Research Roadmap: Environmental Impact of Fires in the Built Environment

Final Report by:

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Foreword

Concern for the health of the natural environment is growing as human population grows and as new levels of contamination of scarce resources are revealed. Current efforts to improve the sustainability of buildings focus on increasing energy efficiency and reducing the embodied carbon. This overlooks the fact that a fire event could reduce the overall sustainability of a building through the release of pollutants and the subsequent re-build.

Most fires occurring in the built environment contribute to air contamination from the fire plume (whose deposition is likely to subsequently include land and water contamination), contamination from water runoff containing toxic products, and other environmental discharges or releases from burned materials. The environmental impact also has economic consequences for communities and regions and while the direct and indirect costs of fire on a community can be devastating, they are not usually reported at a local scale beyond an account of the human deaths and injuries and the amount of property destroyed or damaged.

To calculate the true cost of fire to society we need to be able to quantify the impact fire has not only on the people or structures involved but also to the environment. Studies have been done to examine the environmental impact of fire but we cannot yet fully quantify this impact and its consequences to the local economy. Therefore, the Foundation initiated this research project to develop a research road map identifying needed research to be able to quantify the environmental impact of fire from the built environment and its economic consequences. This project focused on structure fires and excluded wildland and wildland urban interface (WUI) fires.

The Fire Protection Research Foundation expresses gratitude to the report author Margaret McNamee, who is with the Division of Fire Safety Engineering at Lund University located in Lund, Sweden; Guy Marlair and Benjamin Truchot, who are with INERIS located in Verneuil-en-Halatte, France; and Brian Meacham, who is with Meacham Associates located in Shrewsbury, MA, USA. The Research Foundation appreciates the guidance provided by the Project Technical Panelists and all others that contributed to this research effort. Thanks are also expressed to the National Fire Protection Association (NFPA) for providing the project funding.

About the Fire Protection Research Foundation

NFPA RESEARCH FOUNDATION
RESEARCH FOR THE NFPA MISSION

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: **fire safety, environmental impact, cost-benefit assessment, life-cycle assessment, cost**

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Lund 2019

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Summary

Concern for human health and the environment is growing as the human population grows and recognition of scarcity of resources and climate change grows. Indeed, it was recently stated by the International Association of Fire Safety Science that the world is facing enormous challenges in terms of access to resources, increasing and diversifying population and extreme weather events. There is a clear and pressing need to understand the environmental impact of fires and the cost of such impact. In the context of competing societal needs, it is important that we understand the cost of fires relative to the cost of other societal challenges to be able to make informed decisions concerning investments in public safety.

This report has been prepared at the behest of the Fire Protection Research Foundation, to provide a state-of-the-art summary of what we know about the environmental impact of fires and a proposal for a research roadmap to close identified gaps. The project has been divided into three main parts:

- *Literature study:* This part of the project focused on identifying existing research in the field of the environmental impact of fires and the cost of said impact.
- *Case studies:* A small number of case studies have been presented where existing emissions models are tested and limitations identified as input to necessary research.
- *Gap Analysis:* A summary of the gaps identified in the first two parts of the study is given together with a proposed high-level research roadmap.

The findings of the literature study have indicated that most information concerning emissions from fire is available in the field of gaseous emissions from fires. Less information is available concerning emissions from fire to aquatic environments or soil and even less has been found concerning the environmental impact of firefighting choices. Although this final area has received more attention in recent years in light of scares concerning the contamination of soil and waterways due to the emission of, e.g. firefighting foams.

The case studies indicate that while dispersion models exist, these are most well developed for gaseous emissions and dispersion using atmospheric models. However, despite the broad application of such models, the estimates of gaseous species is tenuous based as it is often based on the development of source terms using models which are applied beyond their original field of application. Further, models for dispersion of emissions in water and soil are underdeveloped.

The gap analysis identifies the need for significant research to improve our understanding of the environmental impact of fires and their cost. The gap analysis has identified that research needs can be divided into three main thematic areas: Data related research and development, research and development in support of policy development, and the development of modelling tools. These thematic areas are in turn divided into research in support of the development of modern emission factors, receptor characterisation, identification of tolerable exposure levels and the development of life-cycle based and cost-based models including the need new and improved input parameter characterisation.

Preface

This report has been developed as a collaboration between Lund University, INERIS and Meacham Associates in response to a request for proposals developed by the National Fire Protection Association (NFPA), Research Foundation. The findings are based on a literature review and input from the NFPA Reference Group (RG). The RG is comprised of the following members:

Francine Amon, RISE
Cameron Bardas, Edmonton, Alberta Fire Department
Alissa Cordner, Whitman College
Chris Gallo, US EPA
John Shafer, Washington Twp./Avon (Indiana) Fire Department
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Birgitte Messerschmidt, NFPA
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The members of the RG are thanked for their generous input.

Lund, December, 2019.

Table of Contents

List of Figures

1. Introduction

1.1 Background

Concern for the health of the natural environment is growing as human population grows and as new levels of contamination of scarce resources are revealed (Rockstrom et al., 2009, Steffen et al., 2015). Current efforts to improve the sustainability of buildings focus on increasing energy efficiency and reducing the embodied carbon (Yates et al., 2015). This overlooks the fact that a fire event could reduce the overall sustainability of a building through the release of pollutants and the subsequent re-build. Most fires occurring in the built environment contribute to air contamination from the fire plume (whose deposition is likely to subsequently include land and water contamination), contamination from water runoff containing toxic products, and other environmental discharges or releases from burned materials. The environmental impact is, therefore, multifaceted including emissions to air, soil and water as illustrated in Figure 1.

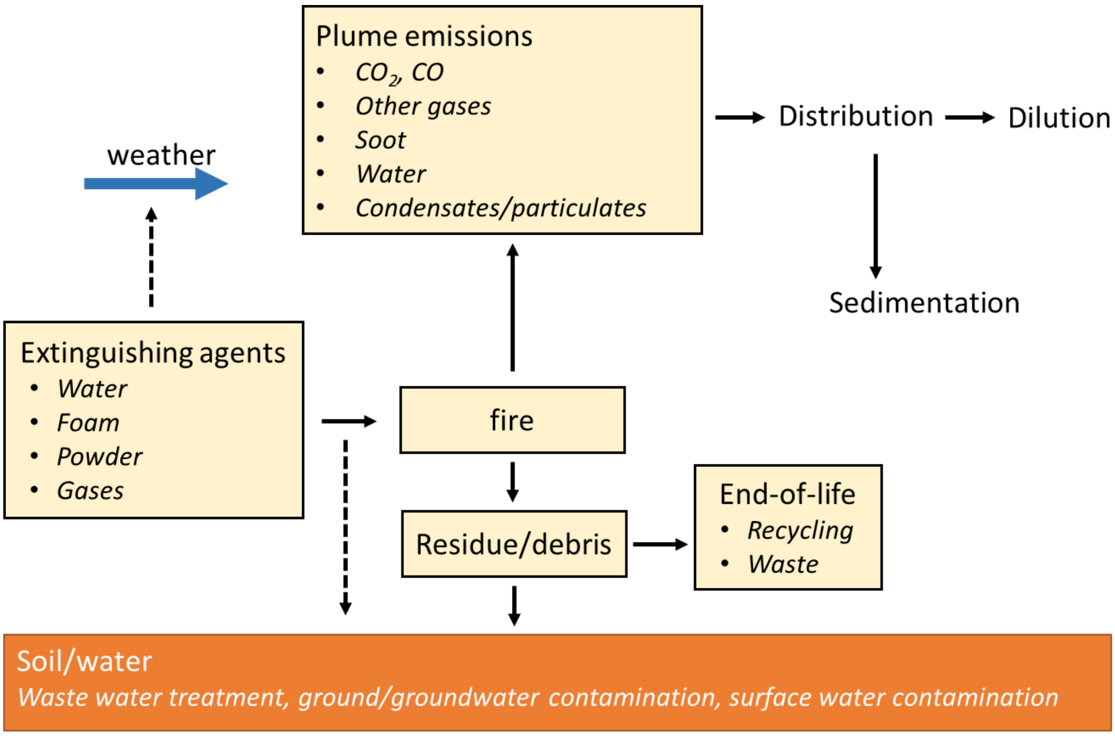

Figure 1: Schematic representation of impact of fire on the environment.

This impact also has economic consequences for communities and regions and while the direct and indirect costs of fire on a community can be devastating, they are not usually reported at a local scale beyond an account of the human deaths and injuries and the amount of property destroyed or damaged (Evarts, 2018). To calculate the true cost of fire to society we need to be able to quantify the impact fire has, not only on the people or structures involved, but also to the environment. Studies have been done to examine the environmental impact of fire (Blomqvist and Simonson McNamee, 2009, Simonson McNamee et al., 2011, Amon et al., 2014, McNamee and Andersson, 2015, Amon et al., 2019), but we cannot yet fully quantify this impact and its consequences to the local economy.

1.2 Project Aim

This project aims to develop a research road map, identifying research needs to be able to quantify the environmental impact of fire in the built environment and its economic consequences. This project has focused on structure fires, although some data for wildland and wildland urban interface (WUI) fires, as the boundaries between the built environment and its surroundings are often blurred, has been considered.

1.3 Project Tasks

The project is divided into two main tasks:

Task 1: Using the Foundation's Phase 1 literature review (Martin et al., 2015) as a starting point, review existing information on environmental impact of fire in the built environment with a focus on quantification and economic consequences. This information includes:

- Research since the previous report was published
- Case studies of actual structure fires that includes information on the impact of the fire on the environment

Task 2: Based on the information found in Task 1, perform a gap analysis on what future research is needed to adequately quantify the environmental impact of fire in the built environment and its economic consequences on the local economy and develop a research road map to fill the identified gaps. The road map considers gaps as well as the prioritization of the needs in order to achieve this goal.

1.4 Limitations

The work in this study focuses on providing a state-of-the-art survey of prior work to identify and (if possible) quantify the cost of the environmental impact of fires in the built environment. Emissions from wildland fires are, therefore, outside the scope of the work presented. The Wildland-Urban interface, however, is dealt with as part of the built environment which means that some data concerning emissions from large wildland fires have been included in the literature study.

The focus of the work is on the cost of the *environmental* impact of fires in the built environment. Therefore, the impact on health due to emissions from fires is outside the scope of the work presented. In particular this is important when dealing with the impact of the use of some firefighting techniques, e.g. employing firefighting foam which has been largely outside the scope of this study. This limitation is discussed in more detail in Chapter 4.

1.5 Project and Report Structure

In order to prepare the tasks given above, the project has been structures in a series of steps which will approximately correlate to the chapters of this report as illustrated in Table 1.

Table 1: Description of project and report structure

STEP	***CHAPTER***
Step 1: Brainstorming approach, identifying data sources and refinement of scope *Step 2: Literature review of in-house and public*	Chapter 2: Literature Review
Step 3: Quantification of fire impact to the environment	Chapter 3: Quantification of Fire's Impact on the Environment
Step 4: Methodology to evaluate the economic impact of fires	Chapter 4: Evaluating the Cost of the Environmental Impact of Fires
Step 5: Compilation of impacts analysis, economic analysis and gap analysis	Chapter 5: Case Studies Chapter 6: Gap Analysis Chapter 7: Research Roadmap

2. Literature review

2.1 Methodology

The literature review presented in this chapter was based on three main methods:

1. Review of the Final Report developed by Martin et al. (2015)
2. Collation of published (and if relevant unpublished) work by the Consortium Partners, relevant to the topic of the Environmental Impact of Fires, focussing on the Built Environment.
3. Traditional literature review based on a selection of search strings in the LUBsearch function offered by the Library at Lund University, and using the INERIS literature databases. The full list of databases included in this search function is found in Appendix 1.

The search strings that were investigated in all cases were:

- "emissions from fire/fire emissions"
- "environmental impact of fire"
- "economic impact of fire"
- "CBA fire"
- "fire water runoff "
- variations of the above, including searching references within identified articles.

The results of the searches have been grouped according to whether they relate to experimental or field results concerning emissions from fires, environmental impact of fires, or economic impact of fires.

2.2 Emissions from Fires

A significant amount of work has been done since the 1980's onwards to characterise the emissions of various chemical species from burning materials or from fires (see for example (Braun and Levin, 1987, Gurman et al., 1987, Huggett and Levin, 1987, Levin, 1987, Paabo and Levin, 1987a, Paabo and Levin, 1987b). The vast majority of studies found through the literature search are related to material emissions or forest fire emissions (see for example (Bombelli et al., 2009, Hao et al., 2016, Marlier et al., 2015, Martins et al., 2012, Preisler et al., 2015, Qu et al., 2006, Samsonov et al., 2005, Wiedinmyer and Neff, 2007)) with few being available for products that are relevant for the built environment (see e.g. (Blais and Carpenter, 2015, Blomqvist, 2005, Blomqvist et al., 2011, Blomqvist et al., 2004b, Blomqvist et al., 2004a, Blomqvist and Simonson McNamee, 2009, Krüger et al., 2016, Larsson, 2017, Lecocq et al., 2016, Lönnermark and Blomqvist, 2006, Lönnermark and Blomqvist, 2005, Lönnermark et al., 2007, Persson and Simonson, 1998, Truchot et al., 2018, Wieczorek et al., 2011, Calogine et al., 2011, Meacham, 2012)).

It appears, however, that the only attempt to comprehensively estimate emissions from fires of a whole country is relatively out of date (Persson and Simonson, 1998) and needs to be revisited, expanded to include additional country estimates and updated using modern estimates of residential and office fuel loads. Even recent collations of fire emissions, e.g. that developed by Amon et al. (2014), refer to Persson and Simonson (1998). The US Environmental Protection Agency (US EPA) provides some guidance concerning generic methods to estimate global emissions from building fires (Abraham et al., 2001) and vehicle fires (EPA, 2000), both of which refer to general compilations of emission factors from the 1990's (EPA, 1996). More details are provided below on the methodology developed by Abraham et al. (2001), including its application to a full case study in Chapter 4.

More recently, Love et al. (2010) produced a document concerning greenhouse gas emissions from building and vehicle fires in New Zealand. Love et al. (2010) gives CO_2-equivalents rather than emissions, however, making it difficult to compare to other methods or to validate against experimental data. Further, as noted in the introduction, the impact of fires on the environment (and their associated cost) is far more complex than that which can be expressed using CO_2-equivalents.

Emissions from fires are typically divided into two main categories either based on geographic distance from the seat of the fire (i.e., local or global emissions), or based on their potential temporal impact (i.e., short-term effects or long-term effects). Table 2 gives a summary of common emissions which are relevant to consider when investigating the environmental impact of fires. It is important to keep in mind that the impact (and potential cost) of emissions is highly dependent on the sensitivity of the recipient.

Table 2: Summary of main emissions from fires, impact categories and main recipients.

Emission	**Distance of greatest impact**	**Temporal window of greatest impact**
CO, HCN, acid gases, NO_x, SO_x, aldehydes, isocyanates	Local	Short-term (acute toxicity)
Acidification	Local	Long-term
Firefighting agents (e.g. FF-foam additives, powder)	Local/Global	Long-term
Metals	Local/Global	Long-term
Particulates	Local/Global	Long-term
Dioxins, PAH, PCB, POPs, VOC	Global	Long-term
Greenhouse gases (e.g., CO_2, CH_4, N_2O)	Global	Long-term
Ozone depletion (e.g. NOx, VOC)	Global	Long-term

Fire emissions can, however, be due both to direct emissions from the fire and from firefighting activities which take place as an intervention ostensibly to minimise the overall impact of the fire. Recently, a study of the impact of firefighter intervention on fire emissions and their environmental impact (Amon et al., 2019) addressed the question of how to assess the combined environmental impact in terms of local and global effects using the Fire Impact Tool. The work is based on division of the risk assessment into an Environmental Risk Assessment which considers local impacts and the use of an LCA-based methodology to assess the global impacts.

Key to developing an understanding of the cost of the environmental impact of emissions from fires, is an understanding of emissions themselves. The international standardisation committee for Fire Safety (ISO TC92) has a sub-committee (SC3) which focusses on developing a standardised methodology to assess the environmental impact of fires. Their standards represent a series of documents compiling important definitions and instructions concerning assessing the environmental impact of fires and represent an important starting point for the development of a methodology to assess the cost of the environmental impact of fires. ISO TC92 SC3 has to date developed 6 documents:

- ISO 26367 Guidelines for assessing the adverse environmental impact of fire effluents
    - ISO 26367-1 Part 1: General (international standard, 2017, 2019)
    - ISO 26367-2 Part 2: Compilation of environmentally significant emissions from fires (international standard, 2017)
    - ISO 26367-3 Part 3: Sampling and analysis (working draft)
    - ISO 26367-4 Part 4: Incorporating Fires into Models of Environmental Impact (internal committee document)
- ISO 26368 Environmental damage limitation from fire-fighting water run-off (international standard, 2012)
- ISO 19677 Guidelines for assessing the adverse impact of wildland fires on the environment and to people through environmental exposure (international standard, 2019).

Numerous methods exist to quantify the emissions from fires, the choice of which depends both on whether the fire is on-going or has been extinguished, and the susceptibility of the recipient. A methodology to identify potential sampling methods is presented in ISO 26367-1 and is reproduced in Figure 2. This simple flow chart also provides guidance concerning which international standards provide more details concerning emissions sampling and measurement.

