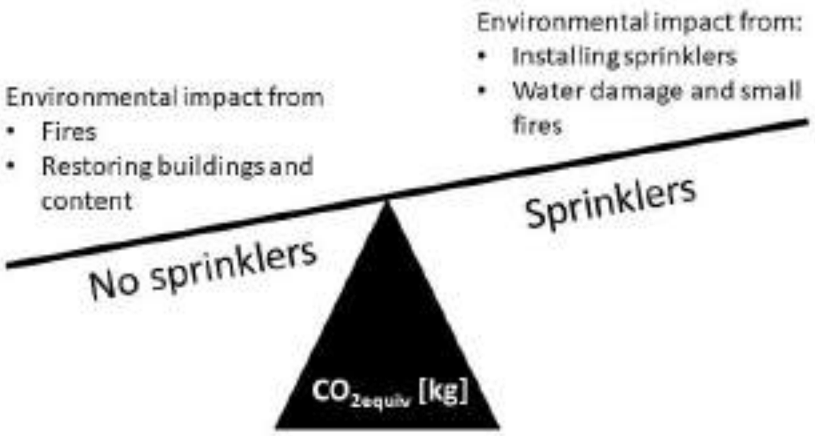

Figure 43: The environmental balance measured in 〖CO〗_2-equivalent during the lifetime of sprinkler systems in Swedish schools.

6.2 Methodology

The environmental impact from fires without sprinklers in schools is compared with the environmental cost of adding sprinklers to all Swedish schools. This study should mainly be considered as a demonstration of a concept rather than giving the final answer. A large number of assumptions are made in terms of input and more work is needed to develop validated input parameters. In the present study, the impact of variation of the input variables on the result is investigated using parameter studies on: (i) the lifespan of the sprinkler system, and (ii) the estimation of damage from activation of the sprinkler system and the impact of the fire. The methodology used is summarized in Table 18, followed by a description of each step in the analysis. Step A1-A3 follows a methodology developed at RISE (Blomqvist and Simonson McNamee, 2009).

Table 18: The two cases compared in the study.

No sprinklers	Sprinklers
A1. Fire statistics for schools divided in the following categories: • In object of ignition • In room of origin • In compartment of origin • In building of origin • Spread to other buildings	B1. Estimation of material density of a typical school sprinkler system [kg/m^2] B2. Estimation of emissions from material manufacturing of sprinkler system [kgCO_2-equiv/kg] using TRACI 2.1 (Bare et al., 2003) B3. Estimation of total size of all schools in Sweden[5] (Hellberg and Tolstoy, 2007)

[5] Schools in Sweden 2017/18 according to statistics from www.skolverket.se, Downloaded March 2019

A2. Fire size assumptions for the different categories. Following the methodology of Blomqvist & Simonson McNamee (2009) A3. Estimation of emissions from combustion. Following the methodology of Blomqvist & Simonson McNamee (2009) A4. Estimation of emissions from replacing building materials and contents using TRACI 2.1 (Bare et al., 2003) and Athena Impact Estimator for Buildings v5.3 (2019)	B4. Estimation of lifespan of sprinkler system *(parameter study)* B5. Estimation of damage from activation of sprinkler system and associated (small) fire *(parameter study)*
A1-A4 = CO_2-equivalent emissions from fires in schools during chosen lifetime of sprinkler system.	B1-B5 = CO_2-equivalent emissions from including sprinkler systems in all schools and partial damage of sprinkler activation and associated (small) fires.

<u>A1. Fire statistics for schools</u>

In Sweden, fire statistics are collected in the incident database (IDA), administrated by MSB, the Swedish Civil Contingencies Agency. In this database, estimates of the size of the all fires that the rescue service had been involved in, are registered. The statistics for school fires per year, was used as an input to the model. The values shown in Table 19 are based on an average value for year 2013-2017. More detailed statistics are shown are shown in Figure 44.

Table 19: Fire statistics for schools per year used in the model. Average values for years 2013-2017.

Total number of fires	Fire in object of ignition	Fire in room of origin	Fire in compartment of origin	Fire in building of origin	Fire spread to other buildings
417	135	56	9	17	1.2

