Environmental Benefits of Rapid Fire Detection

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Abstract

A study has been undertaken to investigate the environmental implication of early detection of a fire for the environmental impact of the fire when taking into account the global impact of the intervention itself and the need to replace building and contents as a function of the size and duration of the fire. The various scenarios investigated show that the greatest benefit is gained if a fire is detected early and can be extinguished while small without the intervention of the fire service. Significant savings can also be made if a sprinkler can keep the fire small while the fire service is on their way to the fire so that they meet a small fire which they can rapidly extinguish once they are on the scene. The methodology is based on an assumption of a single enclosure size, a generic fire load, detection and response. Future work should investigate different building typologies, fire loads and response types.

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Summary

The work was undertaken as a proof-of-concept evaluation of the environmental impact of fires as a function of the time for detection and response. An analysis of the environmental impact of a single story, timber-framed building, with contents that generically represent a range of occupancies, such as apartments, hotels, offices, medical suites, and similar, was undertaken using a modified version of the Fire Impact Tool. The modifications allowed the inclusion of the structure and contents in the fire, and fire service response to the fire, to be included or not depending on the timing of detection and response. The specific aim was to investigate the potential contribution of early fire detection and early fire suppression on reducing the overall environmental impact of fire in the structure. As part of the analysis, six scenarios were investigated, which ranged from early fire detection and suppression with a manual fire extinguisher, to no early detection and burnout without suppression activities. Environmental impact was estimated based on estimated percentage of contents and structure consumed and associated replacement, using environmental the ecological scarcity method, which combines environmental impacts using the metric of eco-points.

Based on the analysis, the outcomes show that early fire detection, response and extinguishment yields the best environmental results, i.e., lowest environmental impact. The analysis showed that the primary drivers of environmental impact from fire in the scenarios considered were the structural materials and contents. Deployment of the fire service is a minor environmental cost relative to the cost of replacement of contents and structure. Replacement of the structure dominates once this has become involved in the fire.

Future work should investigate additional building typologies, construction materials and fuel loadings. Further, additional investigation of the impact of specific types of detectors could be useful. This research would require additional LCA calculations. If such calculations are undertaken in the future, it would also be useful to investigate alternative impact assessment methods as a complement to the eco-point method presently implemented into the Fire Impact Tool.

Preface

This work has been conducted as part of a Honeywell International Inc. funded project (purchase order no. A001443293).

The work has been peer-reviewed by a reference group of Honeywell staff comprised of:

- Scott Lang
- Andrew Berezowski
- Udaya Shrivastava
- Richard Roberts
- Adam Gibson
- Brad Hill

The work presented is that of the project team. The work represents a first proof-of-concept of a methodology to assess the environmental impact of different sizes of fires depending on their time of detection. The work is based on previous studies concerning the environmental impact of fire service intervention to a fire and their choice of tactical response using the Fire Impact Tool.

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1 Introduction

1.1 Background

An unintended fire in a large building can have a significant, negative impact on the environment. The negative impact is not only due to the release of toxic gases, particulate matter, and other products of combustion [1-3], but also due to potential impacts of responder fire service apparatus [4], and the potential for contaminated water run-off from fire suppression [2, 5, 6]. In addition, there is also an inherent environmental impact due to the replacement of the structure and/or the contents of the building after the event [7]. In most instances, fire protection measures in a building are typically installed to facilitate protection of life and property, either mandated by building codes or insurance. However, fire protection measures can also serve to reduce the impacts of fire on the environment [2, 5-9].

The two main active fire protection measures for buildings are automatic fire detection and alarm systems (AFDAS) and automatic fire suppression systems (AFSS) (typically fire sprinkler systems (FSS), but also other types of extinguishing systems, such as water mist or inert gas), which often work in concert with manual fire suppression (MFS) efforts. While AFDAS do not themselves control the size of a fire, they are essential in facilitating rapid notification of on-site personnel and the responding fire service. Since some types of fire detection can sense a fire at very early stages (e.g., smoke detection, CO detection, flame detection), if they are connected to systems that promptly notify local responders and the fire service upon detection, this can result in faster manual intervention than would be possible if no fire detection device had been present.