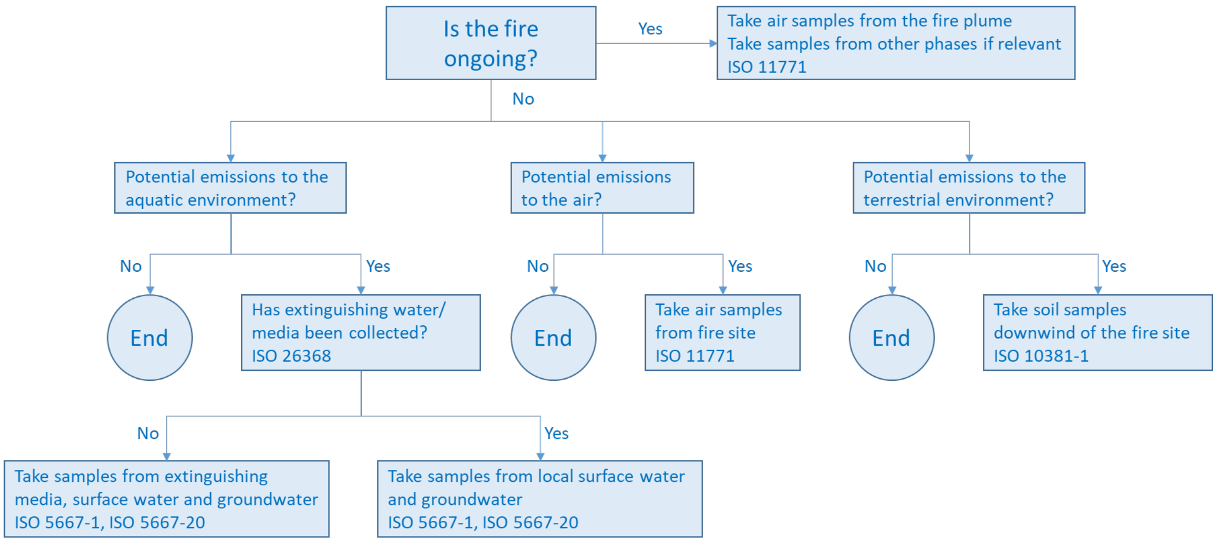

Figure 2: Flow chart designating potential sources of sampling information for emissions from fires. ©ISO. This material is reproduced from ISO 26367-2: 2017, with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization. All rights reserved.

In addition, it is possible to estimate emissions from fires to assess the cost of their environmental impact using emission factors as proposed by the US EPA (Abraham et al., 2001), data from the US EPA National Emissions Inventory (NEI) concerning "event" sources (EPA, 2017), or that developed by Persson and Simonson (Persson and Simonson, 1998). The methodology developed by Persson and Simonson (1998), follows essentially the same as that outlined by Abraham et al. (2001). This methodology is based on the estimation of the emissions per object times the number of fires. For structural fires this can be described using the equations below:

$$M_c[kg] = (M_{structure}[kg] + M_{contents}[kg]) \times \%_{loss}$$

$$M_{structure}[kg] = m_{structure}\left[\frac{kg}{m^2}\right] \times A_{structure}[m^2]$$

$$M_{contents}[kg] = m_{contents}\left[\frac{kg}{m^2}\right] \times A_{contents}[m^2]$$

$$E_{structure}[kg] = EF_i \times v_{fire} \times M_c$$

Where M_c is the fuel load in the structure in kg, $M_{structure}$ is the combustible mass of the structure in kg, $m_{structure}$ is the combustible mass of the structure per square meter, $A_{structure}$ is the area of the structure, $M_{contents}$ is the combustible mass of the contents in kg, $m_{contents}$ is the mass of the contents per square meter, $A_{contents}$ is the floor area of the contents, $E_{structure}$ represents the emissions from burning structures in kg, EF_i is the emission factor for species i, and v_{fire} is the frequency of fire events to be studied. Using this methodology, it is possible to estimate all emissions for which emission factors exist, over a specific temporal or geographic area.

While wildland fire is outside of the scope of this project, it is worth noting that there has been some investigation of firefighting chemicals used for wildland fire, including long-term, short-term, foams and wetting agents (Kalabokidis, 2000, Bell, 2003, Backer et al., 2004), Kalabokidis noted that "relatively little information is available on the toxicity of these chemicals to aquatic and terrestrial life" and that "less information is available concerning impacts at the community and ecosystem level." Indeed, work just prior to Kalabokidis (2000), by the Canadian Forest Service, which looked at three fire retardant chemicals and two fire suppressant foams found that no toxic responses were evident, concluding that "these retardants and foams do not pose an acute hazard to adult birds, mammals, or earthworms" (Vyas and Hill, 1994).

2.3 Examples of Environmentally Significant Fires

Much can also be learned by the investigation of significant fires and their environmental impact. A list of environmentally significant fires, and associated publications concerning the incidents, is contained in Table 3. The table should be seen as illustrative rather than exhaustive given that the number of potential events that could be of interest to include internationally is prohibitively large. The SEVESO accident that occurred in 1976 is not detailed in this table but should be kept in mind since, at least in Europe, it has a significant influence regarding industrial accidents and how they are seen in terms of their environmental impact. This incident included a toxic cloud dispersion following the overheating of a chemical, the could contain among others species 2,3,7,8-TCDD, now known as "SEVESO dioxin".

In this section we define "environmentally significant" to include fires that have a significant potential to create an immediate and lasting impact on the environment. These include mainly large scale events where information is available concerning interaction between the fire and the environment. The case can be made that the many small fires from the built environment, that provide the background "noise" to large scale events have a significant potential to impact the environment on an everyday basis. Therefore, annual emissions from typical fires in the built environment are included as one example in the table. This example is expanded and updated as a full case study in Chapter 4.

The table contains data for the <u>object</u> burning in the chosen example, the <u>ignition source</u>, a summary of the <u>fire load (burned)</u> (qualitative or quantitative) and the <u>environmental exposure</u>, if known. The "environmental exposure" describes the recipient of fire emissions and the quantity of emissions if this information is available.

Table 3: Description of environmentally significant fires in modern history with a focus on the built environment (including manufacturing). Note that the list is illustrative rather than exhaustive. A small number of illustrative case studies are presented in Chapter 5 for three incidents from this table.

Fire incident (Name and Year)	Description	Reference
London, England, 1666	Object: City of London Source: Bakery fire Fuel load (burned): 13 200 houses, 87 parish churches, St Paul's Cathedral, and most of the buildings of the City authorities in central London. It is estimated to have destroyed the homes of 70,000 of the city's 80,000 inhabitants. Environmental exposure: Unknown	Garrioch (2016)
Salzburg, Austria, 1982	Object: Chemical Warehouse Source: Welding/Hot works Fuel load (burned): 400 tons of fertilizers and pesticides Environmental exposure: Large gas cloud, dispersed due to favourable weather conditions.	Christiansen et al. (1993)
Woodkirk, UK, 1982	Object: Chemical Warehouse Source: Unknown Fuel load (burned): 1,5 Mlitres solutions based on paraquat and diquat, 20 tonns octyl phenol Environmental exposure: Herbicides entered the drains and were carried into a watercourse, polluting the surrounding area	Christiansen et al. (1993)
Ipswich, UK, 1982	Object: Chemical Warehouse Source: Welding/Hot works Fuel load (burned): 1380 tons fertilizers Environmental exposure: Fire plume exposure to surrounding buildings, corrosion from nitrogen oxides	Christiansen et al. (1993)

Fire incident (Name and Year)	Description	Reference
Basle, “Sandoz Fire”, Switzerland, 1986	Object: Chemical Warehouse Source: Blowtorch incorrectly applied to shrinkwrap Fuel load (burned): 1 300 metric tons of agrochemical products and other chemicals Environmental exposure: Run-off water into Rhine river causing extensive contamination Comment: a) A full special issue of Chemosphere has been released with all gathered information about lessons learnt from that dissater, notably in terms of air and water pollution b) Corporate Environment protection strategy of SANDOZ was fully reviewed as the aftermath of this disaster and New guideline for plant safety n°28 entitled “Warehousing” was implimentted within the group for the protection of the environment in case of a fire event	Capel et al. (1988) Suter et al. (1989) Giger (2009) Vince (2016)
Nantes, France, 1987	Object: Chemical Warehouse Source: burning material among fertilizers or electrical fault Fuel load (burned): 1 450 tons fertilizers, 750 tons ammonium nitrate, 200 tons urea gas Environmental exposure: Extensive fire plume (estimated 25 000 evacuated). Comment: as the aftermath of this event, French CA ordered a large-scale experiment perfomed by CERCHAR (former name of INERIS) to better uderstand self-sustained decomposition of NPK fertilisers and related thermal and toxic hazard.	Christiansen et al. (1993) Marlair and Cwiklinski (2003)
Dayton, USA, 1987	Object: Paint Warehouse Source: Spillt flammable liquid, ignited by spark from electric motor Fuel load (burned): full warehouse of paints (5,5 millions of liters) Environmental exposure: fire plume and minor exposure of nearby waterway.	Copeland and Schaenman (1987) Fischer and Varma (2016)
Tours, France, 1988	Object: Manufacturer hazardous chemicals Source: Explosion and fire due to poor facilities maintenance Fuel load (burned): Chemical fire spread to flammable and toxic chemicals Environmental exposure: Fire plime zone some 30 km long and 12 km wide. Loire river poluted by toxic waste causing the death of some 15 ton fish and prompted decision to cut water supplies to Tours (pop. 155 000) for a week.	Szarka (2002) Marlair et al. (2004)

Fire incident (Name and Year)	Description	Reference
Hagersville, Canada, 1990	Object: Tire storage Source: Arson, molatov cocktail type device Fuel load (burned): estimated 14 million tires Environmental exposure: Toxic plume for 17 days. Evacuation approx. 4,000, cost the province more than $10 million for a year-long clean up. It remains the worst environmental disaster in Ontario history.	Schneider (1990) Nolan (2015)
Woking, UK, 1990	Object: Wood treatment installation Source: The fire started on a lindane storage Fuel load (burned): Several chemical products including lindane Environmental exposure: More than 30 t of lindane flew to the Bourne river (connected to the Thames) that was polluted over 80 km. Environmental cleaning evaluated to 150 000 £.	
Perth, Australia, 1991	Object: tanker Source: unkown Fuel load (burned): a large amount of petroleum Environmental exposure: toxic product atmospheric dispersion and petroleum spillage (2,9 million gallons crude oil) over the sea, more than 30 km².	NYT (1991)
Bradford, UK, 1992	Object: Allied Colloid Source: Proximity of incompatible chemicals Fuel load (burned): Chemicals Environmental exposure: 16 000 m3 of contaminated run-off water.	HSE (1993) Marlair et al. (2004)
Macassar, "Somerset West Fire", South Africa, 1995	Object: Sulphur stockpile Source: Grass fires over several days depleting water reserves Fuel load (burned): 15 700 ton sulphur Environmental exposure: Emission of estimated 14 000 ton SO_2 over a 20 hour period. Thousands evacuated and long-term impact on people and agriculture up to 30 km from site. Comment: at that time, the only industrial fire to our knowledge that killed some people (and likely also local fauna species specimen) at remote location from the fire	Batterman et al. (1999) Jeebay (2005)

Fire incident (Name and Year)	Description	Reference
Wilton, UK, 1996	Object: BASF Plant Source: Unconfirmed fault in fluorescent lighting Fuel load (burned): 10 000 tons polypropylene Environmental exposure: minor contamination through smoke plume	Carty (1996) HSE (1996)
Twin towers, USA, 2001	Object: World Trade Center, New York Source: Terrorist attack. Ignition through airplane impact. Fuel load (burned): Building contents Environmental Exposure: minor contamination through smoke plume and dust cloud from collapse of buildings.	Kean et al. (2004)
Cartagena, Escombras Valley, Spain, 2002	Object: Warehouse for fertilizer Source: Self-sustained decomposition process, no conclusion on the actual activating heat source that trigger the SSD phenomenon Fuel Load (burned): 15000 tons ammonium-nitrate based ternary fertilizer 15-15-15 Environmental Exposure: The smoke plume was entrained towards the sea. The cloud affected Cartagena, a city of 200,000 inhabitants and some 50 persons from the plant itself, 130 people from the various emergency services involved and 3500 people from the local population were affected, essentially by eye and throat irritation. The economic activity in the Valley was frozen during more than 24 hours, while at risk population was ordered to stay confined. Limited air pollution occurred, as assessed from NO_x measurement and post-event modelling exercise, and no significant water pollution was found due to appropriate fire water run-off containment.	Baraza et al. (2020)

Fire incident (Name and Year)	Description	Reference
Mishrag (near Mosul), Irak, 2003	Object: Al-MIshraq State Sulfur Plant, heap of sulphur extracted and refined from largeest native sulphur deposit (500 million tons eq. elemental S) Source: believed tobe arson Fuel load (burned): huge amounts of sulphur Environment exposure: 600 ktons SO2 dense plume over one month affected a large area including nearby population, fauna and flora ; acute short term injuries in exposed military staff and population, including 2 deaths at least among the nearby residents, possibly also linked to long term adverse medical effects (incl. Bronchiolitis ; local wheat crop field polluted by fire and smoked resulted in US$40 million loss ; area affected by smoke plume ~100 sq km, reaching the Turkish city of Arbil Comment:This huge fire lasted almost one month and present significant similarities to the Somerset West sulphur fire in South Africa that occurred in 1995 ; the site has caught fire several times after ths major event, including in 2016 and 2019	Carn et al. (2004) Baird et al. (2012)
Kolding, Denmark, 2004	Object: N.P.Johnsens Fire Works Factory Source: Fire works dropped by workers clearing a container Fuel load (burned): Large volume of fire works burned and exploded Environmental exposure: Approx. 355 houses reported damaged (176 rendered uninhabitable). Altogether, 2,107 buildings were damaged by the explosion, with the cost of the damage rounding to an estimated € 100 million. Comment: According to ARIA French database, and surprinsingly, environmental damage rated 0 out of 6 on European scale, while financial damage was rated the maximum value on the same scale (6/6). Fireworks fires are known to have to potential of significant soil pollution risk from heavy metal and related salts particles deposition	Beredskabsstyrelsen (2005) ARIA (2009)

Fire incident (Name and Year)	Description	Reference
Hemel Hempstead, UK, 2005	Object: Buncefield oil storage depot Source: Overfilling of Tank 912 due to faulty control gauges Fuel load (burned): 20 fuel tanks, millions of litres of fuel Environmental exposure: bunds for spill capture overflowed causing contamination of surrounding soil and waterways. Comment: in 2010, 5 companies ordered to pay £ 9.5 million for their responsabilities in this accident, including £1.3 million fine for pollution offense, a UK record for a single accident	MacDonald (2005) Newton (2008) Atkinson (2017)
Lviv, Ukraine, 2007	Object: Train that carries yellow phosphorus Source: Train derailment with spontaneous igntion of phosphorus after carriage opening and phosphorus spillage Fuel load (burned): about 700 t of yellow phosphorus involved Environmental exposure: dispersion of highly toxic gases and ground pollution (fire reignition because of residual phosphorus 15 days after the first fire.	UNIAN (2007)
Quezon City, Philippines, 2011	Object: Informal Settlement Source: Unknown Fuel load (burned): Informal housing Environmental exposure: 20 000 homeless	Rini (2018) AAP (2011)
Iowa City, USA, 2012	Object: Tire landfill Source: Unknown Fuel load (burned): estimated 1,3 million tires Environmental exposure: Impact on Iowa City (pop 152 586 US 2010 census) through smoke exposure.	Singh et al. (2015)

Fire incident (Name and Year)	Description	Reference
West (near Waco), USA, 2013	Object: Warehouse fertiliser storage Source: not known with certainty Fuel load (burned): seeds, woodframe buildings, as the aftermath of the fire event, mass explosion of of sf some 50 tons AN-based fertilizers Environment exposure: mnay built infrastructures on a large area, including several schools and medical care for elderly people Comment: 15 fatalities incl. 14 firemen, and more than 260 injured , have lead to concentrate the analysis of the techncial understanding of the reasons for this incident, incl. the regulatory context gaps ; no information so far on damage to the environment, beyond destruction of many built infrastructures	Banks (2016) CBS (2016)
Lac Megantic, Canada, 2013	Object: Petroleum fire in Lac Magantic downtown Source: Train derailment with petroleum spillage Fuel load (burned): 5 400 m^3 of petroleum Environmental exposure: Petroleum flows to the lac Megantic and to the Chaudiere river. The decontamination cost is estimated to more than 150 M$.	Galvez-Cloutier et al. (2014) Saint-Laurent et al. (2018)
São Francisco do Sul, Brazil, 2014	Object: Warehouse containing fertilisers imported from Russia some 20 days before the event Source: not actually evidenced by local investigation Fuel load (burned): SSD of 10,000 tons NK fertiliser Environment exposure: some 5,000 tons of gases and smoke plume dispersed over a period of three days. Wind conveyed the plume towards the nearby harbor in parallel to a high traffic raod where several sectors had been evacuated ; more than 100 people treated for smoke inhalation, no reported death Comments: local investigator of that fire contacted INERIS to get some support in the analysis. From information collected, contamination of the fertiliser during transport may be one of the caise of the incident	Marlair (2014)