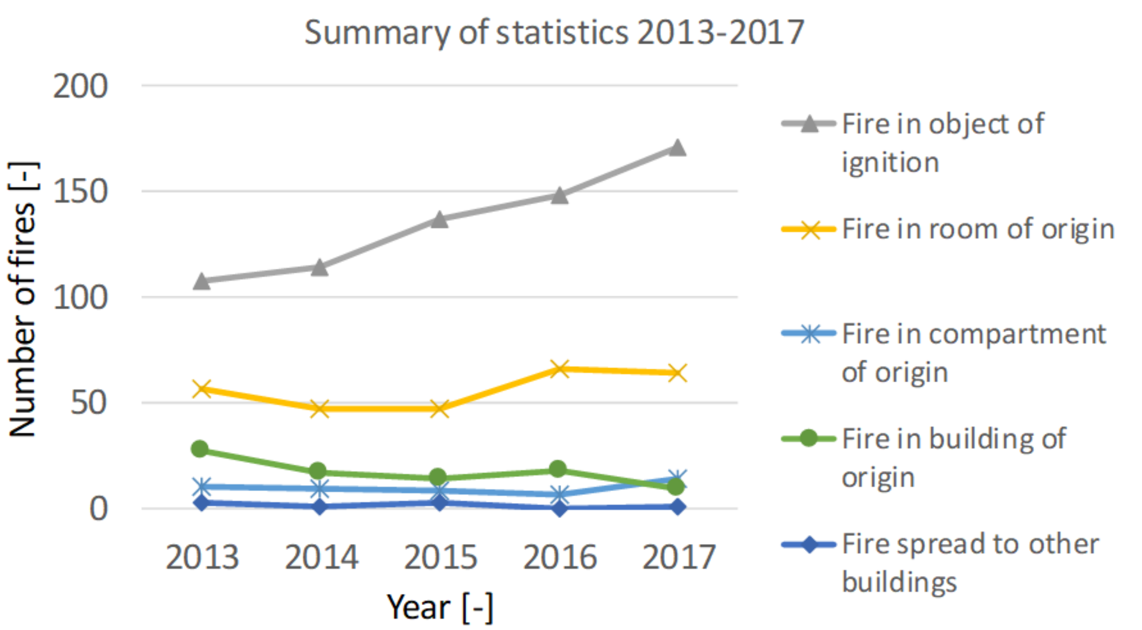

Figure 44: Fire statistics for school fires 2013-2017.

A2. Fire size assumptions

The fire statistics shown in *Table 19* need to be coupled to an estimate of the size of the fires. This was done following the methodology previously used by RISE (Persson and Simonson, 1998, Blomqvist and Simonson McNamee, 2009, Persson et al., 1995). With a reference size of a school building of 1000 m^2, the following fire size assumptions shown in *Table 20* was used.

Table 20: Assumed fire size for the different categories in the statistics compared with a reference size of 1000 m^2 school building.

In start object	In start space (room)	In start fire compartment	In start building	Spread to other buildings
0	0.05	0.35	0.8	1

A3. Estimation of emissions from combustion

Both burning of the content in the rooms and the structures contributes to the emission of CO_2 from school fires. Estimates for burning of the content in the rooms are based on (Persson and Simonson, 1998)and (Blomqvist and Simonson McNamee, 2009) as shown in Table 21.

Table 21: Material content and yield factors in a typical school according to (Blomqvist and Simonson McNamee, 2009).

	Material content of internal materials in 500 m^2 school [kg]	Estimated yield factor [kgCO_2/kg]	Emissions per square meter [kgCO_2/m^2]
Wood and Paper	5600	1.45	16
Cotton	800	1.44	2
PVC	1600	1	3

The emissions from burning of the structure is based on a detailed investigation of three school fires with total damage (Blomqvist and Simonson McNamee, 2009). In this study, it was estimated that the burning of the structure contributed to the total emissions with 136 kg CO_2-equiv/m^2.

A4. Estimation of emissions from replacing building materials and contents

The estimation of emissions from replacing building materials was performed using Athena Impact Estimator for Buildings (Athena, 2019). A representative structure was created, in this case a fire compartment comprised of four school classrooms. The Impact Estimator generates a bill of materials report for the structure; these materials were then analysed using the TRACI 2.1 life cycle assessment (LCA) method (Bare et al., 2003)to predict the environmental impacts of constructing the structure from cradle to gate, where the gate is a finished structure ready for occupancy. Note that tearing down and recycling of burnt material is not included in the model. This process resulted in an estimate of 546 kg CO_2-equiv/m^2.

The environmental impact of replacing the contents was estimated using the same TRACI 2.1 LCA method used for the structure materials. The content materials were taken from (Blomqvist et al., 2004b), in which emissions from furnished room fires were measured. Scaled to our material density it resulted in an estimate of 65 kg CO_2-equiv/m^2.

B1. Estimation of material density of a typical school sprinkler system

To examine the amount of steel used for a sprinkler installation in a typical Swedish school, we used the drawings for Kästa elementary school in Huddinge. This two and a half story school is a typical Stockholm school comprised of regular class rooms, a small gymnastics hall, a kitchen area and rooms for art and crafts. The total area of the school was 6600 m^2. From the drawings we could determine how many meters of each pipe dimension that had been used for the sprinkler system, as well as how many couplings would be needed. Based on this evaluation, we could develop a medium density per square meter of the material used in the sprinkler system. It was found that 11655.2 kg of piping was used and 2383.5 kg of couplings which gave a total material density of 2.13 kg/m^2.