With respect to AFSS, the aim is typically to control fire spread to the area of origin by automatic application of a suppressant until the fire service can arrive to extinguish the fire. Some special suppression systems may use smoke detectors for actuation. However, many AFSS use thermal fire detection devices, such as the fusible link in an automatic sprinkler. While this can result in a longer time to actuation than is the case for some other types of fire detection devices, the total time to begin fire suppression / control can actually be shorter than relying on the fire service, since no travel from off-site is required before initiation of suppression activities [10].

Until now, while it is generally accepted that early detection and response (AFDAS and AFSS) can reduce the time to suppress a fire, and that early suppression can lessen environmental impacts, the reduction of environmental impact given AFDAS and AFSS has not been extensively explored or quantified, in particular AFDAS, with some notable exceptions [7, 11-13].

Estimating actual environmental impacts of fire is complex and dependent upon numerous factors, including type and amount of materials that are burning, contaminants that are released, compartment geometry and ventilation, fire development and growth rates, mass emission production rates, suppressant effectiveness, firefighting tactics, environmental conditions (e.g., wind, temperature, humidity, etc.), exposure pathways (i.e., air, soil, water), movement dynamics (e.g., thermal buoyancy, water flow rates), retention basins (or not), and so forth. Examples for estimating environmental impacts of fire can be found in [1-5, 14-16].

This work makes use of the Fire Impact Tool [5, 6], developed at the Research Institutes of Sweden (RISE). The Fire Impact Tool is comprised of three components: fire models, environmental risk assessment (ERA) and lifecycle assessment (LCA). The Fire Impact Tool expands from an earlier tool, the Enveco tool [4], which was designed to apply to warehouse fires. The Fire Impact Tool uses ERA modelling to predict environmental impacts to the local surroundings from fire water run-off, and an LCA methodology to assess the global environmental impact of fires and firefighting.

1.2 Estimating early intervention on the environmental impact of fires

For this 'first order' (rough) estimate approach, we aim to draw a parallel to the 'available safe egress time' versus 'required safe egress time' approach (ASET/RSET) used for life safety analysis in case of fire [17]. Simply, the ASET/RSET approach compares development of the fire against time required for evacuation, with the available time being a function of tenability. In this case, however, instead of considering time that occupants reach a place of safety outside of the building, we look at the steps and timing from fire initiation until fire suppression, with a focus on the time difference (and associated fire size and environmental impact differences) until suppression occurs for different interventions. In concept, while manual suppression could occur by an occupant using a fire extinguisher, after detection and notification [18], in this effort we focus on manual suppression by the fire service. The reason is to include both the occupied and unoccupied status of the building more globally.

In concept, this approach can be reflected as follows:

$$t_{supp} = t_{det} + t_{not} + t_{resp} + t_{setup} + t_{agent} + t_{ext}$$

where,

t_{det}= time from ignition until detection

t_{not} = time from detection until fire service notification

t_{resp}= time from notification until fire service arrive at fire

t_{setup} = time from fire service arrives at the fire until they setup on site

t_{agent}= time from fire service setup on site until fire suppression agent begins

t_{supp} = time from agent application begins until fire is suppressed (knocked down)

t_{ext} = time from initial suppression until fire is extinguished (suppressant no longer needed)

Note that each of the times has been applied stepwise after each other from ignition at time $t = 0s$. This is illustrated in the Figure 1.