Fire incident (Name and Year)	Description	Reference
Tianjin, China, 2015	Object: Port of Tianjin Source: First explosion in an overheated container of dry nitrocellulose. A second larger explosion occurred in container with 800 tonnes Ammonium nitrate leading to spread and burning over many days. Fuel load (burned): Significant amounts of material across the port and surrounding facilities, e.g. >12 000cars, 300 building and 7 500 containers were damaged. Environmental exposure: estimated 165 fatalities, 104 of which were firefighters. Significant environmental damage due to toxic chemicals stored in large quantities.	Zhang et al. (2018)
Mishrag (near Mosul), Irak, 2016	Object: Al-MIshraq State Sulfur Plant, heap of sulphur extracted and refined from largeest native sulphur deposit (500 million tons eq. elemental S) Source: deliberate ignition, as a warfare tactic by Daesh Fuel load (burned): huge sulphur stockpile Environment exposure: environmental impact mainly associated to huge SO_2 and H_2S releases, included casualties (2 deaths, > 1000 persons suffering breathing problems). SO_2 mass release of 161 kt over 6 days, estimated to correspond to minor volcanic eruptions	Björnham et al. (2017) Rudaw (2019)
Fort McMurray, Canada, 2016	Object: Horse River Wildfire Source: Unknown Fuel load (burned): 2 400 homes and businesses + 590 000 hectare wildland Environmental Exposure: total disruption of a community with mandatory evacuation of approximately 88 000 residents. An estimated insurance cost of USD 3.58 billion. Emissions to air, water and soil. Significant increase in mental health symptoms.	Woolf (2019) Brown et al. (2019) Adams et al. (2019)
London, UK, 2017	Object: Grenfell Tower Source: Combined refridgerator/freezer unit on 4th floor Fuel load (burned): 127 apartments in high-rise residential building Environmental exposure: Emissions to the soil have been posed as toxic and an enquiry is still underway.	GOV.UK (2019)

Fire incident (Name and Year)	**Description**	**Reference**
Kemerovo, Russia, 2018	Object: Winter Cherry Shopping mall and entertainment complex Source: Ignited in fouth floor in childrens play rooms Fuel load (burned): four storeys of the shopping mall and entertainment center, 64 dead. Environmental exposure: no report of specific environmental exposure	Chronicle (2018) Interfax (2018)
Fire SIAAP Achères, 2018	Object: fire in a wasterwater treatement plan on the clarifocculation process (process dedicated to particles capture) Source: unknown Fuel load (burned): wastewater treatment installation, some toxic product were involved in the fire as ferric chloride Environmental exposure: Strong reduction of the oxygen level in the Seine river with numerous fish death (more than 5 t, more 10 km of river concerned)	TR78 (2018)
Paris, France, 2019	Object: Notre Dame cathedral fire Source: The source of ignition is unkown but probably linked with renovation works that sere in progress. Fuel load (burned): The wood that consituted the frame of the cathedral (oak) Environmental Exposure: The cover was made of lead that was melt during the fire and then produced lead oxyde that was partitally dispersed with the fire smoke. More than 200 t of lead was present.	Tiago Miguel (2019) Tognet and Truchot (2019)
Rouen, France, 2019	Object: Warehouse fire Source: Unknown, under investigation Fuel load (burned): Lubricant additives for the automotive industry Environmental Exposure: Environmental impact of that fire is under investigation.	

Fire incident (Name and Year)	Description	Reference
Cumulative small scale fires, every year	Object: Numerous structural fires Source: Variety of sources. Electrical and cooking are typically the main sources of ignition together with smokers materials (which is on the decline). Fuel load (burned): Combustible structural material and building contents Environmental Exposure: Emissions to air, water and soil to varying degrees depending on the size and duration of the fire. Estimates from Persson and Simonson put emissions from fires in Sweden on an annual basis to approximately 21 kton CO_2, 1 kton CO, 1 ton HCN, 42 ton NO_x, 131 ton SO_2, 138 ton HCl and 1 kton particles for a population of 9 Million. A possible US scenario is included in the case studies presented in Chapter 5.	Persson and Simonson (1998) Abraham et al. (2001) Love et al. (2010)

Note: In a recently published safety guideline about fire water run-off management (UNECE, 2019 – under press), the reader may find some other fire incidents not included in the list that are analysed in terms of water impact, brief data on environmental impact costs are also mentioned

2.4 Modelling the environmental impact of fire in the built environment

Fire can impact on the environment as a result of the fire itself, fire suppression activities, or both. The initial source of the impacts are emissions from the fire, i.e. the products of combustion that are carried in the plume and dispersed into the air. When these products settle, aquatic and terrestrial impacts can follow. Impacts of fire suppression are largely aquatic and terrestrial, with firefighting water runoff carrying fire products and suppression agents (including chemical additives) into waterways or ground water, or directly into the soil.

Much of the work to date that has considered the environmental impact of fire has focused on Life cycle assessment (LCA) or similar methodologies. Life cycle assessment is typically used to evaluate the potential environmental impacts of a product, process, or activity from a systemic or holistic point of view. The methodology was established in the 1970's due to the rising need to measure the environmental impact of product choices made by industry or regulators. It is a comprehensive method for assessing impacts across the full life cycle of the system being studied from the cradle to the grave. Typically this includes materials acquisition through manufacturing, use, and end of life. An internationally recognised procedure for conducting an LCA has been developed by the International Organization for Standardization (ISO) and is summarized in ISO 14040 and ISO 14044 ((ISO, 2006a, ISO, 2006b)). LCA-based environmental impact methods can be used to assess a wide range of environmental impact categories, including but not limited to: global warming, eutrophication, resource depletion, ecotoxicity of soil and water bodies. Thus, an LCA is essentially equipped to consider both the environmental impacts from fires directly and from firefighting activities. However, an LCA is typically performed in an "accident-free" life cycle meaning that fire is not traditionally included as part of the LCA. A Fire-LCA methodology was developed in the 1990's (Simonson et al., 1998), which includes emissions due to fires as shown in Figure 3.

The Fire-LCA methodology identifies a number of categories which need to be quantified in order to establish the size of the environmental impact of fires and their associated cost. These include: the potential environmental impact of firefighting activities, the replacement of materials burned in the fire (both those caused by the functional unit, designated as "primary fires", and replacement of the functional unit which burns in a fire originating through another ignition source, designated as "secondary fires"), and decontamination activities. Details of the environmental exposure (and associated cost) will be highly dependent on questions of recipient (air, water or soil) and its sensitivity.

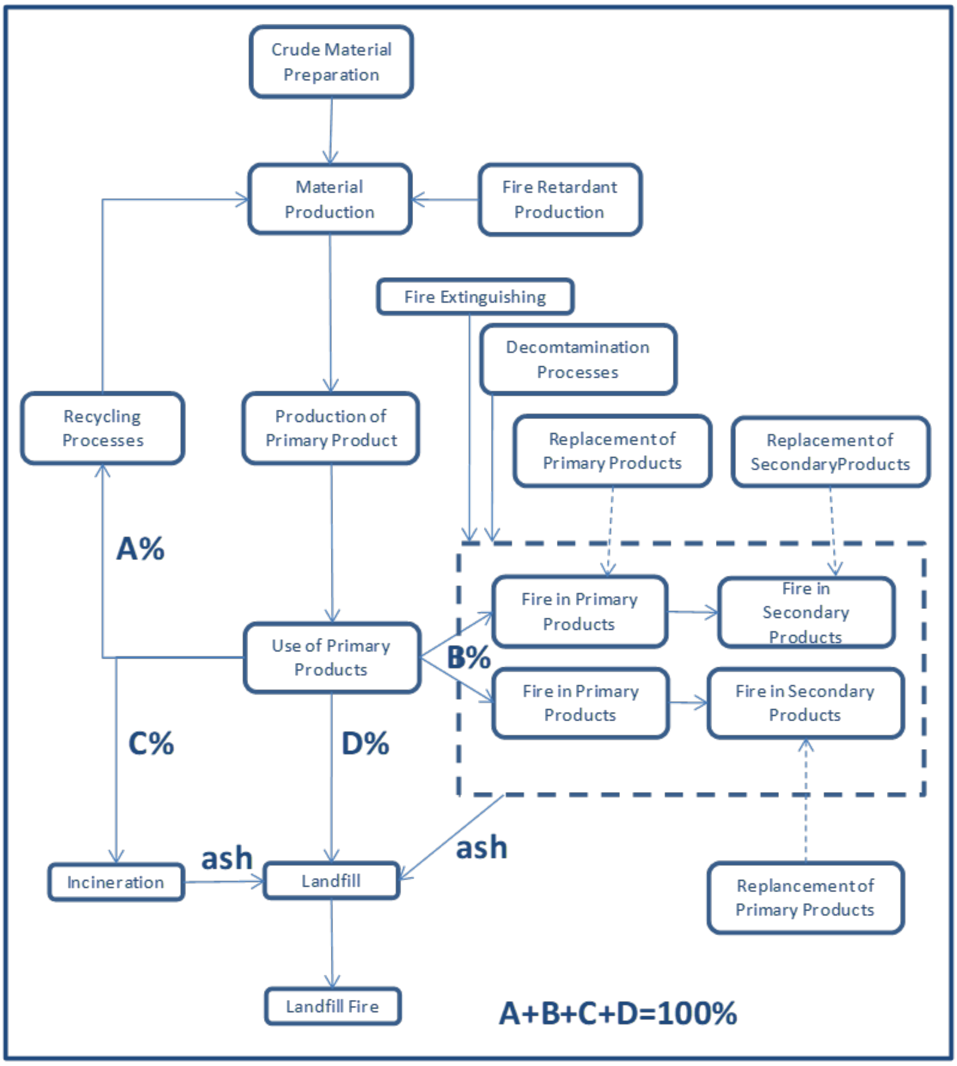

Figure 3: Fire-LCA framework (Simonson McNamee et al., 2011).

In the work conducted as part of the 2015 *Environmental Impact of Fire* project report (Martin et al., 2015), various studies using LCA were considered, including the Building for Environmental and Economic Sustainability (BEES) tool (Lippiatt et al., 2010), and the Fire-LCA Model (Andersson et al., 2003, Andersson et al., 2007, Andersson et al., 2004, Simonson et al., 2001, Simonson et al., 2000, Hamzi et al., 2008, Wieczorek et al., 2010, Wieczorek et al., 2011). Little additional work has been identified that is not related to the studies presented in the previous project. Of the work reviewed previously, only the Fire-LCA research explicitly endeavours to include the environmental impact of fires as part of a full product or service life cycle.

Challenges exist in both the modelling of the physical distribution and impact, as well as the economic valuation of the damage of in particular firefighting activities. However, models for transport and fate of pollutants exist, some of which are being used for assessing firefighting impacts, e.g. the work of Amon et al. (2019) cited previously. Further, Lindim et al. (2016) developed a model to predict PFOS and PFOA concentrations in the main European rivers to provide a European-wide perspective on the current contamination by these substances. Using the STREAM-EU model (Spatially and Temporally Resolved Exposure Assessment Model for European basins), they looked at various rivers, including an application to the Danube River basin and comparison of model predictions to recent monitoring data.

2.5 Modelling the economic cost of the environmental impact of fire

In the 2015 *Environmental Impact of Fire* project report (Martin et al., 2015), two primary types of impact assessment were highlighted: cost-benefit analysis (CBA) and life cycle analysis (LCA). The LCA articles have been listed in the section above for the present study. A selection of applications of approaches were reviewed previously, e.g. Gritzo et al. (2011), Fraser-Mitchell et al. (2012), and McNamee and Andersson (2015). A selection of literature related to economic impact of wildland fire has also been identified (e.g., (Morton et al., 2003, Dale, 2010, Doerr and Santin, 2013)). These are pertinent to this effort from the perspective of identifying different approaches to estimating environmental impact and remediation costs. Although the focus of this study is on the built environment rather than wildland fires, some work addressing the economic cost of the environmental impact of wildfires has been included as methodology that is developed could be applied to the built environment (Thomas et al., 2017).

In the present study, the search has included articles in the above areas that have been published since the Martin et al. report (2015) or were missed in that report. In addition, with a stated focus on the economic cost of environmental impacts due to fire, we expand the scope to include literature that considers more broadly the quantification of the economic costs of environmental damage. To date, much of this literature tends to be focused around economic analyses that are intended to be used for policy analysis, i.e. to support decisions about activities that may result in environmental impact. An example of the literature in this area is reflected in recent standardisation (ISO, 2019a), guidelines and government documents (EPA, 2009, EPA, 2014, Schwermer, 2012, Pearce et al., 2006, DOI, 2012), and review articles (Thomas et al., 2017).

In addition, this effort looked more closely at environmental impacts associated with suppression activities, including chemical additives to enhance suppression effectiveness, such as the group of per- and polyfluorinated substances (PFASs), including perfluorooctanoic acid (PFOA) and perfluorooctane sulphonates (PFOS), which were used in firefighting foams (NZFSC, 2017, ECHA, 2018). A common application of PFOS was in Aqueous Film Forming Foam (AFFF), which was used for years in many aspects of operational firefighting, with a particular focus on liquid fuel fires (Hagenaars et al., 2011, DOD, 2017, NZFSC, 2017). While much of the literature reviewed is focused on health effects, there are related impacts to the environment, for general use (NZFSC, 2017) and wildland fire use (González-Prieto, forthcoming).

Although the focus of this study is on the built environment rather than wildland fires, some work addressing the economic cost of the environmental impact of wildfires has been included as methodology that is developed could be applied to the built environment. For example, there is a developing body of literature on modelling the economic cost of environmental impacts of fire (e.g., Butry et al. (2019) and Barrett (2018)). Of particular note, however, is the observation by Headwater Economics that ecological impacts are "more difficult to quantify than other wildfire impacts (p23)," citing wide ranges in costs of impacts. In their study case on the 2013 Rim Fire in California, they note that the magnitude of impact is "between $100 million and $736 million for loss of ecosystem services – that is, environmental benefits" and that "these costs are being tabulated more often as ecosystem service valuation becomes more accepted in courts to support damage assessments." (p14).

More details of the methodology presented in these papers is discussed in Chapter 4.

3. Quantification of Fire's Impact on the Environment

3.1 The European scale of industrial accident

While there are many studies regarding life safety impacts of fire and impacts to business (e.g. the significant work that is conducted annually by the NFPA and others (Ahrens, 2013, Brushlinsky et al., 2018)), there are relatively few studies on the environmental impact of fire in the built environment, outside of industrial/storage type facilities as outlined in Chapter 2. One comprehensive approach to quantifying environmental impacts of fire in the built environment – focused on industrial accidents – is the European Scale of Industrial Accidents (ARIA). One of the main interests of such a scale is to provide a comparison tool between accidents. A secondary interest that is specific to this study is to identify the limitations of the tool in defining a Research Roadmap for establishing the cost of the environmental impact of fires.

3.1.1 Presentation of the scale

The European Scale of Industrial Accidents is an established methodology to assess the impact of fires on humans and the environment (ARIA, n.d.). This scale was made official in February 1994 by the Committee of Competent Authorities (CCA) of EU Member States as a means of applying the SEVESO Directive (Directive 82/501/EEC), which was later updated to the SEVESO II Directive (Directive 96/82/EC). The European Scale of Industrial Accidents considers 18 parameters distributed between four items, summarised in Table 4.

Table 4: Main items used for environmental impact quantification (ARIA, n.d.).

Item	Number of parameters	Symbol
Dangerous material released	2	
Human and social consequences	7	
Environmental consequences	5	
Economic consequences	4	

Each parameter is given a value from 0 to 6, with the maximum value reached by one of the parameters of the category giving the final value for this category. This means that for each criterion, each line is considered individually and, then the maximum for each family gives the final value for the category. For environmental consequences, the corresponding parameters are given in Table 5, those for economic impact are given in Table 6.

Table 5: Environmental consequences parameter and quotation rules, reproduced from (ARIA, n.d.).

Environmental consequences		1	2	3	4	5	6
Env. 10	Quantity Q of wild animals killed, injured or rendered unfit for human consumption (t)	Q < 0.1	0.1≤ Q <1	1≤ Q <10	10≤ Q <50	50≤ Q <200	Q ≥200
Env. 11	Proportion P of rare or protected animal or vegetal species destroyed (or eliminated by biotope damage) in the zone of accident	P < 0.1%	0.1%≤ P <0.5%	0.5%≤ P <2%	2%≤ P <10%	10%≤ P <50%	P ≥50%
Env. 12	Volume V of water polluted (in m³)	V < 1000	1000 ≤ V < 10 000	10 000 ≤ V < 0.1 million	0.1 million ≤ V < 1 million	1 million ≤ V < 10 million	V ≥ 10 million
Env. 13	Surface area S of soil or underground water surface requiring cleaning or specific decontamination (in ha)	0.1 ≤ S ≤0.5	0.5 ≤ S < 2	2 ≤ S < 10	10 ≤ S < 50	50 ≤ S < 200	S ≥ 200
Env .14	Length L of water channel requiring cleaning or specific decontamination (in km)	0.1 ≤ L < 0.5	0.5 ≤ L < 2	2 ≤ L < 10	10 ≤ L < 50	50 ≤ L < 200	L ≥ 200

Table 6: Economic consequences parameter and quotation rules, reproduced from (ARIA, n.d.).