B2. Estimation of emissions from material manufacturing of sprinkler system

The emissions from manufacturing the material in the sprinkler system was estimated using the TRACI 2.1 LCA method (Bare et al., 2003). According to the tool the manufacturing of steel pipes produced 2.24 kgCO_2e/kg and the parts and couplings 1.64 kgCO_2e/kg. By scaling the total weights of the parts from B1 we get an average of 2.12 kgCO_2e/kg.

B3. Estimation of total size of all schools in Sweden

Based on statistics from the Swedish Education Agency[6] we know that for the school year 2017/2018 we had 4832 elementary schools and 1316 high schools in Sweden, in total 6148 schools. During an inventory of 94 schools spread out in the country it was found that the average size of the schools was 4781 m^2 (Hellberg and Tolstoy, 2007). Based on this information we assume that the total area of all schools in Sweden are 29.39 million square meters.

B4. Estimation of lifespan of sprinkler system

The lifespan of a sprinkler system in a school building is difficult to estimate as it includes both the technical life span of the system and the time until major changes or renovations are done to the building. Therefore, the lifespan of the sprinkler system is varied in the study, to investigate the influence of the lifespan on the results.

B5. Estimation of damage from activation of sprinkler system and small fires

Damage due to sprinkler activation and the occurrence of restricted small fires are difficult to estimate. Therefore, this parameter was also investigated in a parameter study, where the damage is defined as a percentage of the emissions from fires occurring without sprinkler activation.

6.3 Limitations and assumptions

When doing the estimation of environmental effects form introducing sprinkler systems in all schools a variety of simplifications have been done. These simplifications point in both directions, i.e. both under- and overestimation of environmental impact form introducing sprinklers and deserves further investigating. This is a summary of limitations:

- Mounting and maintenance of sprinkler systems is not included in estimate of the environmental impact from adding sprinklers, which gives an underestimation of the environmental impact from using sprinkler systems.
- It is assumed that no sprinklers are installed in schools today, i.e. the baseline of environmental impact from fires with no sprinklers are underestimated.
- We assume that sprinklers have 100% functionality (but the size of damage due to sprinkler activation and small fires are included in a parametric study).
- We assume that the rescue service comes in both sprinkler and no sprinkler case, i.e. no different from an environmental point of view. This makes the environmental impact from the larges occurring fires to be underestimated as more vehicles is used compared with when a sprinkler system limits the fire to a small one.

[6] Schools in Sweden 2017/18 according to statistics from www.skolverket.se, Downloaded March 2019

6.4 Results

According to our estimates in the previous chapter we have a material density in the sprinkler system of 2.13 kg/m^2 floor area based on a case study. As we have 29.39 million square meters of schools in Sweden and we estimate the average emissions from manufacturing the material to 2.12 kgCO_2e/kg the total emissions form adding sprinkler system in all Swedish schools are 133 million kgCO_2e. This value does not include mounting of the system or maintenance during the lifetime, so it is an underestimation of the environmental impact from introducing the sprinkler system, but we assume that the emissions from material manufacturing is the main component of the environmental cost.

In Figure 45 and Figure 46 results from the study are shown by plotting the environmental cost of all school fires in Sweden minus the environmental cost of introducing sprinklers in all Swedish schools. Positive values in the diagrams are savings in environmental costs from introducing sprinklers. Two of the factors are included as variating parameters, the lifetime of the sprinkler system and the damage form activating the sprinkler system. The lifetime of the sprinkler system is difficult estimate as it is a mix of the technical lifetime and the lifetime based on major changes of the schools. Included in the damage parameter are both the water damage due to activation of the sprinklers and the damage from fires not controlled by the sprinkler system. The percentage given in the diagram is the percentage of the total damage form fires not including sprinklers. The reference, 100%, is the damage from all fires in Sweden without sprinkle activation. This is a simplification/limitation as there are already now sprinkler systems installed in some Swedish schools so our baseline for the statistics underestimate the total size of fires without sprinkler systems.