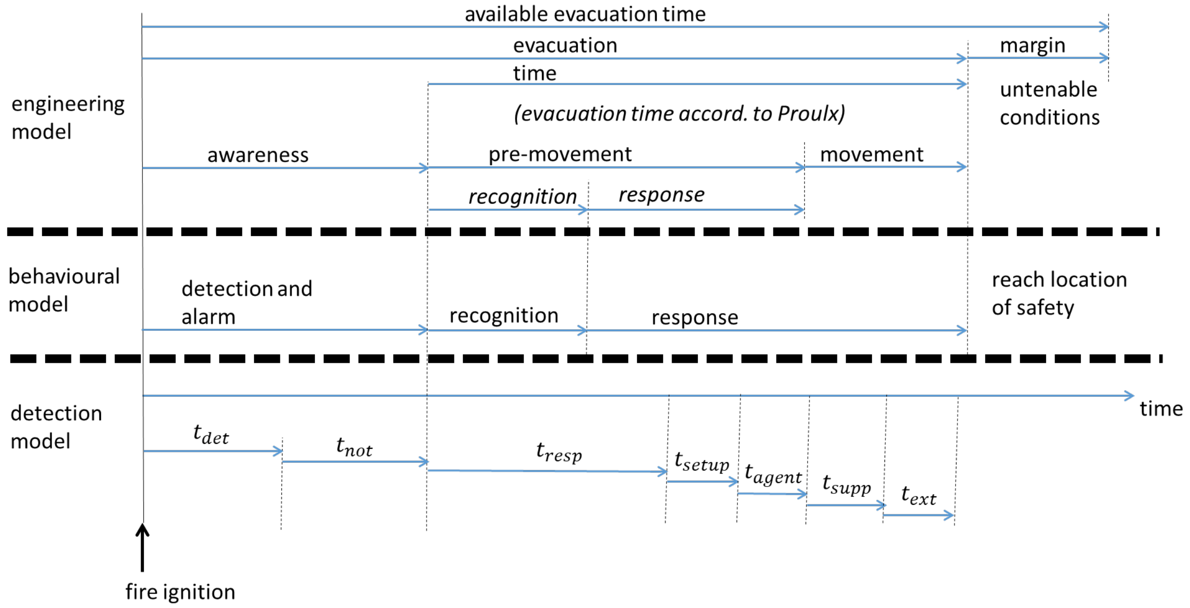

Figure 1: Overview of timing of detection and response sequence as applied in this project. The detection model is juxtaposed with the engineering and behavioral models as previously presented by Forssberg et al. [17].

For the environmental impact, this is related to several types of emissions and environmental costs:

1. The emissions from the fire itself;
2. Emissions associated with Fire Service response;
3. Emissions associated with replacement of burned contents;
4. Emissions associated with replacement of a damaged structure.

Emissions from the fire itself are estimated based on the size of the fire, i.e. the amount of fire effluents produced is related directly to an assumed fire effluents rate curve, see Figure 2. The overall heat release rate (HRR) curve can then be used to estimate emissions as a function of time to suppression. In the methodology developed within the Fire Impact Tool, the structural system is timber, the building is a single story, and the fire emissions are scaled based on the size of the enclosure and its associated openings. These limits help illustrate the calculation approach without changing too many variables. Future work could consider other structural system material types.