€ Economic consequences		1	2	3	4	5	6
€15	Property damage in the establishment (C expressed in millions of €)	0.1 ≤ C < 0.5	0.5 ≤ C < 2	2 ≤ C <10	10 ≤ C < 50	50 ≤ C < 200	C ≥ 200
€16	The establishment's production losses (C expressed in millions of €)	0.1 ≤ C < 0.5	0.5 ≤ C < 2	2 ≤ C <10	10 ≤ C < 50	50 ≤ C < 200	C ≥ 200
€17	Property damage or production losses outside the establishment (C expressed in millions of €)	-	0.05 ≤ C < 0.1	0.1 ≤ C < 0.5	0.5 ≤ C < 2	2 ≤ C < 10	C ≥ 10
€18	Cost of cleaning, decontamination, rehabilitation of the environment (C expressed in millions of €)	0.01 ≤ C < 0.05	0.05 ≤ C < 0.2	0.2 ≤ C <1	1 ≤ C < 5	5 ≤ C < 20	C ≥ 20

Cost in this table are expressed based on the reference cost in 1993. As indicated in Table 5 and Table 6, this scale considers the different topics mentioned in the general scheme of environmental impact, i.e. impact on water, impact on live organisms, the surface area of soil to be cleaned in case of deposit and, in terms of cost, the cost for cleaning, when determining the classification of an industrial accident. As for environmental impact, each criterion should be considered individually, after which the maximum criterion defined the value for the category.

3.1.2 Application to some representative fires

Application of this scale to identified representative fire is a key method to evaluate both its relevance and its limits. Table 7 shows the application of the scale to some fires selected from the table given in the previous chapter. Values given in this table come from the French national instance for accident analysis, the BARPI. Accidents given in the table have been selected as representative of a variety of impacts.

Table 7: Application of the European scale of industrial accident to some relevant fires.

Accident				€	Comments
Basel, Switzerland, 1986	4	6	6	6	The 5 environmental criteria were individually quoted for that case: • Env 10 quoted 5 for the death of 190 t of eels; • Env 11 quoted 1, no information about rare species impacted; • Env 12 quoted 1, no information about the volume of water polluted; • Env 13 quoted 1, some groundwater polluted; • Env 14 quoted 6, the Rhin was polluted over more of 1 000 km. The cost for environment cleaning is larger than 39 M€ for this fire.
Nantes, France, 1987	3	5	0	0	The environmental and economic indicators were not quoted because of the lack of information.
Tours, France, 1988	1	6	4	5	The environmental quotation is due to the pollution of two rivers, the Cisse and the Brenne over 23 and 5 km respectively. 20 t of fishes were killed. Underground water was polluted, and drinking water was forbidden for use during 8 days for 200 000 inhabitants.
Hagersville, Canada, 1990	1	6	3	5	The Environmental indicator is fixed to 3 since the fire polluted some underground water and 4,5 ha of ground. The economic factor is 5 because of the cost of pollution and cleaning (€18).
Saint Amable, Canada, 1990	1	4	0	0	14 000 t of sand used for firefighting and a large amount of gases release but no environmental quotation mainly due to the lack of data.
Somerset West fire, Macassar, South Africa, 1995	1	5	0	0	No information for quotation, indicators set to 0.
Lac Megantic explosion and fire, Canada 2013	0	6	5	6	Chaudiere river pollution over 80 km together with the pollution of Lac Megantic. Large amounts of fish killed. The cost for environmental cleaning was huge (estimation to more than 150 M$).

Another method to identify environmentally significant fires consists of searching in the database for all fires classified as 5 or 6 in terms of their environmental or economic consequences. Very few such fires exist in the database. In terms of the environmental consequences, the following were found:

- Classified as 6:
  - Basel in Switzerland (1986),
  - The Buncefield fire in the UK (2005),
  - A fire in a wood recycling industry, in St Cyprien, France (2008),
  - The explosion and fire of an offshore platform near New Orleans in the US (2010);
- Classified as 5:
  - Explosion and fire in Lac Megantic, Canada (2013),
  - Phosphorus fire after train derailment, Ukraine (2007),
  - Tanker fire in Perth, Australia (1991),
  - Wood treatment facility in Woking, UK (1990).

3.1.3 Limitations

This comparison highlights some of the model limitations. The main limitation is the requirement for a large amount of input data regarding fire consequences for a classification of the level of impact to be given. Such data should be obtained in the hours or days after the fire occurs. Without such data the classification becomes irrelevant.

As described in Chapter 5, for example in the *a posterior* analysis of the Lac Megantic case, when no data are measured, it is not possible to use the model to compute real consequences since the uncertainties are too great. In some cases, data are available for one of the criteria. In this case a classification can be made for that criteria; but it should be kept in mind that other criteria may be worse than stated in the evaluation due to missing data.

3.1.4 Conclusions

This analysis shows both the potential interest and the main limitation of the application of the European Scale of Industrial Accidents. There is a clear international interest in having defined criteria to achieve a classification or specific numeric assessment of a specific incident based on a common point of view, independent of the characteristics of the specific fire. The application, however, shows that some additional guidance is needed to ensure a similar understanding and application of the scale for all cases. Such guidance should typically include a methodology to evaluate each criterion, including information concerning sampling or modelling or how to use a combination of both.

Clearly, some sampling and modelling method should be given to prevent deviations in terms of analysis and to ensure that the result will be the same independent of where the analysis takes place. Those topics are typically addressed at the ISO level in the TC92/SC3 committee. A connection between the European Scales of Industrial Accidents and current work of the ISO TC92/SC3 is imperative to ensure that standards are developed to support the application of the scale in an international context.

3.2 Fire consequences modelling: state of the art and limitations

The quantification of the environmental impact of fire is currently difficult since several important data points are missing. This section details the available methods to predict environmental consequences and highlights the limitations and requirements to improve this prediction. Quantification modelling should be based on the schematic representation of impact on the environment as outlined in Figure 1. The different corresponding sequences are detailed below.

However, before proceeding into the detailed mechanism for each media, we should emphasise that atmospheric transport mechanisms remain the most important methodology to assess the environmental impact of fire emissions as these are largely emissions to a fire plume. Atmospheric models are also quite well known compared to other transportation carriers. The atmosphere is typically responsible for the transfer of gases, soot, condensates and all other pollutants that can be produced by the fire and emitted to the fire plume. Following this atmospheric transportation, those pollutants could be deposit directly on land and water-based targets, including human, flora and fauna.

Regarding water, several transfer mechanisms should be considered:

- Direct pollution via firefighting water runoff since water may be contaminated by toxic products, toxic combustion products or extinguishing media;
- Toxic product deposition or condensation on free surface waters;
- Permeation of surface water or soil deposit to the underground water, e.g. as commonly observed in water quality survey.

Each transportation mechanism is described below based on available knowledge. Limitation are highlighted specifically when known.

3.2.1 Fire characteristics

Since the fire is the source of potential environmental impact in this study, its properties should be carefully determined. Those properties should be set in accordance with prediction objective. Consequently, main characteristics to be evaluated are the:

- heat release rate (HRR);
- acute toxic gases flow rate;
- chronic toxic products, gases and particles, flow rate; and
- chemical composition of residuals for water composition evaluation.

Considering that HRR is the product of combustion velocity and heat of combustion, predicting the HRR may appear relatively straightforward in many fires, since combustion velocity and heat of combustion is known for a large variety of fuels (SFPE, 2016). It should be pointed out that, for most of significant (very large) fires, the fuels involved are not only well-known. In such cases, the fire typically involves a mixture of combustible products together with non-flammable materials. Considering the recent Notre Dame fire (2019), predicting the HRR to evaluate the consequences, requires consideration of the wood from the roof, the wood located inside as chairs and other interior items, but also the steel, rock, concrete and other building material and contents. It should also be considered that for solid fuels, depending of the material structure, the combustion velocity varies, and the actual combustion velocity should consider the non-combustible material that acts on the fire through thermal absorption. Finally, to complicate the matter further, the action of firefighters should be considered, since firefighting activities will contribute both to reduce the global HRR and to create a source term for toxic water consequences.

3.2.2 Acute toxic gas dispersion

Considering acute gas dispersion, modelling consists in three main steps, i.e.:

1. Source term calculation;
2. Atmospheric transport modelling;
3. Evaluation of consequences through the application of a suitable threshold.

The first step consists of evaluating the global amount of smoke produced (Heskestad, 1984, SFPE, 2016), assuming that the HRR is known. Such correlations enable computing the characteristics of the plume in terms of temperature and total smoke volume flow rate as a function of the plume height. Once should realise, however, that these correlations were established for very specific configurations of hydrocarbon fires and should be used carefully in real fire situations.

Such correlations do not provide any information about the smoke plume composition. Some additional chemical analysis is required for such estimates to be made. Several guides (INERIS, Persson and Simonson, 1998, Persson et al., 1995) exist to evaluate fire gas composition. Such approaches typically consider each individual element and provide some general laws in terms of fire products. Considering for example Chlorine, such guides consider full conversion to hydrogen chloride. Therefore, determining the proportion of HCl produced requires knowledge of the fuel consumption rate which must also be consistent with the hypothesis made for HRR evaluation. Such evaluation also assumes a constant emission rate for each product while, in a real fire, the emission rate can vary strongly during the fire, even for a quite homogeneous material, depending on ventilation conditions and temperatures.

Keeping these limitations in mind, the environmental impact assessor can know, from the source term calculation, the characteristics of the fire plume along its height and its composition based on the total mass flow rate and the mass production rate of the different chemical compounds. At this point, atmospheric dispersion should be considered. To do this, a temperature cut-off value should be given to define the source term for the atmospheric dispersion modelling. The cut-off value is fixed (INERIS) to 250°C as an averaged temperature in the section of the cloud. Based on this assumption, all source term characteristics should be estimated: velocity, total mass flow rate, composition, etc and atmospheric dispersion modelling started. Dealing with acute toxicity, the target distance is approximately some kilometres, less than ten. In terms of atmospheric dispersion, three main families of model should be distinguished.

- Gaussian model, based on the hypothesis of a Gaussian distribution of the toxic concentration on both sides of the plume centreline. This Gaussian distribution follows an experimentally determined standard deviation. Such a model cannot deal with a vertical dynamic hot gas release and additional sub-models, such as Briggs (1984) over height, should be added. Such a dispersion model can typically be set and run in some minutes.
- Integral models, which solves a simplified (integrated) fluid mechanic equation set in the near field of the fire plume, to consider the properties of the gas such as density. When the gas becomes passive, with a density of the mixture close to that of air, it uses a Gaussian approach. Such a dispersion model can typically be set and run in a dozen of minutes.
- 3D models (Lacome and Truchot, 2013), CFD (Computational Fluid Dynamic) or LPDM (Lagrangian Particle Dispersion Model), that solve the fluid mechanic equations to evaluate concentration in the surrounding fields. Such models are more complex to use but they can take into account obstacles. Such a model requires, before being run, defining a mesh, that could be highly time consuming, and then can require several hours to several days to run.

Whatever the limits of the different atmospheric models are, the main parameter to be consider is the source term. Obviously, the choice of the model will be governed as much by the objective as its intrinsic characteristics. For emergency situation, using CFD model is irrelevant while such an approach can become the best choice to model unsteady local concentrations, assuming the source term can be clearly determined, in post-accidental situations.

Finally, it should be remembered that such products are dispersed by the atmosphere and will not be persistent enough to be measured with the exception of some specific fires lasting an extended period of time. One should keep in mind that concentrations will vary strongly over time.

3.2.3 Chronic products

As in the case of atmospheric modelling, the calculation of toxic products is based on the fire characteristics in terms of temperature and velocity of the plume, but also the characteristics of the products as concentration and diameter when dealing with particles. While some guidance exists for acutely toxic products, no general rules are available for *chronically* toxic products. As mentioned previously, it is possible to use source terms for well-defined fuels but caution should be used when applying such source terms as a real fire does not contain a theoretical well-defined fuel.

The most commonly used methodology for evaluating the environmental impact of fires consists of predicting the major deposition areas and, using the characteristics of the products, define some measurement in different matrices as soil, water and air. Such measurements, however, require precise enough modelling to define the area to be used for reference situation analysis, free from the actual deposit area, and to predict all possible deposit areas surrounding the fire. Such a model typically requires using realistic meteorological conditions and their variation for the fire duration. In such cases, a typical realistic particle size is considered for atmospheric dispersion modelling. Typical models for such dispersion modelling include adapted Gaussian models that consider particles, such as ADMS (Atmospheric Dispersion Modelling System) or 3D model, LPDM (Lagrangian Particle Dispersion Model) or CFD (computational Fluid Dynamics).

The most important work when dealing with this part of the environmental impact consists of sampling after the fire. The sampling quality is of primary importance and the sampling method should be chosen in accordance with the different products to be measured. Some prescription about this exists in the literature as in the ISO TC92 SC3 standard (ISO, 2019b) or, in local documents.

3.2.4 Water toxicity consequence modelling

This is probably the most difficult topic when dealing with the environmental impact of fires since the source term is generally unknown. Typically, the water quantity used by the firemen is hard to predict, even though some standards exist for designing the required flow rate. Further, the part of the water which actually interacts with the fire is an uncertain parameter, meaning that the toxic products mixed with the fire water runoff can be difficult to predict. While some studies exist (Noiton et al., 2001, Calogine and Duplantier, 2010), these typically consist of very specific studies which do not provide much guidance concerning general predictions.

Therefore, the most efficient way to evaluate the environment consequences regarding water toxicity consists of sampling and analysing water in different locations in the surrounding of the fire. Such sampling should include both surface and underground water. One example of the fire fighters concern about water toxicity is detailed by Fischer and Varma (2016), where they govern there action by considering the potential toxic impacts with appropriate experts who were on the scene.

Numerous pollution mechanisms should be considered. The first is direct water contamination by firefighting water runoff. The pollution source term from firefighter water runoff includes the products of combustion themselves, or their intermediate decomposition, and possible chemical additives used by firefighters (AFFF for example), but also all unburned products that could contaminate water such as chemicals located in the surroundings. This pollution mechanism is probably the most important one regarding water contamination. This contamination pathway has been recognised and measurements are regularly made in connection with industrial fires and recommendations exist concerning water basins for industrial premises (ISO, 2012). Therefore water pollutant concentration measurements are often mandated, such as through the large-scale fish death during the SIAAP fire in France, July 2019 (TR78, 2018). Another interesting situation occurred during the Sherwin Williams Paint Warehouse fire (Copeland and Schaenman, 1987) where firefighters decided not to use water to extinguish the fire specifically to prevent contamination of surrounding water reservoirs. Modelling such a process is highly challenging since its requires the modeller to take into account the interaction between water and fire, water and fuels and other contaminants and water flow in a thin layer along the ground, three complex physical phenomena.

Another pathway for water contamination is that of particle and pollutant deposit after atmospheric dispersion. This is the same mechanisms as for soil contamination and the impact of such deposition can be estimated using atmospheric dispersion models, taking into account their limitations.

Finally, underground water contamination should also be considered following dispersion using hydrological models and soil leaching. Modelling such a phenomenon requires models describing the flow transport of pollutants inside the different soil layers. This is the mechanism which has been included in the recent work by Amon et al. (2019) when evaluating the impact of tactical choices on the environmental impact of fires in the local environment.

3.2.5 Soil pollution modelling

Excepted in some very specific situations, such as an underground fire with smoke propagation directly to the ground as in the Stocamine fire (2002), ground pollution is mainly driven by atmospheric transport and deposition of contaminants, alternatively leaching from water runoff. Soil pollution modelling therefore requires first being able to model deposition, which means all required elements for atmospheric dispersion are needed, plus a relevant deposition and spread model.

In this case, the persistence of pollution over time depends on the leaching phenomena which results of water infiltration and its reaction with contaminants. All reactions with products still present in the different soil layers should also be considered carefully. Therefore, even if some flow model exists for porous media, the complex associated chemistry leads to the great difficulty in having a relevant model for such a process.

4. Evaluating the cost of the environmental impact of fires

In Chapter 2, a literature review presented various documents describing different approaches to estimating the economic cost of environmental impact were overviewed. Two major categories of approaches are cost-benefit analyses (CBA) and derivatives thereof (e.g., see Pearce et al. (2006) and EPA (2014)), and economic valuation approaches (e.g., see Schwermer (2012) and ISO (2019a)). Since CBA requires valuation of benefits as well as costs, economic valuation can be viewed as a component of CBA.

To apply any model to establish the cost of the environmental impact of fire it is important to establish how a fire impacts on the environment and identify potential sources of environmental or other cost. Figure 4 shows one possible way to start with fire as a source term and determine its intersection with potential targets. This project focusses on the right hand side of this figure, i.e. environmental exposure in order to identify potential costs due to environmental impact. It is, however, worth noting that the left hand side ("human exposure") is part of the overall fire exposure with associated costs. In projects where the cost of fires is considered, it is most common to think in terms of this left hand side which is one of the reasons it is outside the scope of the present project, i.e. to place the focus on the cost of environmental exposure. Note that the left hand side of the figure specifically shows that environmental exposure can be due to the fire itself and firefighting activities and that the cost of the environmental impact of fires should include these considerations and others, such as decontamination and remediation/replacement of impacted environments.