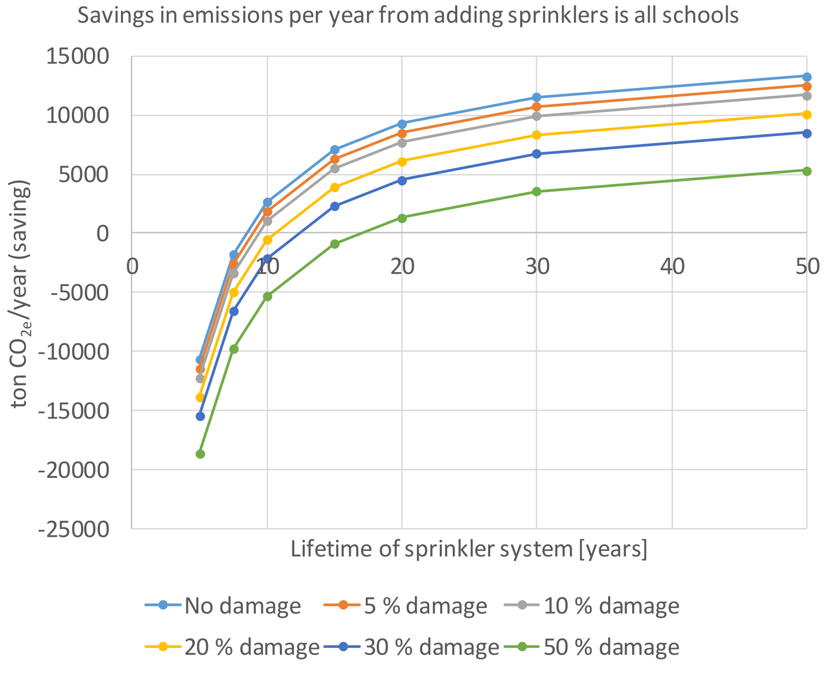

Figure 45: Environmental cost of all Schools fires in Sweden minus the environmental cost of introducing sprinklers in all Swedish schools. Percentage of damage include water damage from sprinkler activation and from small fires (the reference 100% is total fire damage without sprinklers).

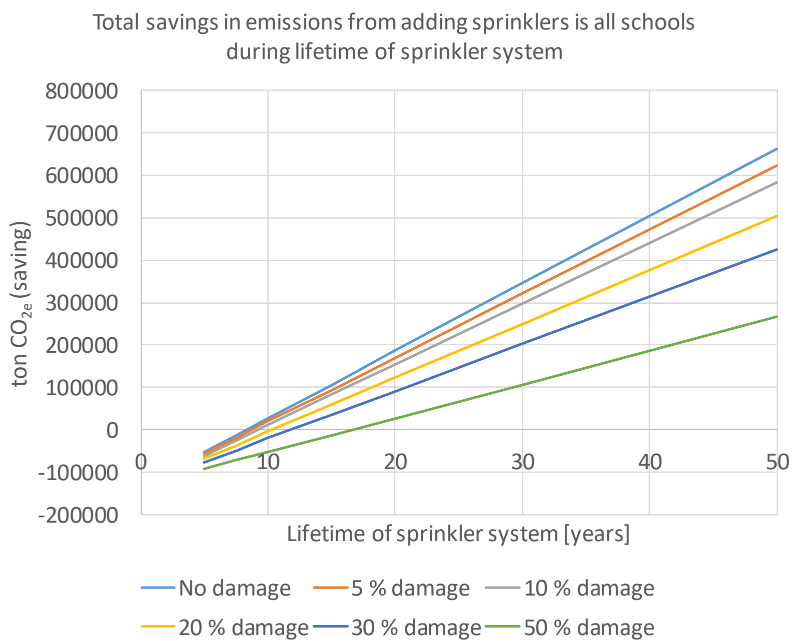

Figure 46: Environmental cost of all Schools fires in Sweden minus the environmental cost of introducing sprinklers in all Swedish schools during the whole lifetime of the sprinkler system. Percentage of damage include water damage from sprinkler activation and from small fires (the reference 100% in in total fire damage without sprinklers).

As illustrated in Figure 45 and Figure 46 the estimate shows that if the sprinkler system is capable of reducing the damage form fires with at least 50% and have a lifetime of 20 years it is a gain in CO_2-equivalent footprint to include sprinklers in all Swedish schools. This is in line findings from a similar study when the environmental impact from introduction of a sprinkler system in a 2500m^2 school was investigated (Olsson and Göras, 2018) to get a more solid foundation for a possible recommendation of introducing sprinklers in all schools further detailed studies of the basic assumptions needs to be performed.

7. Future work

The Fire Impact Tool provides some much needed insight into the environmental impact of tactical decisions concerning a limited number of fire scenarios. It also indirectly trains users in life cycle thinking, which will be helpful in their ad hoc evaluation of tactical decisions associated with scenarios not specifically dealt with in the 2019 version of the tool. In this sense, the tool will be helpful both to the fire and rescue services but also to other stakeholders performing risk assessments in municipalities around Sweden. Ultimately, this knowledge will help to improve the accuracy of the thousands of fire risk evaluations that are performed each year. Despite the advances made with the Fire Impact Tool during this project, there is ample room for future improvements. This chapter outlines some of the most pressing opportunities for future work that have emerged as part of this project.