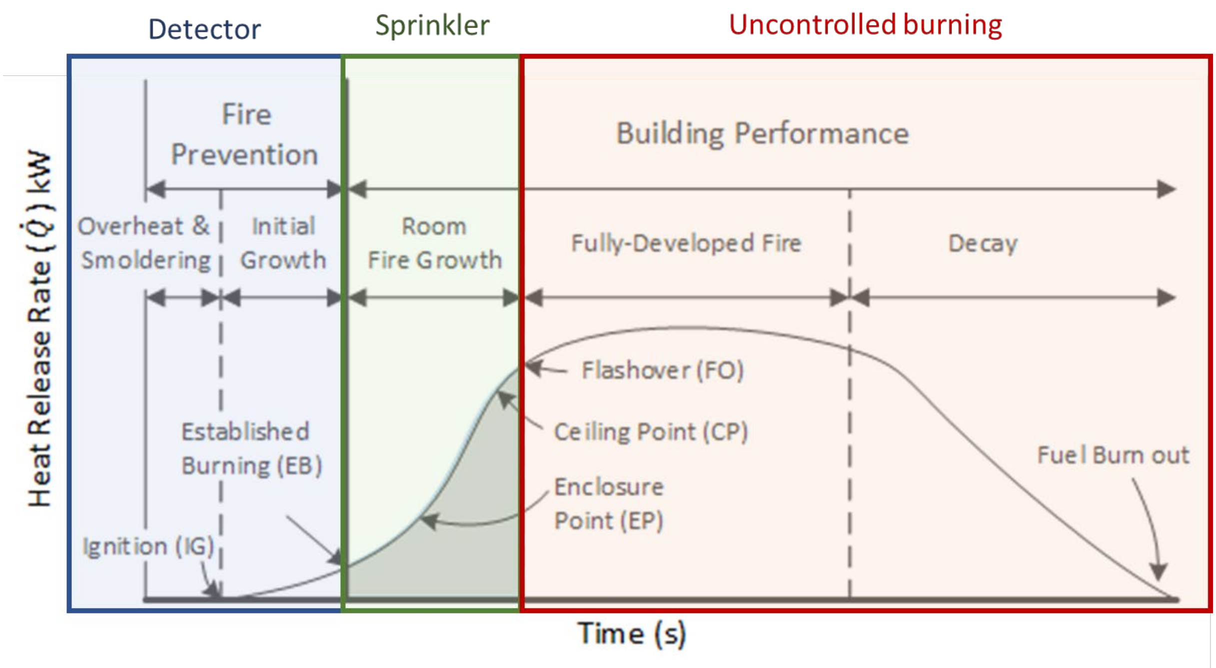

Figure 2. Stages of Fire growth [19], highlighting where intervention of detection and the involvement of sprinklers is expected, i.e. before entry into the uncontrolled burning phase.

Emissions associated with the fire service response depend on the number and type of vehicles which respond to a fire, which in turn depends on the type and size of the fire. Emissions associated with burned contents and the structure are estimated using a lifecycle approach which takes into account the fact that the full (expected) lifecycle of a product or structure is cut short by being involved in a fire and will need to be replaced. These emissions can also be estimated using the Fire Impact Tool.

1.3 Objective

The objectives of this research effort are:

a. to gain an understanding of the influence(s) of automatic fire detection and alarms systems, of automatic fire suppression, and of manual fire suppression, separately and together, on the environmental impact of fire, and

b. to ascertain whether, and to what degree, early intervention could lessen environmental impact and under what conditions.

The basis of the research is limited to desk study and simplified calculation / estimation methods using an updated version of the Fire Impact Tool.

Limitations for this scoping study include: single structural system material type (lightweight timber), single story structure, single compartment, use of relatively small compartment size, use of contents that could reflect a range of building typologies, including residential, hotel, hospital, school and office.

1.4 Report disposition

Chapter 2 provides a summary of the literature reviewed as part of this work. Chapter 3 provides a short introduction to the Fire Impact Tool as applied in this particular study. Chapter 4 introduces a number of fire scenarios to explore the impact of early detection and response and presents the results of the modified Fire Impact Tool calculations. The work is discussed in Chapter 5, conclusions presented in Chapter 6, and future research needs outlined in Chapter 7.

2 Literature overview

2.1 Introduction

Literature as input to the evaluation of the environmental benefit of early detection was not identified through a traditional literature review. Rather the following literature sources were used:

1. Literature from NIST concerning previous studies of detection in various types of occupancies;
2. Literature from previous projects the authors or their organizations had been involved in, or were familiar with;
3. Specific searches of NFPA Fire Protection Research Foundation projects;
4. Investigation of relevant international fire standards.

The main literature used as a basis for the model development is summarized in Table 1.

Table 1: Summary of main literature used in the development of the assessment model presented in Chapter 4.

Main source of literature	Reference (examples, see text and reference list for all references)	How used
NIST (1)	NIST Technical Note 1837 on improving detection systems [20] NIST Technical Note 1455-1 on performance of home smoke alarms [21] NIST Technical Note	Detection timing
Report authors (2)	SFPE Handbook chapter on detection [10] RISE investigation of detection in structures with high ceilings [22] Jensen Hughes evaluation of smoke detector response [23] NIST evaluation of smoke detection activation prediction [24] SFPE Handbook on Fire Loads [25]	Detection timing, fire loads
Fire Protection Research Foundation (3)	FPRF study on digital assessment of fire loads [26] FPRF project on understanding the nature of fire detection and predicting the detection performance [27-30]	Detection timing, fire loads
International standards (4)	Eurocode 1 [31]; NFPA 557 [32]	Fire Load