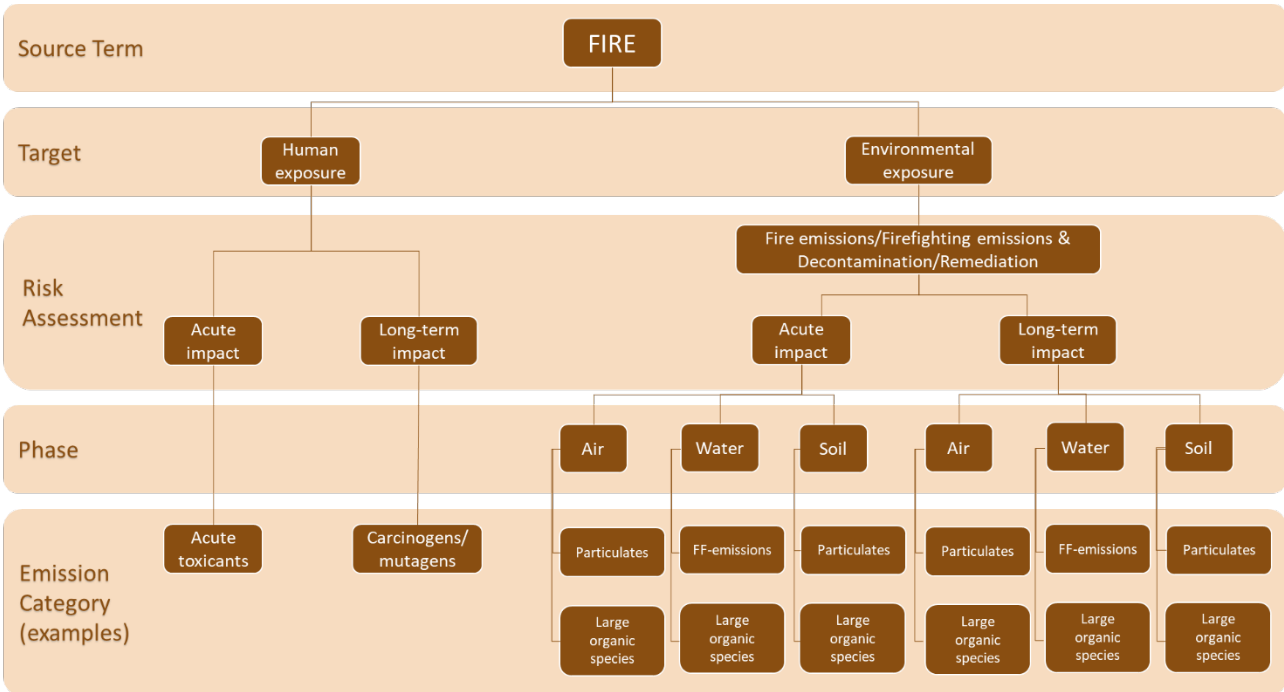

Figure 4: Schematic categorisation of fire emissions based on Human or Environmental exposure.

Figure 4 does not, however, provide guidance for assessing the environmental impact of the emissions or how these might be connected to potential harm and therefore cost. Focussing on environmental exposure, the information in Figure 4 can be presented in a different manner to help identify methodological and data needs to establish harm and ultimately cost, see Table 8.

Table 8: Connection between recipient, fire exposure and cost of the environmental impact of fires.

Recipient	Fire Description	Impact Radius	Exposure	Input Data	Cost
Air	Deterministic description (e.g. statistics, fire specific data) Modelling (e.g. CFD, FEM, Zone, Wildland fire models)	Plume modelling (local and global)	Gases, particulate emissions	Experimental Gaseous measurement in conjunction with real fires, e.g. satellite measurements	Inside scope of Cost of Environmental Impact of Fires • Replacement • Remediation/ Decontamination • Cost of loss of income due to loss of access to biotopes (to businesses or people) • Societal cost for loss of access to biotopes Outside scope of Cost of Environmental Impact of Fires • Loss of life • Injury of people • Long term irretrievable loss of environment
Water	Suppression method, potential to emit to the aquatic environment	Environmental Risk Assessment, transport models to surface water, ground water, assessment of contamination radius for soil (local and global)	Soluble organic compounds, particulate emissions	Experimental Water samples and measurements in conjunction with real fires, e.g. from rivers, lakes, and wells	
Soil	Suppression method, potential to emit to the soil		Deposition of solid waste close to the fire	Experimental Soil samples and measurements in conjunction with real fires	

ISO 14008 *Monetary valuation of environmental impacts and related environmental aspects* (ISO, 2019a), was developed to assist entities with studies or reviews associated with monetary valuation of environmental impacts, including guidance on compiling and using the results. A primary tenant is that monetary valuations can enable comparisons and trade-offs between different environmental issues, as well as between environmental and other issues. Use of monetary valuation does not mean that money is the only metric of value; however, it provides a basis for comparison of options.

A focal point of this standard is development of the Total Economic Value (TEV) for environmental impacts. The TEV is comprised of use values and non-use values. Use values refer to the actual or potential, consumptive or non-consumptive, use of a good by a given individual. They are often divided into direct, indirect and option values. Non-use values refer to the values individuals place on a good, independent of the actual or future use they make of it. Three different elements are generally distinguished: existence value, bequest value and altruistic value. As part of the process, the values need to be monetized. Different monetary valuation methods have different capabilities to assess different environmental impacts and elements of the total economic value, and are therefore applicable to different contexts and objectives. Representative monetary valuation methods include: market price proxies, revealed preference methods, stated preference methods, value transfer, currency and base year adjustments, equity weighting, and discounting. A similar methodology has been proposed by the German Federal Environment Agency (UBA), which has issued a document outlining *Economic Valuation of Environmental Damage: Methodological Convention 2.0 for Estimates of Environmental Costs* (Schwermer, 2012).

Further, the *Guidelines for Preparing Economic Analyses* (EPA, 2014), focuses on economic analysis typically conducted for environmental policies using regulatory or non-regulatory management strategies. The Guidelines are designed to provide assistance to analysts in the economic analysis of environmental policies, and are recommended to be viewed as a summary of analytical methodologies, empirical techniques, and data sources that can assist in performing economic analysis of environmental policies. These guidelines include information on:

- Establishing a baseline
- Discounting future benefits and costs
- Analyzing benefits
- Analyzing costs
- Economic impact analyses.

The OECD has also developed a document providing detailed information regarding the application of cost-benefit analysis (CBA) to environmental policy settings (Pearce et al., 2006), including an overview of CBA, valuation, modelling approaches and more. Pearce et al. (2006) note that CBA is now recognized as an indispensable tool for policy design and decision-making, as environmental policies are becoming more complex and challenging. In addition to the broader economic analyses of environmental impacts for policy analysis, there are some more targeted guidelines as well, such as for protection of ecological systems. Understanding how these more targeted guidelines are structured may be helpful, given the rather focused scope of this work (i.e., economic impact of damage to the environment from fire, excluding human costs (adverse health effects, injury, death), structural property damage, contents and business operations damage, etc.).

Finally, the US EPA has developed guidance, under the oversight of the US EPA's Science Advisory Board (SAB), to specifically assist in better valuing the protection of ecological systems and services (EPA, 2009). Among the focal areas of the study were tasks to (a) assess the state of the art and science of valuing protection of ecological systems and services and (b) identify key areas for improving knowledge, methodologies, practice, and research at EPA. While the scope is targeted to EPA policy-making, it provides useful frameworks and approaches for valuing the protection of ecological systems and services, facilitating the use of these approaches by decision makers, and investing in the research areas needed to bolster the science underlying ecological valuation – all useful concepts to valuing ecological impact due to fire events. The proposed approach to an integrated and expanded framework for ecological valuation is based on the idea that social, behavioural, economic and ecological costs all need to be taken into account when evaluating the ecological impact of policy. This approach has been modified to the specific fire setting in Chapter 6.

With respect to the cost of environmental impact resulting specifically from fire, the literature is sparse. There is some literature associated with wildland fire (DOI, 2012, Butry et al., 2019) which is discussed below. These are noted for the purpose of understanding the approaches used. The area of economic cost of environmental damage from wildland fire was not explored in any detail, however, since wildland fire was specifically excluded from this work.

Economic Impact of Fire Suppression

In addition to direct impacts of a fire on the environment, there is also the concern of the impact of firefighting activities on the environment. Two major concerns are transport of hazardous material from the fire (e.g., stored contents) via firefighting water, and impact of firefighting chemicals and/or combinations of chemicals in water to enhance suppression effectiveness. Fire suppressants that are carrying residue from the fire, or which have additives of concern, can enter the ground, leach into the groundwater, or be discharged into waterways.

Perhaps one of the most infamous examples of firefighting water carrying toxic products from a fire impacting the environment was the 1986 fire at a Sandoz Ltd. warehouse at Schweizerhalle near Basel, Switzerland (Giger, 2009). The warehouse contained some 1250 tons of pesticides, solvents, dyes, and various raw and intermediate materials, almost all of which was consumed by the fire, but with large quantities introduced into the soil and groundwater at the site, into the Rhine River through runoff of the firefighting water. The chemicals discharged into the Rhine River by the firefighting runoff resulted in large-scale kills of benthic organisms and fish, particularly eels and salmonids, with impacts observed as far away at the Netherlands. While the environmental impacts are well documented, the costs of those impacts is difficult to identify, and no comprehensive allocations were identified in this search. Although one resource identified some 100 Million Swiss francs in claims had been presented to Sandoz as of September 1987 (Schwabach, 1989), these largely reflect direct and indirect health and business losses, with valuation of the economic costs unclear.

As introduced previously, a topic that has been attracting more interest in recent years is the environmental impact associated with chemical additives applied during suppression activities to enhance suppression effectiveness, such as the group of per- and polyfluorinated substances (PFASs), including perfluorooctanoic acid (PFOA) and perfluorooctane sulphonates (PFOS), which have been used extensively in firefighting foams (NZFSC, 2017, ECHA, 2018, Hu et al., 2016). These substances have been released into the environment through both firefighting activities and training activities. With respect to the latter, significant attention has been paid to training in the military and civilian airports and associated releases of Aqueous Film Forming Foam (AFFF) (Hagenaars et al., 2011, DOD, 2017, NZFSC, 2017).

As with the runoff of firefighting water discussed above, much of the literature reviewed is focused on direct costs (e.g., clean-up, radiation) and human health effects. As an example of cost estimation, Düsseldorf Airport, which had to remediate land around the airport that had become contaminated with PFOAs due to firefighter training activities (ECHA, 2018), has estimated the cost of remediation of soil and water (including several lakes that were affected) plus recovery of damage, to be as high as €100 Million. At of the time of the cited work, remediation efforts had included collection of some 1200 water samples and 870 soil samples, set-up of a register, risk assessment, and detailed investigations. Some € 6 Million was allocated for remediation of the airport area, including a new functional runoff basin for the fire-brigade, since vehicle function needs to be tested regularly (cost of €800,000).

Established models for reliable estimation of the cost of the environmental impact of these additives are still, however, lacking.

Economic Impact of Wildland Fires

Two main literature reviews have been analysed as part of this work. The US Department of Interior (US DOI) used a review of relevant literature for the benefit-cost analysis of wildland fire management program in 2012 (DOI, 2012) This literature review explores various cost-benefit analysis (CBA) approaches for assessment of wildland fire management, with a particular focus on the valuation issue. As with the other documents outlined above, this report notes that a central challenge is measuring society's full valuation of resources at risk of fire, noting that even if values are quantifiable, there is considerable uncertainty as to how potential losses respond to various wildfire management options. Furthermore, an additional challenge lies in balancing the trade-offs inherent in managing fire-prone forests, as when treatments to reduce fire threat also impact wildlife. While wildland fire is not the focus of this FPRF-supported effort, these considerations are applicable to valuing environmental impacts from other fire sources.

The second seminal document identified in this literature study concerning the economic cost of wildland fire was developed by Butry et al. (2019). This literature review explores various means to assess the economic cost of wildland fire, including its environmental impact. Direct and indirect costs are considered. Several aspects have potential applicability to non-wildland fire events, such as impacts to soil, water, vegetation, as well as carbon emissions. As with other documents discussed above, valuing the cost of ecological damage is considered. Ecosystem services, the term used in this report, is defined as "any positive benefit that wildlife or ecosystems provides to people", with examples including clean natural water services, pollination by insects or birds, and natural reseeding of areas. These types of ecological impacts are pertinent to non-wildland fire as well, as they too can destroy habitat, vital ecological features, and kill or displace local wildlife for potentially significant periods of time, culminating in the loss of ecosystem services in the area of the fire.

5. Case studies

This chapter proposed a detailed analysis of five fire situations considered by the authors as the most relevant. The five cases considered are:

- The West Somerset sulphur fire in South Africa (and similar fires in Iraq);
- The Lac Megantic explosion and fire in Canada;
- Typical building fires over a full year for a number of scenarios;
- The Sandoz industrial fire in Switzerland; and
- The impact of PFOS use by the DOD in the US.

For all those fires, the structure of the paragraph is identical with a first brief description of the event and known consequences, followed by an a-posteriori analysis is proposed in order to point-out the main lack of knowledge for such an analysis.

5.1 The West (South Africa) and Al-Mishraq (Iraq) sulphur fires

5.1.1 Description of the events and their consequences

Two major industrial sites (one in South Africa in Western Cape Province (1995) and in Iraq, near the town of Mosul, experienced very large and long-lasting fires that have heavily impacted the environment, as a result of massive emission of SO_2 (and H_2S in the case of Al-Mishraq site) from elemental sulphur combustion. Figure 5 shows the smoke cloud resulting from the event taking place in Al-Mishraq. An estimation of SO_2 pollution was achieved for the fire that occurred in 2016 in the same place, see Figure 6. It is interesting to mention that the data presented in Figure 6 was obtained from a specific measurement technique using satellite data.

Figure 5: Satellite photograph of Al-Mishraq State Sulphur Plant October 22, 2016 (NASA, 2016).

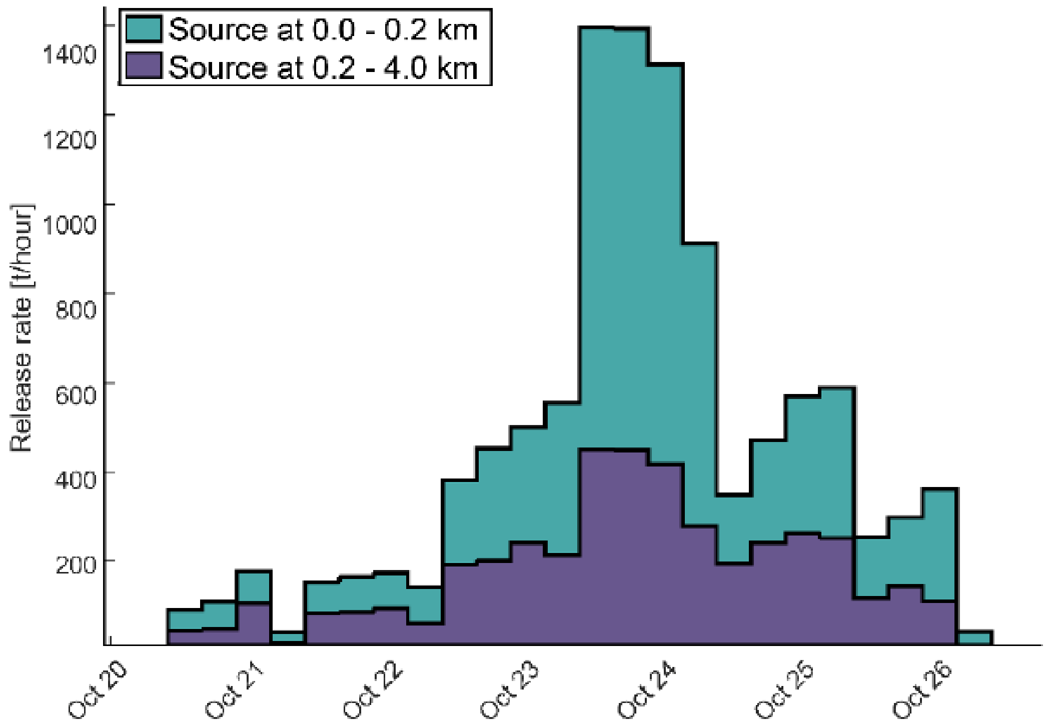

Figure 6: Estimation of the SO2 source term of pollution version time in the Al-Mishraq 2016 event (reproduced without changes from (Björnham et al., 2017)).

A full description of the West fire is given in Batterman et al. ((1999). Before the fire, sulphur was stocked into three piles, 3 m high and about 200x130 m^2 each for a total mass of 15,710 kg of sulphur. During the day before the sulphur fire, several grass fires occur in the surrounding of the storage, before the sulphur ignited, melted and burnt. During firefighting operations, large amounts of water were applied using a helicopter as the closest fire hydrant was more than 1 km away.

The fire lasted about 20 h and concerned 7,250 kg of sulphur of the 15,710 kg that were stored. Some 10 to 15 deaths were reported following this accident, although very few data points are available regarding toxic concentration since only some measurement points were considered.

It should be noted that, according to the post analysis of that accident using the European scale of industrial accident, the environmental impact was set to 0, which means that all of corresponding criteria were 0, due to lack of data.

5.1.2 A posteriori analysis of the environmental consequences of the West sulphur fire

In Batterman et al. (1999), some numerical simulations managed to predict sulphur concentrations in the surrounding of fire. The methodology used is similar to the one described in chapter 4 of this report by first evaluating the source term of toxic gases, mainly SO_2, then using the characteristics of the source term, smoke total volume and temperature were computed to finally be introduce into a dispersion model. In the following paragraph, the main steps of the process as published are reported and discussed regarding recently available data.