There is a need to develop a data base or the framework for a repository of results, so that knowledge is available for training purposes to prepare users for responding to enclosure fires and as input for risk assessments and planning activities as this is developed and experience of applications of the model grows. A “users community” based on an open source version of the tool might be one potential avenue to explore. Some clear extensions of the model that have been outside of the scope of this project include:

- Extension of existing scenarios to include:
  - Fire spread beyond vehicle or fire compartment.
  - Added flexibility in the enclosure geometry
  - Addition of more suppression alternatives

  - Addition of options for the user to provide their own fire emissions, e.g. for additional vehicle or other fire ventilation conditions
  - Improvement of mathematical models for the ERA, in particular connected to how small emissions are dealt with.
  - Improve the variety of soil types beyond a standardized type of moraine, sand and clay to include varieties of these soil types and mixtures of soil type.
- Allow user can add their own fire/suppression models, over and above extensions of the existing scenarios.
- Addition of a GIS facility connecting results to map coordinates to obtain detailed geological information directly and make the analysis of specific locations (as opposed to generic descriptions). This would also allow a municipality to make an analysis of key sensitive areas in their location to identify a list of particular no-fire suppression areas before the event of a fire. In certain areas, this may also impact investments made to restrict accessibility to, e.g. vehicles, to minimize the risk of a fire.
- Addition of plume modelling and toxicity calculations to be able to add features such as recommendations for citizen response, e.g. in terms of recommendations to close windows and doors and stay inside up to recommendations to evacuate.
- Additional details need to be added to the treatment of contaminated soil to include more details about species transportation, rather than wetting of soil, in determination of the need for soil excavation including the volume of soil recommended for removal.
- Future models should allow for the dilution of contaminants in fire water run-off as they flow towards a well. Further, better models for the influence of low dilution should be developed.
- Characterisation factors for firefighting foam should be developed to allow the use of impact assessment methods that do not already include them.

8. Conclusions

In Sweden the responsibility for damage to the environment when emergency responders are called to an incident is increasingly focussing on the responders. The problem is that most incident response personnel do not have the training and expertise to understand the environmental consequences of their field operations. Given the complexity of predicting the environmental impacts of fire, the Fire Impact tool was developed to provide a basic structure for training responders about the environmental consequences of fires and firefighting operations.

The tool results can be used to coalesce knowledge gained from case studies to formulate "rules of thumb" for pre-planning and training so that FRS can answer questions about the environmental risks of response operations for fires. For example, when is it best to let the fire burn? What are the environmental trade-offs regarding the type of suppression media used?

The Fire Impact tool is most efficiently utilized with knowledge regarding its assumptions and limitations as well as how fire surroundings and other variables may influence the tool's results. When using the Fire Impact tool for training, it is advisable to *first* look at the surroundings of the incident and make estimates of the amount of surface water, potentially exposed soil and possible distances to the nearest drinking water well(s). These impacts are usually considered acute and could impose negative consequences on the well-being of the community if not given suitable priority.

The fire models used to predict the quantity and composition of smoke and fire water run-off are based on limited experimental data and simple fire growth equations. They were chosen as a good starting point that optimises the amount of user input required compared with accuracy of model results.

The results provided by the ERA show that environmental impacts due to fire water run-off are largely affected by the volume and type of extinguishant used, and how developed a fire is before intervention begins in the case of vehicle fires. Results may vary significantly depending on which soil type is exposed to fire water run-off.

The LCA model examines the global impacts of the fire response operations that are caused by replacement of suppression media, replacement of building and content materials, treatment of waste suppression media, response travel, smoke, the persistent effects of foam in water, and the treatment of excavated soil. Many of these impacts on the environment are not normally considered in the decision-making process because they are not directly connected to the fire incident, however, these impacts can be significant and should therefore be included.

A variation of the Fire Impact Tool has been used to investigate the environmental impact of the implementation of sprinkler systems in schools. The findings illustrate the need for a holistic approach to the evaluation of such a change, where the impact of replacement of material in the case of a fire is included, in order to obtain a realistic estimate of the environmental costs.

The work performed in this project does not answer every question for every fire scenario, but it does provide a framework for a deeper, broader, more comprehensive training and pre-planning tool. It is a necessary step toward a future in which responders are prepared to make informed decisions about firefighting strategies and tactics that include environmental consequences.

9. References

ALAEE, M. 2006. Recent progress in understanding of the levels, trends, fate and effects of BFRs in the environmen. *Chemosphere,* 64**,** 179-180.