The gas composition is assumed to be mainly SO_2. The mass flow rate of SO_2 production is computed considering the total mass burnt of sulphur, 7,250 kg, and the fire duration, 21 h. To this end, the SO_2 mass flow rate is assumed to be constant, with the exception of the initial 2 h fire growth period, before the fire fighting become efficient, 10 h after its ignition. The surface of the fire is estimated to 25,000 m². Based on these hypotheses, the mass flow rate of SO_2 is evaluated to 185 kg/s. This source term is next coupled with different hypothesised temperature and emission parameters to compute the concentration distribution along the wind using the dispersion model.

Some points should be highlighted regarding this approach. First of all, the equivalent combustion velocity for the sulphur should be compared with existing data. According to the computed emission flow rate and the uncertainty of the real surface of the fire, the used combustion velocity, around 0,004 g/m²/s for a 25 000 m² fire, is in quite good accordance with experimental values, around 0,008 g/m²/s.

Further, while sulphur is not soluble in water, SO_2 is. Therefore, during the firefighting activities, some sulphur might be caught by the water either in sulphur form, with dissolution; or as SO_2, in which case SO_2 dissociates into the ions sulphite, bisulphite and hydrogen and could induce eco-toxicity for organisms even though its persistence in the environment is weak.

One of key parameter for dispersion consists in the source term description. As described in the previous paragraph, this source term is composed of the concentration of toxic products and with thermo-kinetic parameters such as smoke temperature a vertical velocity. This fire typically illustrates the limit of the plume model since correlations such as the one published by Heskestad (1984), are not applicable to model such a plume. Since the air entrainment phenomena is governed by the fire characteristics, the specific combustion of sulphur should be with dealt specifically, as for many of real fire situations. This requires considering the chemical reaction through their representative equations, using the combustion velocity to evaluate the reaction rate and then computing the production rate and toxic gases and their temperature based on the release of chemical energy.

The global analysis of South African and Iraq fires also highlights a key issue when dealing with real fires, i.e. the information about the combustible product. While in South Africa, sulphur burned alone and produced only SO_2. In Iraq, the sulphur was mixed with flammable liquid that lead to H_2S emissions in addition to SO_2. This obviously has an impact on acute toxicity products, and also potentially is significant when dealing with the other aspect of the environmental impact.

5.2 The Lac Megantic fire

5.2.1 Description of the accident

In 2013 on July the 6th, a train containing 72 wagons filled with petrol derailed near Lake Megantic, Canada (Galvez-Cloutier et al., 2014, Saint-Laurent et al., 2018). Approximately 5 700 m³ of burning petroleum fuel spilled and propagated the fire through surface and underground installations. Firefighting lasted 2 days and more than 2 000 people were evacuated. This fire had dramatic human consequences including 47 deaths and many casualties. Environmental impact mainly consisted of pollution of the Chaudiere River along 80 km where fish death was observed, fishing and swimming was forbidden and water extraction for human consumption was stopped for two months.

The atmospheric dispersion and resultant consequences were not discussed although a large smoke cloud was produced, Figure 7.

Figure 7 : Smoke cloud from the Lac Megantic petroleum fire (Wikipedia, 2013).

According to the total amount of petroleum, about 14 000 kg of CO_2 were produced during this accident. Such an approximation obviously depends on the real behaviour of the fire which can vary strongly from one point to another, but this provides a reasonable order of magnitude.

5.2.2 A posteriori analysis of the environmental consequences

Such a fire highlights the properties of the smoke cloud that contains several kinds of gases, including combustion products but also a large quantity of nitrogen, and particles. It offers the opportunity to apply commonly used methods for impact modelling to highlight its limitation. Consequences should be distinguished between immediate toxicity and chronic consequences.

5.2.2.1 Acute toxicity

Regarding acute toxicity, the toxic gas concentration in the cloud is not significant, and the air dilution leads rapidly to a reduction the plume toxicity. However, the relevance of such approaches for very large fire could be discussed.

Considering that a 30 m diameter pool surface, corresponding to a 700 m² pool, can be used to represent the Lac Megantic fire, it is possible to make some computation to evaluate consequences. This surface is probably not the maximum value reached during the fire but as the surface area increases the acute toxicity will decrease.

It is clear that such a huge fire is out of the scope of all existing analytical models. Evaluating consequences, however, requires one to make some assumptions and use some correlations as input of models. Since no more suitable relation is available, the Heskestad (1984) correlation was used to described the smoke plume in the vicinity of the fire despite the fact that this is outside of the typical range of application for this correlation.

Using Heskestad's (1984) equations and considering that smoke is emitted to the atmosphere at a temperature of 250°C, i.e. the temperature that corresponds to the threshold where the wind effect is no longer negligible, it is possible to evaluate the smoke composition, the height of fire plume and the vertical velocity. Knowing the composition of the products, the proportion of each acute toxic gas can be determined. This is typically an application case of the method described in 3.2.2. The relevant values are determined using following equations:

- For the height of emission, h:
$$h = 0{,}166.\, Q_c^{0{,}4}$$

- For the vertical velocity, v_h:
$$v_h = 0{,}5 * 1{,}87 * Q_c^{0{,}2}$$

- For the total mass flow rate of smoke, ϕ_t:
$$\phi_t = 3{,}24 * Q_t$$

In those equations, Q_t is the total fire heat release rate (HRR), Q_c is the convective part of the total HRR which is assumed to be about 66% of the total HRR. If we assume a surface fire corresponding to 70 000 m^2 surface area and considering a combustion rate of 60 $g/m^2/s$ for the petrol with a heat of combustion of 40 MJ/kg, this gives the results presented in Table 9.

Table 9: Main quantities for acute atmospheric dispersion source term.

Quantity	Physical value
Total HRR, Q_t	1 700 MW
Convective HRR, Q_c	1 100 MW
Height of emission, h	45 m
Total smoke mass flux, ϕ_t	5 500 kg/s
Vertical velocity, v_h	15 m/s

Based on a fuel than contain about 2% by mass of sulphur and nitrogen, the smoke composition, assuming that the molecular CO/CO_2 ratio is 0.25 at the height of emission, will be as described in Table 10.

Table 10: Main quantities for acute atmospheric dispersion source term.

Gas	Mass fraction
CO_2	0.75%
CO	0.30%
SO_2	0,015%
HCN	0,012%
NO_2	0,012%
Air, entrained by the plume	98,92%

The equivalent toxic threshold for such a mixture is about 16 214 ppm based on AEGL toxic thresholds. The computed consequences show that, even for such a fire, no acute toxicity is estimated near the ground, Figure 8. On this figure, the smoke cloud was evaluated for different atmospheric stability as defined by Pasquill (1974), from *A* for an unstable atmosphere boundary layer to *F* for a stable one, and different wind velocities, 2 to 10 *m/s*, measured 10 m above the ground. Figure 8 illustrated toxic calculations for the fire plume for a variety of combinations of stability class (A toF) and wind velocity (2 to 10).

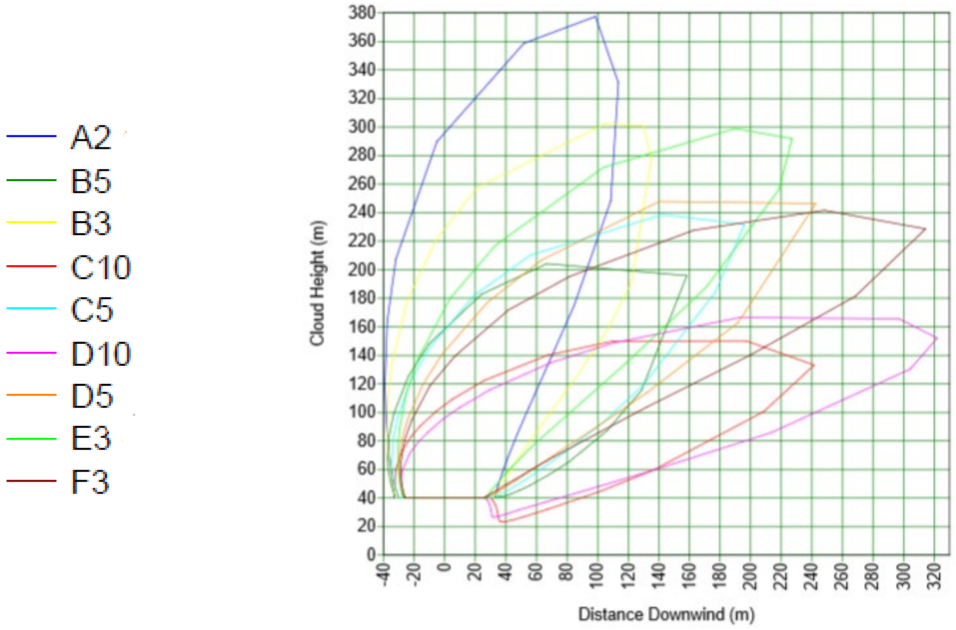

Figure 8: Acute toxicity cloud computation for different wind profiles. The legend denotes the atmospheric stability class (A to F) and wind spead (2 to 10 m/s).

While such results provide some information about human consequences of fire they also raise many questions. The two mains issues with the calculations are: (1) The cloud dispersion was computed at a given time that corresponds to the maximum HRR. According to the equation that described the source term, while the maximum HRR gives the maximum smoke mass flow rate, it also corresponds to the more important emission rate and vertical velocity. As a consequence, it is not obvious to determine the worst situation regarding acute toxicity. An improvement for such a consequence evaluation should be to evaluate the HRR evolution along time and to compute toxicity as a dose. This is however highly complex since evaluating the HRR evolution along time imposes to consider firemen action into the HRR evaluation model. (2) The toxicity calculations assume a CO/CO_2 ratio of 0,25. Typically, the transformation rate of carbon into carbon monoxide and dioxide should be determined, but the CO/CO_2 ratio depends on the fire conditions, whether the fire is underventilated or not, for example. This is exactly the same for all hetero atoms that are present such as sulphur. The application of a global chemical mechanism hypothesis is used since full transformation mechanisms are complex to model.

5.2.2.2 Chronic toxicity

As for acute toxicity, predicting the chronic potential impact due to dioxin, HAP or particles requires being able to model the fire dynamic, the HRR and the corresponding physic characteristics but also the emission factor for all of those products. As mentioned in the literature review in Chapter 2, such emission factors are highly complex and very little data exists. Furthermore, regarding particles, one of the key parameter is the particle diameter that is rarely measured. While some data are available for the global particle emission factor (Tewarson, 1995), very few publications provide information about particle diameter.

Consequently, predicting this kind of impact using modelling is too complex and models should be coupled with analysis based on ground measurement (ISO, 2019b). A simplified calculation provides an illustration of these limitations. Considering particle emission, depending of the diameter, the deposit velocity can be evaluated using the Stokes law, i.e. the equilibrium between the gravity force and the drag force. In such an approximation, the deposit velocity is evaluated using the following formulae:

$$U_p = \frac{2. m_p. 9{,}81}{\pi. r^2. C_d. \rho_f}$$

Where m_p is the particle mass, r its radius, C_d the drag coefficient and ρ_f the density of the gas phase. The drag coefficient is:

$$C_d = \frac{24}{Re_p}$$

Where Re_p is the particle Reynolds number:

$$Re_p = \frac{\rho_f. U_r. d}{\mu_f}$$

Based on the velocity, U_r, the particle diameter, d, and the fluid phase viscosity, μ_f. Assuming that the particle density can be approximated by the carbon density, 2 200 kg.m^3, Table 11 gives the estimated impact distance that corresponds to the required time for the particle to drop at its maximum drop velocity based on an emission at the Heskestad height computed above, e.g. 45 m for a wind velocity of 3 *m/s*. One should keep in mind that this evaluation, as all particle dispersion models, assumes that particles are emitted at the Heskestad height which could be a large overestimation in several situations.

Table 11: Estimation of particle drop distance.

Diameter [µm]	Re_p [-]	C_d [-]	Drop Speed [m/s]	Distance of dispersion
1	1.73E-01	1.39E+02	1.57E-04	> 500 km
15	2.60E+00	1.19E+01	2.74E-02	≈ 350 m
30	5.19E+00	6.77E+00	9.66E-02	≈ 1 000 m
50	8.65E+00	4.61E+00	2.37E-01	< 400 m

So, while this aspect is the most critical in terms of environmental impact, its prediction still requires strong improvement to make it relevant. There is also many questions regarding the impact in terms of water toxicity and ecotoxicity that is virtually unpredictable since very little data exists regarding the pollutant transfer into water.

5.3 A typical building fire

5.3.1 Description of the accident

Building fires occur regularly in all countries around the world. The potential environmental impact of a single building fire will naturally depend on the type of building and its size and contents. A single house fire is unlikely to have a significant environmental impact or associated cost; but it is well established that a significant number of house fires occur any given year, meaning that the aggregate emissions from these individual fires are likely to be significant. Indeed, in the 1990s, Persson and Simonson (1998) established that the overall emissions from fires in Sweden was of the same order of magnitude as emissions from heavy goods vehicle transport during the same time period.

The emission factors for a typical 1-2 family villa and a typical apartment are given in Table 12 for both Sweden and the US, using the methodology developed by Persson and Simonson (1998) and by Abraham et al. (2001). Note that the emissions presented for a typical Swedish villa or apartment have been updated relative to those published in 1998 by returning to the original data (Persson et al., 1995). It is clear from Table 12 that there are significant differences between the estimated emissions. This will also result in significant difference between estimates for the potential environmental impact of residential fires. More work is needed to establish which estimate is closer to the actual emission values.

Table 12: Fire emissions typical Swedish residential properties based on Persson et al. (1995) and Abraham et al. (2001).

Emission	Typical Swedish House ($120\ m^2$) [kg/object]			Typical US House (1 350 sqf) (7,91 lb/sqf combustible contents) (11 tons combustible structure) [kg/object]	Typical Swedish Apartment (nominally $80\ m^2$) [kg/object]		
	Structure	Interior	TOTAL		Structure	Interior	TOTAL
CO_2	15 803	7 880	23 683	-	-	5 245	5 245
CO	600	312	912	445	-	208	208
NO_x	13	28	41	10,4	-	18	18
HCN	0,1	0,48	0,57	263	-	0,32	0,32
HCl	16	77	93	112	-	51	51
SO_2	193	-	193		42	-	42
Particulates	1331	89	1 420	80	271	59	330
Formaldehyde				7,6			
Acrolein				33			
VOC				82			

5.3.2 A posteriori analysis of the environmental consequences

The environmental impact of a single house fire is arguably small. Therefore, this analysis includes the calculation of the emissions expected from all house fires in the US based on an assumption concerning the number of fires in the US using published data from the NFPA (Ahrens, 2013, Ahrens, 2018). Table 13 contains a summary of fires a typical year based on these statistics.

Table 13: Residential fires (5 year average) classified according to the extent of the fire based on NFPA data (Ahrens, 2013, Ahrens, 2018)

# residential fires (2007-2011 averages)	Spread beyond building of origin	Spread beyond room of origin	Beyond object but confined to room	Confined to object of origin
283 500	4%	21%	17%	58%

Using the Swedish methodology the equivalent Total burn is calculated as:

$$Full\ House\ Equivalent = Full\ house\ fire + 30\% \cdot Medium\ house\ fire$$

In terms of the US statistics, the first category ("spread beyond the building of origin") is equated with a "Full house fire", while the second category ("spread beyond the room of origin") is equated to the category "Medium house fire". In this case the Full House fire equivalent used to calculate the Swedish emissions is 29 200 House fires a typical year. For the EPA fire emissions methodology the fire loss rate summarised across all fires is assumed to be 7,3%, which corresponds to a full house equivalent of 20700 House fires a typical year. These numbers have been used to estimate annual emissions from House fires in the US a typical year, see Table 14.

Table 14: Emissions for a typical year based on the single house emissions multiplied by a full house equivalent.

Emission	Annual emissions a typical year based on Swedish emissions data (29 200 Full House Equivalents) [metric ton]	Annual emissions a typical year based on US emissions data (20 700 Full House Equivalents) [metric ton]
CO_2	692 k	-
CO	26,6 k	9 204
NO_x	1 190	215
HCN	167	5 440
HCl	2 710	2 320
SO_2	5 630	
Particulates	41,5 k	1 660
Formaldehyde		157
Acrolein		677
VOC		1 690

As can be seen in Table 14, the estimates vary significantly depending on whether the Swedish or US-based emission factors are applied. This would indicate that even in cases where emission factors do exist there is a need to validate existing data to identify applicability and limitations.

5.4 Sandoz chemical storage fire

5.4.1 Description of the event
(from Giger (2009), unless otherwise noted)

From the night of October 31 into November 1, 1986, a fire engulfed a Sandoz Ltd. warehouse at Schweizerhalle near Basel, Switzerland. The warehouse contained some 1250 tons of pesticides, solvents, dyes, and various raw and intermediate materials. The 90m by 50m warehouse was originally constructed to store machinery, and therefore lacked smoke detection and sprinkler systems and only contained one dividing wall. This contributed to late detection and poor containment of the fire. Given the amount of stored materials, considerable water was needed to control the fire. This was exacerbated by the need to control the fire from reaching a nearby warehouse containing phosgene, a highly poisonous gas. While almost all the stored materials were consumed by the fire, large quantities were introduced into the soil and groundwater at the site, into the Rhine River through runoff of the firefighting water, and into the atmosphere. Although the site was equipped with a sewer system that could be sealed off in the event of an oil spill, on the night of the fire the seals were not closed. However, even if the system had been sealed off, the firefighting water, estimated at between 10,000 and 15,000 m^3, would still have made its way into the Rhine, as much of the runoff was discharged into the Rhine via a drain designed for uncontaminated cooling water.

5.4.2 A posteriori analysis of the environmental consequences

Approximately 9 tons of pesticides and 130 kg of organic mercury compounds infiltrated the soil. The pollutants could be detected at depths of up to 11 m. Remediation of the fire site and the contaminated soil took about 6 years, with 2,700 tons of semi-combusted material being disposed of.

The chemicals discharged into the Rhine River by the firefighting runoff resulted in large-scale kills of benthic organisms and fish, particularly eels and salmonids, with impacts observed as far away at the Netherlands. Of particular note was the eel kill, which spread from Schweizerhalle some 400 km downstream to Loreley (near Koblenz). In addition, other fish species were also severely affected, including grayling, brown trout, pike, and pikeperch, as well as typical food for the fish.

While the environmental impacts of the Sandoz event are well documented, the costs of those impacts are difficult to identify, and no comprehensive allocations were identified in this search. Although one resource identified some 100 Million Swiss francs in claims had been presented to Sandoz as of September 1987 (Schwabach, 1989), these largely reflect direct and indirect health and business losses, with valuation of the economic costs unclear.

5.5 US Department of Defense (DoD) and PFOS

5.5.1 Description of the situation
(from DOD (2017), unless otherwise noted)

Perfluorinated chemicals (PFCs), including perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), were utilized in some formulations of Aqueous Film Forming Foam (AFFF) for some decades. In the 1970s, the DoD began using AFFF that contained PFOS and, in some formulations, PFOA, at several airfields and other mission critical facilities. AFFF was used due to it being highly effective for fighting petroleum-based fires, so much so that the Federal Aviation Administration (FAA) required its use at airports nationally.

In the 1990s, health concerns with PFCs had started to emerge, and in 2009, the US Environmental Protection Agency (US EPA) Office of Water established a provisional short-term health advisory for PFOS at 200 parts per trillion (ppt) and PFOA at 400 ppt under the Safe Drinking Water Act (SDW A). On May 19, 2016, the US EPA issued a SDWA lifetime health advisory (LHA) recommending that the individual or combined levels of PFOS and PFOA concentrations in drinking water be below 70 ppt – significantly lower than the 2009 short-term health advisory.

In June 2016, DoD issued a policy requiring the DoD Components to sample and test drinking water systems where DoD is the water purveyor and to take action where the EPA LHA was exceeded. The DoD Components also developed strategies under the Defense Environmental Restoration Program (DERP) to start proactively investigating and addressing DoD releases of PFOS and PFOA.

5.5.2 A posteriori analysis of the environmental consequences

As of December 31, 2016, DoD has spent approximately $202 million on PFOS and PFOA sampling, analysis, and clean-up, including about $199 million that was originally programmed for clean-up activities at other sites.

In addition, DoD followed a comprehensive approach to identify installations where DoD used AFFF containing PFOS or PFOA, since releases of PFOS and PFOA on DoD installations are primarily associated with firefighting training areas, hangars, fire suppression systems, and aircraft crash sites. As of December 31, 2016, DoD identified 393 active and Base Realignment and Closure installations with one or more areas where there is a known or suspected release of PFOS and/or PFOA.

The source report does not address costs of remediation, nor are costs for replacement of AFFF reported. It can be assumed that the impacts could be significant.

5.6 Overall Conclusions

The application of available methodologies to past events has made it possible to point out the main limitations of existing models for spread of fire emissions in the atmosphere, to water and soil. Further an assessment of existing emission factor data has indicated that there is a clear (and acute) need to update such factors and validate the limits of their application. Finally, an assessment of the impact of firefighting activities in conjunction with an industrial fire and firefighting training activities indicates the importance of emissions from firefighting activities as one component of the cost of the environmental impact of fires.

Modelling methods applied to the spread of emissions when considering the environmental impact evaluation should consider the different steps of such an evaluation. It appears that there are large uncertainties for input data, including the nature of the fuel, the surface of the fire, and the validity of models. The most relevant example may be the Heskestad correlation used for the smoke plume characterisation. Such a correlation was developed for pure hydrocarbon pool fires and its validity for fuel mixtures or for very specific fires, such as sulphur fires, in complex environment is questionable, but alternative methods are not available. This is only one part of the uncertainty in fire modelling since, when dealing with real fire, the nature of the fuel is often unknown. If we consider, for the sake of illustration, the Lac Megantic fire, determining the nature of the fuel to obtain its fire properties and chemical composition, required detailed analysis.

In a nutshell, these examples point out that the environmental impact of fire can only be estimated by a strong coupling between models and analysis. Typically, for atmospherically dispersed substances, models can be used for the evaluation of the potential contaminated area, then sampling is necessary to evaluate the real contamination. Water and ground dispersion is even more difficult that atmospheric dispersion, since very few models exist and sampling and analysis are presently the best methods to estimate the level of pollution and contamination of specific sites based after a large scale fire.

6. Gap analysis

6.1 Gaps in policy context for framing situation

As overviewed in this report, the topic of environmental impacts of fire is diverse, with good understanding in some areas and only limited understanding in others. In many respects, quantifying the impacts, economically and otherwise, is easier after a fire has occurred, providing that the necessary data have been collected. However, predicting impacts prior to fire occurrence faces several challenges, including lack of scientific data on materials (for model inputs); variability in fuels that may actually be in a structure at the time of a fire; transport, deposition and persistence data; modes and mechanisms of impact, including what and how; and valuation of the potential economic cost of fire impacts on the environment should they occur. This lack of knowledge and data can have an impact on the ability to establish science-based policy decisions for mitigating fire impacts on the environment. The preceding chapters present what we presently know about the environmental impact of fires and the cost of said impact. This chapter presents the gaps that have been identified in the context of policy-setting challenges.

These policy-setting challenges are not particularly unique to fire impacts on the environment. As discussed in Chapters 2-4, there are various approaches used within the areas of environmental impact analysis and economic valuation of environmental impact to draw upon. Fire is somewhat different, however, in that unlike emissions from vehicles, power generation, and the like, for which some mitigation can occur at the point of emission, there are no scrubbers or other point of discharge mitigation of fire effluents available during or after a fire. Further, fire is stochastic and difficult to predict meaning that the impact from one set of fire conditions is significantly different to that created by another set of conditions. Mitigation is limited therefore to preventing fire, limiting the size of fire, and limiting the extent of effluent distribution.

Selecting from diverse options can be viewed through the lens of policy-setting analyses for other environmental impacts. This is exemplified in Figure 9 which is adapted from a US EPA representation of environmental valuation of ecological impacts (EPA, 2009). We suggest that this can be a useful framework for identifying research needs in this area.

On the left side of the diagram is the policy context, described here as minimizing the social, economic and environmental impact of fire. There are six primary steps that one arguably must go through to come to a policy decision, framed here as delivering regulations for a fire safe and sustainable built environment. The six steps identified in Figure 9 have been discussed below in terms of the limitations and gaps that have been identified in this project.

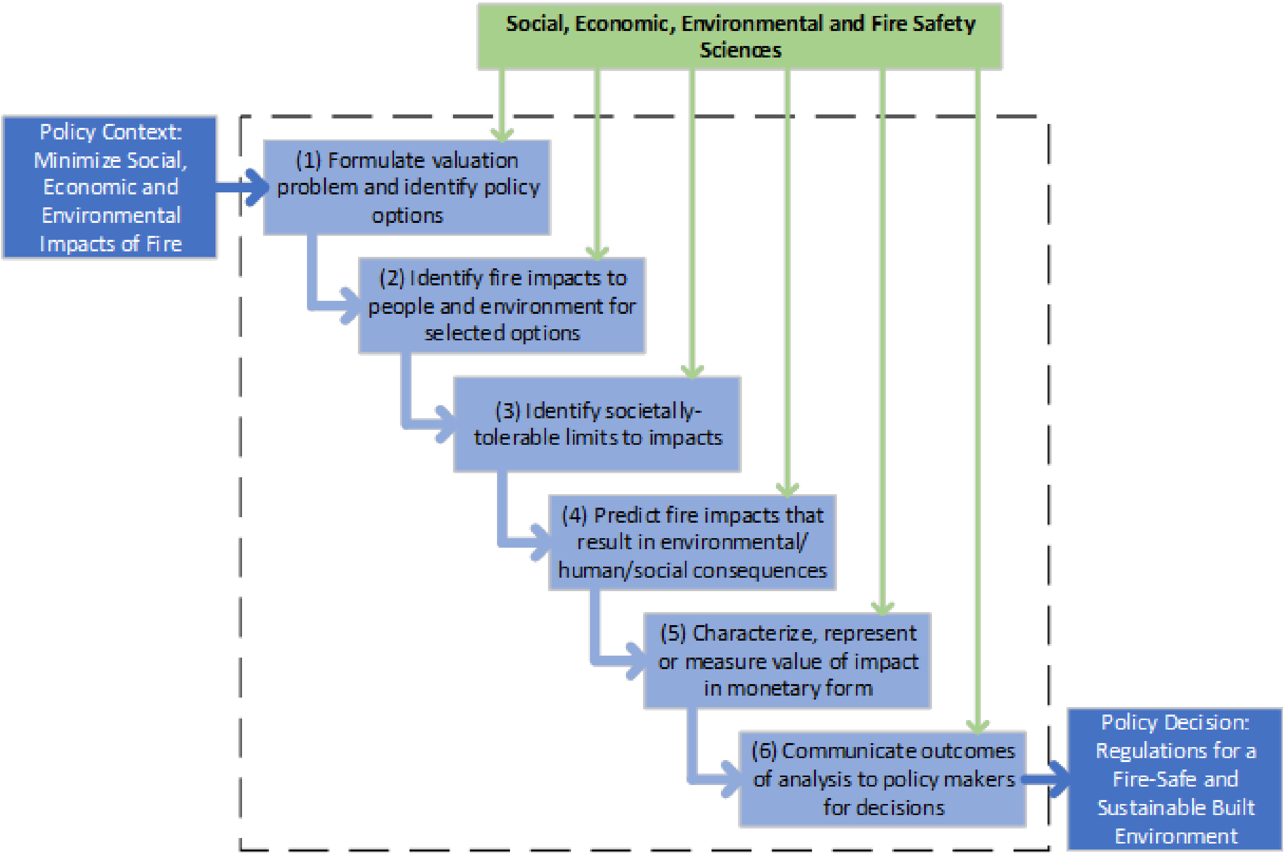

Figure 9: Policy Decision Framework for Valuing and Mitigating Environmental Impacts of Fire.

Step 1: Formulate valuation problem and identify policy options

Except in the case of very large fires, particularly in the industrial arena (and wildland fire arena), this research effort suggests that fire is not perceived by most of the lay public or by policy makers to have a particularly significant environmental impact. While methodologies exist to a priori estimate the physical environmental impacts of fire (i.e., development, transport and deposition of effluents, and impacts of effluents on environment from the fire or firefighting activities), there are few proactive mitigation policies associated with environmental impact of fire. Even in the case of PFOS / PFAS in AFFF, it was not fire that drew the attention of regulators, and the focus is largely on human health effects and not on broader ecological system impacts or environmental impacts. This makes it difficult to engage in discussions on valuing the impact of fire on the environment and on policy options for impact mitigation. This is a significant gap.

To address this gap, research is needed to better illustrate to the public and to policy-makers (a) the physical impacts of fire on the environment, (b) the economic cost of fire impacts on the environment, and (c) the role of public policies in mitigating some of the risks. As part of this, benefit-cost analysis may be needed to support the case.

While some options might seem rational from a 'fire only' perspective, such as using only non-combustible building materials, this is not practical in many cases. It might be that the cost of non-combustible materials is significantly higher than combustible. It might also be that non-combustible materials have more environmental impacts throughout their lifespan than combustible. Likewise, the environmental benefits of installing automatic sprinklers may be less than requiring more energy efficient heating, cooling and lighting options. From an existing building perspective, deep energy retrofits may do more to lower overall GHG emissions across a building's lifespan than investing in sprinklers.

Nonetheless, 'policy' options would relate to factors such as fire prevention options; fuel control options, including limits on construction materials and contents, such as type, constituent components and mass; fire control options, including compartmentation and suppression systems and components, including additives, and; control of fire-related materials, such as firefighting water runoff. Policy options might range from 'do nothing' (status quo) to multiple layers of protection. There would likely be different options and/or limits based on regulation for new versus existing construction.

Step 2: Identify fire impacts to people and environment for selected options

Fire impacts to people and the environment are as discussed in detail in Chapter 2. They will depend on the materials burning, size of the fire, and related factors. Significant gaps in our knowledge of the environmental impact of emissions from fires remain due to our limited knowledge and characterisation of emissions from fire, in particular in relation to emissions to water and soil. Further, the application of emission factors for emissions to air given in chapter 5 section 3, indicates that updating of existing emission factors to air is also urgent.

Step 3: Identify societally-tolerable limits to impacts

This is amongst the most challenging of the steps. Since impact to the environment from fire is largely not on the policy agenda (except industrial and wildland fires), the tolerability level is arguably the current level of impact. However, this is based on somewhat of a 'revealed preference' approach, extracted from current regulatory focus, and might change under a 'expressed preference' approach, if people (the public) are asked to their views on the fire impact on environment problem (and as later in the process, their willingness to pay to mitigate it).

Arguably, there are significant gaps in our understanding of what people are willing to tolerate, since this research has not identified literature that reflects such studies (for fire impact to the environment).

Step 4: Predict fire impacts that result in human/social/environmental consequences

Predicting fire impacts utilizes data, tools and methods such as discussed in Chapter 3. While a number of analytical and computational tools exist, there are gaps in:

- Data on fire properties of construction materials and building contents
- Data on fuel loads in buildings (type, amount, arrangement, etc.)
- Data on products of combustion released during fire for a wide range of materials under a range of combustion modes and conditions
- Confidence in model predictions given uncertainty and variability in data
- Data on persistence of various products of combustion in the environment, particularly water and soil
- Data on potential environmental impact of a range of firefighting additives
- Validated methods or tools environmental impact to nearby flora and fauna and potential sanitary problem (eg from the food or feed chain)

Step 5: Characterize, represent or measure value of impact in monetary form

Chapter 4 provides an overview of steps needed to characterise a fire and define its potential environmental impact in connection to economic and cost assessment tools. As stated above, significant gaps exist in our knowledge of how the public perceives the environmental impacts of fire, so research in this area is needed. Then, options exist for economic valuation of the impacts. At this time, very little research on either topic was identified with respect to the built environment (some was identified in the wildland fire area). Some further gaps are identified below.

With respect to valuing the cost of environmental impacts to fire events after they occur, actual costs of cleaning, decontamination and rehabilitation of the environment can be estimated, calculated or measured, where the extent of impact is known. Loss of ecology, wildlife, scenic value, and related factors may be difficult to estimate, but the wildland fire area may have guidance here, e.g., see Thomas et al. (2017).

Step 6: Communicate outcomes of analysis to policy makers for decisions
For specific types of facilities, such as chemical process and industrial facilities, the potential for environmental impact has been communicated to policy makers at various levels, and has resulted in the need for specific types of mitigation, such as firefighting runoff water containment and remediation. Mitigation also exists for some facilities in the form of limits on certain types and quantities of hazardous materials, and to some extent, the presence of automatic fire suppression systems (to keep the fire smaller and less need for firefighting water).

However, gaps arguably exist in communicating the same benefits to a broader range of facilities. Since the fire impact on environment is largely missing from the political agenda for non-industrial buildings, the benefits of material control, automatic suppression (sprinkler) systems, and others remain to be communicated.

6.2 Gaps in modelling fire effects and physical impacts

As stated under section 6.1.4, predicting fire impacts utilizes data, tools and methods such as discussed in Chapter 3. While a number of analytical and computational tools exist, there are gaps in:

- Data on fire properties of construction materials and building contents
- Data on fuel loads in buildings (type, amount, arrangement, etc.)
- Data on products of combustion released during fire for a wide range of materials under a range of combustion modes and conditions
- Confidence in model predictions given uncertainty and variability in data
- Data on persistence of various products of combustion in the environment, particularly water and soil
- Data on potential environmental impact of a range of firefighting additives

6.3 Gaps in modelling economic cost of fire impacts on the environment

Arguably, there are significant gaps in what people are willing to tolerate, since this research has not identified literature that reflects such studies (for fire impact to the environment).

Chapter 4 provides an overview of various economic and cost assessment tools. As stated above, significant gaps exist in our knowledge of how the public perceives the environmental impacts of fire, so research in this area is needed. Then, options exist for economic valuation of the impacts. At this time, very little research on either topic was identified with respect to the built environment (some was identified in the wildland fire area). Some further gaps are identified below.

With respect to valuing the cost of environmental impacts to fire events after they occur, actual costs of cleaning, decontamination and rehabilitation of the environment can be estimated, calculated or measured, where the extent of impact is known. Loss of ecology, wildlife, scenic value, and related factors may be difficult to estimate, but the wildland fire area may have guidance here (e.g., see Thomas et al., 2017).