AMON, F., GEHANDLER, J. & STAHL, S. 2016a. Development of an Environmental and Economic Assessment Tool (Enveco Tool) for Fire Events. *Brandposten***,** 32.

AMON, F., GEHANDLER, J., STAHL, S., TOMIDA, M. & MEACHAM, B. 2016b. Development of an Environmental and Economic Assessment Tool (Enveco Tool) for Fire Events. Springer.

AMON, F., MCNAMEE, M. S. & BLOMQVIST, P. 2014. Fire effluent contaminants, predictive models, and gap analysis. Borås: SP Fire Research.

ATHENA 2019. Athena Impact Estimator for Buildings- User Manual and Transparency Document, Impact Estimator for Buildings v.5. Athena Sustainable Materilas Institute.

AVINO, P., NOTARDONATO, I., PERUGINI, L. & RUSSO, M. V. 2017. New protocol based on high-volume sampling followed by DLLME-GC-IT/MS for determining PAHs at ultra-trace levels in surface water samples. *Microchemical Journal,* 133**,** 251-257.

BACKER, D. M., JENSEN, S. E. & MCPHERSON, G. R. 2004. Impacts of fire-suppression activities on natural communities. *Conservation Biology,* 18**,** 937-946.

BARE, J. C., NORRIS, G. A., PENNINGTON, D. W. & MCKONE, T. 2003. TRACI – The Tool for the Reduction and Assessment of Chemical and Other Environmenatl Impacts. *Journal of Industrial Ecology***,** 49-78.

BERGGREN KLEJA, D., ELERT, M., GUSTAFSSON, J. P., JARVIS, N. & NORRSTRÖM, A.-C. 2006. *Metallers mobilitet i mark,* Stockholm, Stockholm : Naturvårdsverket.

BLOMQVIST, P., LÖNNERMARK, A. & SIMONSON, M. 2004a. Miljöbelastning vid bränder och andra olyckor- Utvärdering av provtagning och analyser. *The Environmental Impact of Fires and Other Accidents. An evaluation of samples and analyses*. Borås: Räddningsverket.

BLOMQVIST, P., ROSELL, L. & SIMONSON, M. 2004b. Emissions from Fires Part II: Simulated Room Fires. *Fire Technology,* 40**,** 59-73.

BLOMQVIST, P. & SIMONSON MCNAMEE, M. 2009. Estimation of CO2-emissions from Fires in Dwellings, Schools and Cars in the Nordic Countries. *SP Report,* 2009:13.

BLOMQVIST, T. & TISTAD, L. 1998. Förorening av vattentäkt vid vägtrafikolycka. Hantering av risker vid petroleumutsläpp. https://trafikverket.ineko.se/se/förorening-av-vattentäkt-vid-vägtrafikolycka: Swedish Transport Administration (Trafikverket).

CCME. n.d. *Canadian Council of Ministers of the Environment. (1999). CCME Summary table, 1–2.* [Online]. Available: http://st-ts.ccme.ca/en/index.html.

CORNELL 2014. Best Management Practices for NY State Golf Courses. Fate and Transport Mechanisms. *In:* UNIVERSITY, C. (ed.).

EPA, U. n.d. *National Recommended Water Quality Criteria - Aquatic Life Criteria Table* [Online]. US Environmental Protection Agency. Available: https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table 2019].

ERIKSSON, M. 2008. *Förslag till gränsvärden för särskilda förorenande ämnen stöd till vattenmyndigheterna vid statusklassificering och fastställande av miljökvalitetsnormer,* Bromma, Naturvårdsverket.

FAIRMAN, R. 2008. The use of risk assessment in environmental management. *In:* MEAD, C. D. & WILLIAMS, W. P. (eds.) *Environmental risk assessment*