7. Research Roadmap

In chapter 6, the gaps are outlined in terms of their connection to framing the problem, quantifying the size of the environmental impact and finally estimating the overall consequences and cost of that impact. In all cases, a lack of input data is an important hindrance to accurate estimates of the consequences-including post exposure and subsequently cost of fire's impact on the environment. In terms of framing, the definition of acceptable levels of environmental impact is missing in many cases. Information can be drawn from experience with industrial incidents but this misses a large part of the fire issue in terms of incidents which occur often but are in themselves relatively small. Finally in terms of establishing the economic cost of the environmental impact of fires, traditional methods which establish the environmental impact of products and services, such as LCA and CBA, should be extended to include costing of lost environmental access, loss of societal value from the recipient in question in addition to extension of our traditional understanding of remediation costs, willingness to pay, relevant discounting rates etc.

Significant gaps have been identified to establishing the cost of fire's impact on the environment. The development of estimates of the cost of fire's impact on the environment is not contingent on filling all of these gaps although the more gaps we can fill, the greater the confidence we can have in resulting model estimates. The research roadmap suggested in Figure 10 presents a "high"-level approach identifying specific topics which need addressing, rather than a specific research project level approach as there are so many individual areas where research is needed. This high-level approach can be used to develop research topics at a project level either to cover the whole gamut of research needs or to focus on a specific need, e.g. data collection, validation or case studies. Depending on the research goals of future projects (long-term or short-term) different pieces of the puzzle may be addressed. The high-level approach is also in recognition of the fact that there are many ways to fill the gaps identified. More details are provided for each of the main tracks of research and development suggested in Figure 10.

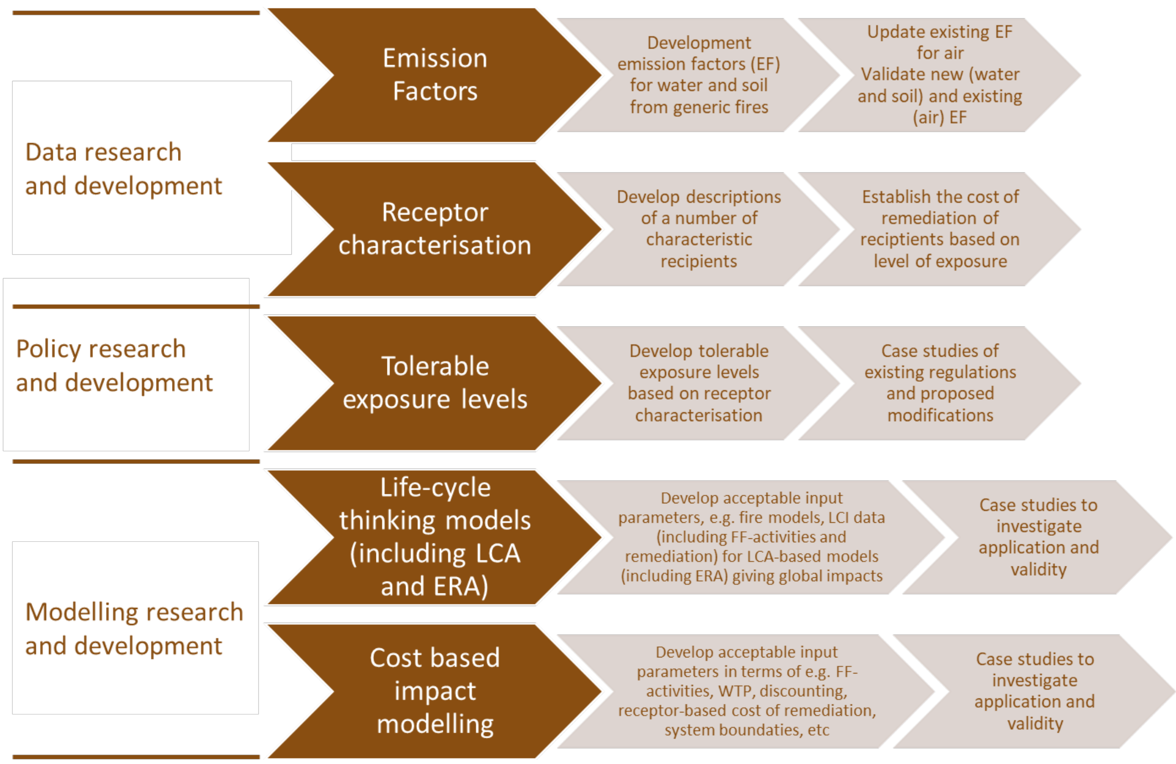

Figure 10: Overview of research roadmap for determining the cost of the environmental impact of fires.

7.1 Data research and development

7.1.1 Emission factors (EF)

Emissions factors should be considered regarding the different targets, i.e. air, soil and water. While the emission factors to the atmosphere are quite well known for numerous substances, emissions factors for emissions to water and soil are nearly unknown. It should, however, be kept in mind that the atmospheric EF are given for specific fire conditions and existing EF for air give wildly different emissions as exemplified in Chapter 5 when applied to building fires. Ideally EF should vary as a function of the fire conditions, in particular one would expect EF to be different for well-ventilated and under-ventilated fire conditions. The conditions in which those emission factors are measured should then be considered before being used for a given fire environmental impact evaluation. One should also have in mind the potential impact of firefighting on the emission factor, even without considering the potential toxic impact of chemical additives, the action of foam or water on the fire could modify the chemistry and, consequently the EF.

Furthermore, EF are typically based on measurements collected for pure substances. In real fire situations, the fuels are complex and detailed information about individual fuels may not be available. In most of real fire situation, the fuel is composed of several chemicals, some of them can be mixtures. This was typically the case during the Lubrizol fire that occurred in France in September 2019 where near 10 000 t of chemical burnt producing a very huge smoke cloud, visible kilometre around. During this fire, the exact nature of the chemical was difficult to determine and, typically, the information available in MSDS (Material Safety Data Sheet) are not enough to develop a reasonable EF, without obtaining additional information concerning the nature of the fuel, the fire ventilation conditions and the impact of firefighting on the fire chemistry. The development of typical "building" emission factors, per category or subcategory of stored combustible chemicals in industrial premises could help alleviate this for some generic mixtures. With the same guiding idea, establishing or consolidating conversion efficiencies of chemical elements chemically bounds to burning materials into relating toxics and pollutants (eg carbon into COx, halogens into parent halides, N into NOx/HCN…) from appropriate tests and lessons from past incidents should could also help in appraising first order environmental impact during crisis management

Another example related to the challenges associate with developing generic EF, is the Notre Dame fire (Tiago Miguel, 2019). In this specific case, the complication of a lead cover on the roof and the location of the building close to a major waterway meant that not only the emission to the atmosphere should be considered. Huge uncertainties concerning the particle size and behaviour in the air, coupled to the emission to water, highlighted the lack of accepted EF to assess the environmental impact of the fire.

On a more general way, EF of aerosols and particulate matter also need consolidation, in particular for particulate matter that significant differ from carbon based soot

This part of the proposed research needs should address the need to develop updated EF for atmospheric emissions and couple this to the development of acceptable EF for emissions to water and soil. The work should consider both pure substances and relevant mixtures. Coupled to the development of the experimental EF, real fire consequence measurements should be made to build supplement and validate the EF. Considering, for example, the two fires mentioned above, atmospheric dispersion was modelled, and various sampling was analysed. This is typically the case in most of the recent fires. Based on this analysis, a database could be built to provide relevant emissions factors, in real situations. Those factors could then be compared to the ones developed in the laboratory to establish a new methodology for the EF development and application.

7.1.2 Receptor characterisation

In accordance with the limitations given previously, it is clear that defining relevant receptors is a key aspect for measurements. This receptor characterisation could be divided into the development of a number of generic recipients which could be applied in a variety of modelling situations, e.g. the Fire Impact Tool (Amon et al., 2019) or a variety of LCA-based or cost-based models. Further, there is a need to establish accepted methods for the post-incident characterisation of specific recipients after a major fire.

Typical recipients will require new research to identify and characterise a number of generic examples. This would should include the limitations of the models developed.

This second aspect is typically the aim of a document such as the ISO 26367 series of standard that provide some methods to measure consequences in the context of the recipient. To obtain a detailed evaluation of the impact, one should consider both consequences of atmospheric dispersion of pollutants including air, soil, plants and others. The analysis of those sampling can provide information about the long-term effects in the environment and in living organisms. Such elements that could be used for impact evaluation should be then clearly determined in terms of capability to be polluted and of persistence of this pollution.

Sampling in the air should (if possible) be done during the fire, since pollutant persistence in the atmosphere is very limited considering both deposit and very large-scale mixture. This consequently means that air quality sensors, used in many countries should be able to measure some of specific fire pollutants as this would create a network of measurements to access in the case of a fire. Alternatively, models should be developed that are calibrated to translate deposition contamination into atmospheric transportation of fire emissions.

Focussing on the soil, the problem is slightly different since the pollutant migration period could be longer, and the decrease in emissions is mainly due to the leaching process. It is, however, possible to increase the depth of sampling to take the vertical migration into account. This is one of the main interests of sample as plants or animals since they can keep a sign of this pollution during days to months, milk contamination is typically a sign of dioxin contamination during months.

Considering water emissions, the behaviour is somewhere in between. For open water, rivers typically, pollutants will be transported downstream and then diluted and mixed in to the sea. The pollution tracers became animals and aquatic plants in this a case. Regarding closed or underground water, since the characteristic flow is slower, the pollution persistence could be longer, keeping in mind that sampling could be difficult because underground flow might be very complex. One way that can be further explore with regard to ecotoxic impact of potential fire effluent when dissolved in the water is combining simple OECD tests making use of daphnia or algae as receptors for conventional rating of the hazard to the environment of chemicals according to GHS with multicriteria analysis as pioneered by Bado-Nilles and co-workers for ionic liquids (Bado-Nilles et al., 2015)

There is, then, several improvements to be considered regarding receptor characterisation.

- The first should be the development of generic receptor descriptions to default application in modelling.
- The second concerns improving our ability to characterise actual recipients and determine their resilience given exposure to specific pollutants. While some information exists on this point, more quantified information would be helpful. The approach concerning characterisation of specific recipients in the case of a fire incident will be slightly different depending on the phase of the recipient.
    - Regarding soil, a leaching and transport model into soil could help to determine the relevant depth to be sampled. Considering a depth larger than the contaminated one could lead to false measurement and measurements should be kept to contaminated layers.
    - Regarding water, measurements and characterisation will vary depending on whether the water is surface or ground water.
    - Regarding the atmosphere, improving the deposition model should help to establish correlation between soil and water sampling and modelling. Such an approach could then be used to develop an understanding of the fire consequences.
- One corollary of conducting the suggested research is to provide detailed guidance to manage sampling both during and after a fire incident.

7.2 Policy research and development

7.2.1 Tolerable exposure levels

Determination of tolerable exposure levels is a key in terms of environmental impact evaluation and associated cost quantification. Independent of whether it is possible to measure or model fire consequences, without any relevant and accepted tolerable exposure levels, no quantitative evaluation of the environmental impact of fires is possible and the development of relevant policies is potentially blocked.

Many thresholds exist to establish the impact of acute exposure (AEGL, ERPG, VSTAF, …) for different situations, but these are most related to the human health impact. While interaction between gases could be complex, combinations of these thresholds enables one to evaluate the number of possible human death or casualties in case of smoke exposure. Similar threshold does not exist for animals which makes quantification of death of wildlife more difficult. This is, however, an important criterion in terms of environmental cost evaluation. The current way to proceed is to measure consequences by counting or estimating actual numbers of dead animals, as for example during the SIAAP fire in July 2019, in France, where thousands of fish were killed in the Seine River. There are presently no accepted models to estimate loss of wildlife after a fire. A slight improvement (as done as the aftermath of the Sandoz fire) was to follow affected living species in surface water versus time: as reported by ICPR (2016), it took more than 10 years to recover normal number counts of salmons in the Rhine river after this disaster: however, this measurement only gives very late indicators of exposure levels

Regarding flora, there are no recognised limit values to identify acceptable levels of contamination. In most cases, depending on smoke cloud modelling and sampling, collecting plants would be forbidden and some area, it was typically the case after the Lubrizol fire. The design of the restricted area is however quite complex since no threshold exist. Existing threshold for potable water should also be mentioned since this is one of the ways to detect a contamination of water. However, they are not always relevant for a water contamination by fire since test are commonly achieved after treatment.

7.3 Modelling research and development

7.3.1 Life-cycle thinking models (including LCA and ERA)

Life-cycle based models have been developed since approximately the 1970's but the application of LCA thinking to include fire began to develop first toward the turn of the century. In recent times the use of an holistic approach incorporating life-cycle thinking has gained popularity as the need for a full life-cycle assessment is not always present while the use of many of the basic precepts behind life-cycle thinking is generally application to most situations. The quality of life-cycle based models is heavily dependent on the input data that is available. Much has been done since the development of LCA methodologies to improve input data and publically available databases exist for many products, even if the data can at times be costly. There is a need to improve the application of such models to include fire safety. Some of the work which has been proposed in relation to emission factors and receptor characterisation would be useful also for life-cycle based applications.

In relation to modelling the environmental impact of fires it is necessary to use both life-cycle assessment (LCA) based models and environmental risk assessment (ERA) based models. One drawback of life-cycle assessments is the fact that they provide information that is presented in a global sense, i.e. emissions over the full life-cycle of the functional unit, and are difficult to interpret in terms of the environmental impact of a specific fire incident. Environmental risk assessment methods allow the assessment of local environmental impacts. Coupling ERA to LCA creates a powerful tool that is able to take into account both short term and long-term impacts. More work is needed to investigate the boundary for the application of these methodologies in particular in relation to their application to fire scenarios and the effect of firefighting on the emissions from such scenarios.

Further, validation of the models through comparisons between experimental data and model calculations is necessary to improve their acceptance.

7.3.2 Cost based impact modelling

Costing of the environmental impact of fires is an area that has received very little attention in terms of the build environment. Some work has been found relating to specific fires but this is typically based on post-fire analysis rather than projections. Some models that have been developed and applied to wildland fires could provide a sound basis for establishing models for the cost of the environmental impact of fires in the build environment. In most cases the fundamental building bricks of cost models are available but input data is lacking or out of data. Even in this case, life-cycle thinking provides a sound basis for developing tools to establish the cost of the environmental impact of fires. Table 15 provides a summary of the building blocks that create the foundations for costing.

Table 15: Summary of topics related to development of models to assess the cost of the environmental impact of fires.

Topic	Comment	Development needs
Model components	Willingness to Pay (WTP), discounting for benefits in the future relative to costs now. The cost of a statistical life has been considered previously but the cost of a statistical eco-system should be considered	Basic methods exist and should be explored in fire applications
Cost categories	Prevention, mitigation, suppression, remediation, rebuilding. Direct and indirect costs	Basic methods exist for general fire costs need to be tailored to suit the environmental impact of fires. In particular, more research is needed to establish indirect costs, e.g. the social impact of the loss of important environments.

Appendix 1: List of databases in LUBsearch and at INERIS

Licensed databases in LUBsearch

- Academic Search Complete (ASC)
- AMED - Allied and Complementary Medicine Database
- Art & Architecture Source
- ATLA Religion Database with ATLASerials
- Avery Index to Architectural Periodicals
- Bibliography of Asian Studies
- Business Source Complete
- CINAHL Complete
- Communication Source
- Criminal Justice Abstracts with Full Text
- EconLit
- Economist Historical Archive
- eHRAF Archaeology
- ePublications
- ERIC
- FSTA - Food Science and Technology Abstracts
- GeoRef
- GreenFILE
- HeinOnline
- Henry Stewart Talks
- Humanities International Complete
- IEEE Xplore Digital Library
- IMF eLibrary
- Inspec
- LGBT Life with Full Text
- Library, Information Science & Technology Abstracts with Full Text
- Literary Reference Center
- MathSciNet via EBSCOhost
- MEDLINE
- MLA International Bibliography
- New Testament Abstracts
- OECD iLibrary
- Old Testaments Abstracts
- Oxford Competition Law
- Philosopher's Index
- Political Science Complete
- PsycCRITIQUES
- PsycINFO
- PsycTESTS
- Regional Business News
- RILM Abstracts of Music Literature
- Rock's Backpages
- SAE Technical Papers

- SAGE Video
- Scopus
- Short Story Index (H.W. Wilson)
- SocINDEX with Full Text
- Sustainable Organization Library (SOL)
- Teacher Reference Center
- Urban Studies Abstracts
- Very Short Introductions Online (Arts and Humanities)

Open-access databases in LUBsearch

- Aphasiology Archive
- Archive of European Integration
- arXiv
- British Library EThOS
- CogPrints
- Directory of Open Access Journals
- eScholarship
- Industry Studies Working Papers
- LUNA Commons
- Minority Health Archive
- Networked Digital Library of Theses & Dissertations
- OAPEN Library
- OJS vid Lunds Universitet
- Open SUNY Textbooks
- Open Textbook Library
- Persée
- PhilSci Archive
- SSOAR - Social Science Open Access Repository
- SwePub

Free Index/Catalogues in LUBsearch

- Publications New Zealand Metadata
- SveMed+
- Swedish National Bibliography

INERIS Licensed databases

- Science direct*
- EBSCO
- Springer link
- Wiley on-line Library

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