approaches, experiences and information sources. Copenhagen: Copenhagen : European Environment Agency.
FINKBEINER, M., SCHAU, E. M., LEHMANN, A. & TRAVERSO, M. 2010. Towards Life Cycle Sustainability Assessment. *Sustainability,* 2**,** 3309-3322.
FRISCHKNECHT, R. & BUSSER KNÖPFEL, S. 2013. Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological fundamentals and their application in Switzerland. Bern CH: Federal Office for the Environment.
GUSTAFSSON, T. 2014. Utvädering efter Insats. Enköping: Räddningstjänsten Enköping - Håbo.
HELLBERG, C. & TOLSTOY, N. 2007. *Energianvändning & innemiljö i skolor och förskolor – Förbättrad statistik i lokaler, STIL2*, The Energy Agency.
HOLGERSSON, E., ANDERSSON, K. & CHRITIANSON, S. 2013. Parkeringsplan, Höörs kommun (Remissutgåva 2013-12-02). Tyréns.
HVMFS. 2018. *Havs- och vattenmyndighetens författningssamling (HVMFS)* [Online]. Retrieved from https://www.havochvatten.se/hav/vagledning--lagar/foreskrifter.html. Available: http://st-ts.ccme.ca/en/index.html.
IADC 2016. Facts About Soil Improvement. *In:* COMPANIES, I. A. O. D. (ed.) *Website.*
KARLSSON, B. & QUINTIERE, J. G. 2000. *Enclosure fire dynamics*, CRC Press.
KARLSTADSREGIONEN 2018. Fördjupad olycksundersökning gällande brand i traktor på vattenskyddsområde.
KÄRRMAN, A., BJURLID, F., HAGBERG, J., RICKLUND, N., LARSSON, M., STUBLESKI, J. & HOLLERT, H. 2016. Study of environmental and human health impacts of firefighting agents. Sweden: MTM Research Centre, School of Science and Technology, Örebro University.
KÄRRMAN, A., ELGH-DALGREN, K., LAFOSSAS, C. & MÖSKELAND, T. 2011. Environmental levels and distribution of structural isomers of perfluoroalkyl acids after aqueous fire-fighting foam (AFFF) contamination. *Environmental Chemistry,* 8**,** 372-380.
KISHI, T. & ARAI, M. 2008. Study on the generation of perfluorooctane sulfonate from the aqueous film-forming foam. *Journal of Hazardous Materials,* 159**,** 81-86.
LEEUWEN, C. J. V. & HERMENS, J. L. M. 2007. *Risk Assessment of Chemicals: An Introduction,* Dordrecht, Dordrecht: Springer Netherlands.
LIND, A., KOTSCH, M., ALMQVIST, H., HANSSON, K., NORDÉN, L., PALMGREN, T. & STENLUND, A. 2009. *Råd vid mottagande av avloppsvatten från industri och annan verksamhet*, Svenskt Vatten.
LINKOV, I. & PALMA-OLIVEIRA, J. 2001. *Assessment and Management of Environmental Risks,* Netherlands, Springer.
LIVSMEDELSVERKET 2015. Livsmedelsverkets föreskrifter om dricksvatten. *In:* LIVSMEDELSVERKET (ed.) *SLVFS 2001:30.*
LIVSMEDELSVERKET. 2018. *Riskhantering - PFAS i dricksvatten och fisk* [Online]. Available: https://www.livsmedelsverket.se/livsmedel-och-innehall/oonskade-amnen/miljogifter/pfas-poly-och-perfluorerade-alkylsubstanser/riskhantering-pfaa-i-dricksvatten.
LÖNNERMARK, A. & BLOMQVIST, P. 2006. Emissions from an automobile fire. *Chemosphere,* 62**,** 1043-1056.
LÖNNERMARK, A., STRIPPLE, H. & BLOMQVIST, P. 2006. Modelling of emissions from fires. Borås, Sweden: SP Technical Research Institute of Sweden.
LÖNNERMARK, A., STRIPPLE, H., ROSÉN, B., HAEGER-EUGENSSON, M., AXELSSON, J., ANDERSON-SKÖLD, Y., COUSINS, A. P. & SIMONSON, M. Emissions from Fire - Methods, Models and Measurements. Interflam 2007, 2007 Royal Holloway College, University of London, UK. Interscience Communications, 1625-1630.
MSB. 2019. *Rekommendationer för minskad användning av brandsläckningsskum (Recommendations for reduced use of firefighting foam)* [Online]. MSB (Civil Contingencies Agency)

KemI (Swedish Chemical Inspectorate)

Naturvårdsverket (Swedish EPA). Available: https://www.msb.se/sv/Insats--beredskap/Brand--raddning/Slackmedel-for-raddningstjanst/Skumvatskor-och-tillsatsmedel/.

NATURVÅRDSVERKET 2009. *Riktvärden för förorenad mark modellbeskrivning och vägledning,* Stockholm, Naturvårdsverket.

NATURVÅRDSVERKET 2016. Riktvärden för förorenad mark. Generella riktvärden för förorenad mark 2016. *In:* NATURVÅRDSVERKET (ed.). Retrieved from https://www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/ISBN/5900/978-91-620-5976-7/.

NOITON, D., FOWLES, J. & DAVIES, H. 2001. The Ecotoxicity of Fire-water Runoff. Part II. Analytical Results. New Zealand Fire Service Commission.

OLSSON, N. & GÖRAS, T. 2018. *Hållbart Brandskydd – En handbok om hållbara brandskyddsutformningar (Sustainable Fire Protection - A handbook about sustainable fire protection design),* othenburg, Bengt Dahlgrens.

PALM, A., COUSINS, I. T., MACKAY, D., TYSKLIND, M., METCALFE, C. & ALAEE, M. 2002. Assessing the environmental fate of chemicals of emerging concern: a case study of the polybrominated diphenyl ethers. *Environmental Pollution,* 117.

PALMQVIST, M. 2018. Fördjupad olycksundersökning gällande brand i traktor på vattenskyddsområde. Karlstad, SE: Räddningstjänsten Karlstadregionen.

PERSSON, B. & SIMONSON, M. 1998. Fire Emissions into the Atmosphere. *Fire Technology,* 34**,** 266-279.

PERSSON, B., SIMONSON, M. & MÅNSSON, M. 1995. Utsläpp från bränder till atmosfären (Emissions from fires to the atmosphere). *SP Report*. Borås: SP Technical Research Institute of Sweden.

SGI. 2019. *Jordarter* [Online]. Statens geotekniska institut. Available: http://www.swedgeo.se/sv/kunskapscentrum/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/jordmateriallara/lera-och-kvicklera/ 2019].

SGU. n.d. *Morän - spår av inlandsisen* [Online]. https://www.sgu.se/om-geologi/jord/fran-istid-till-nutid/inlandsisen/moran-spar-av-inlandsisen/. Available: https://www.sgu.se/om-geologi/jord/fran-istid-till-nutid/inlandsisen/moran-spar-av-inlandsisen/ 2019].

STANDARDIZATION, I. O. F. 2006a. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. Geneva, Switzerland: ISO/TC 207/SC 5.

STANDARDIZATION, I. O. F. 2006b. ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines. Geneva, Switzerland: European Committee for Standardization.

SUTER, G. 2010. Assessment Endpoints. *In:* PARK, C. & ALLABY, M. (eds.) *Ecological Risk Assessment*. 2 ed. Oxford: Oxford University Press.

WIECZOREK, C., DITCH, B. & BILL, R. 2011. Environmental Impact of Automatic Fire Sprinklers: Part 2. Experimental Study. *Fire Technology,* 47**,** 765-779.

WIECZOREK, C. J., DITCH, B. & BILL, J., ROBERT G. 2010. Environmental Impact of Automatic Fire Sprinklers. Technical Report: FM Global.

WU, X., LU, G., WU, Z., HE, H., ZHOU, J. & LIU, Z. 2018. An integration approach for mapping field capacity of China based on multi-source soil datasets. *Water,* 10.

Through our international collaboration programmes with academia, industry, and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our 2,200 employees support and promote all manner of innovative processes, and our roughly 100 testbeds and demonstration facilities are instrumental in developing the future-proofing of products, technologies, and services. RISE Research Institutes of Sweden is fully owned by the Swedish state.

I internationell samverkan med akademi, näringsliv och offentlig sektor bidrar vi till ett konkurrenskraftigt näringsliv och ett hållbart samhälle. RISE 2 200 medarbetare driver och stöder alla typer av innovationsprocesser. Vi erbjuder ett 100-tal test- och demonstrationsmiljöer för framtidssäkra produkter, tekniker och tjänster. RISE Research Institutes of Sweden ägs av svenska staten.

RISE Research Institutes of Sweden AB
Box 857, SE-501 15 BORÅS, Sweden
Telephone: +46 10 516 50 00
E-mail: info@ri.se, Internet: www.ri.se

Safety
RISE Report 2019:60
ISBN:

RISE Research Institutes of Sweden
P.O. Box 857, 501 15 BORÅS, SWEDEN
PHONE: 0046-10-516 50 00
E-post: info@ri.se,
Internet: www.ri.se

OUR SPONSORS & PARTNERS:

NFPA RESEARCH FOUNDATION
RESEARCH FOR THE NFPA MISSION

LUNDS UNIVERSITET

BRANDSKYDDSLAGET

Brandforsk

BRANDFORSK REPORTS FROM 2019:

2019:1 Measuring the impact of fire on the environment. Fire Impact Tool, version 1

The Swedish Fire Research Board, Brandforsk, is a non-profit body, formed in collaboration between insurance companies, industry, associations, government agencies and local municipalities. The purpose of Brandforsk is to initiate and fund research and knowledge development within the field of fire safety in order to reduce the negative social and economic impact of fire.

The work is under the leadership of the board of directors and is undertaken in the form of projects at universities, institutes of technology, research organisations, government agencies and industrial enterprises. The Secretariat of Brandforsk shares the pre¬mises of the Swedish Fire Protection Association, SFPA, which is also the principal organization.

Brandforsk

Årstaängsvägen 21 c
P.O. Box 472 44, SE-100 74 Stockholm, Sweden
Phone: 0046-8-588 474 14
brandforsk@brandskyddsforeningen.se
www.brandforsk.se