2.2 Traditional Detection methods

As introduced previously, fire detection systems are common in most commercial facilities, assembly premises, hotels and health care facilities and false alarms can be a significant problem [33, 34]. A false fire alarm creates unnecessary interruptions to business operations, forces people to evacuate and introduces a high unnecessary traffic risk. The reasons for false alarms vary depending on the type of detector, its application and position; but, reasons may include non-fire particles in a dirty industrial environment or produced by cooking in a kitchen (whether domestic or industrial), or steam produced in industrial or domestic situations. In essence, there are two solutions to this problem, either false alarms are stopped by organisational measures, i.e., a fire must be confirmed by a complementary means before activating the detection system to initiate a response; or the reliability of the detector is increased through a variety of technical measures. In the latter category, some effort has been made to study multi-sensor fire detection to improve the reliability of detection and reduce the number of false alarms [35, 36]. Such systems typically rely on a combination of traditional sensors and data treatment to reinforce detection reliability by confirmation of detection through several fire characteristics such as, e.g. smoke, temperature, CO-emissions and CO_2-emissions (see e.g. [37, 38]). While such efforts have been successful in improving the level of detection compared to single sensor detectors [37], they typically rely on a range of chemical (e.g. species) detection methods, heat and particle detection [39].

Traditional detection methods can be divided into three main types [10]:

- Smoke detection methods
- Heat detection methods
- Flame detection methods.

Smoke detection methods

Smoke is produced in the early stages of a fire which means that smoke detection is often the method of choice when early detection is critical. Smoke can be released both from the ignition source itself if it is a combustion source, or from an incipient fire, i.e., before flames are present. Fire smoke is warm and rises due to thermal buoyancy. Traditional smoke detectors use point sources that are ceiling or wall mounted and detect smoke as the concentration of particulate matter. These can be photoelectric or ionization in nature.

A photoelectric, or optical, smoke detector functions by detecting particles are detected by scattering of light from a light source [40]. In point source detectors (which are often applied to small open spaces), the light source and detector is typically located in a chamber in the detector itself. In larger rooms (such as industrial applications) an optical beam can be projected across a specific volume to facilitate detection. A drawback of this type of detection system is that the light source cannot distinguish between fire generated smoke and other types of airborne aerosols, such as dust. In an industrial scenario this can be particularly problematic.

Ionization detectors detect particles when these pass through an ion field created between two plates [40]. The response of ionization smoke alarms is proportional to the product of the number concentration and the particle diameter, although it is probable that the charge of the particles influences the detection. Ionization type alarms provide somewhat better response to flaming fires than photoelectric alarms and photoelectric alarms often provide faster response to smouldering fires [40, 41].

Heat detection methods

Heat detection is typically conducted using either spot detectors (sometimes in combination with other spot detection methods) or linear heat detectors [41].

Spot detectors in sprinkler systems rely on the solution of a gas bubble in a glass bulb containing an incompressible fluid, causing the bulb to shatter and activate the sprinkler [42]. Spot detectors in alarm systems typically are based on the use of metal plates that are separated by air under normal conditions, but which expand in such a way that they connect and close a circuit to cause the emission of an alarm at a pre-determined elevated temperature [43]. Additionally, electronic heat detectors which use a thermistor as the heat sensor are common in fire alarm systems.

Line detectors have been developed using a variety of technologies depending on the application [44]. The primary types of line detectors include continuous thermocouples, heat sensitive cables, electrical conduction, fiber optics [41]. While the actual mode of detection varies, they can be essentially divided into methods which require a circuit to be either broken or closed, or a differential method. In the first case, a specific temperature threshold needs to be exceeded for detection to occur while in the second case a certain rate of change of temperature is necessary for the temperature differential to be created.

Flame detection methods

Fire product not only smoke but also flames in certain situations. While smoke detectors have the advantage of detecting even smouldering fires, flame detectors can measure radiant energy emitted by the flames at specific wavelengths indicative of fires [41]. The wavelength detected can be tailored to detect specific types of flames which can be particularly interesting in industrial applications where the expected type of fire can be distinguished from background noise.

2.3 Historical experimental studies of fire detection

Over the past 20 years, numerous experimental studies have been conducted into the performance of fire detectors under a variety of conditions, i.e. room size and configuration, fire size and detector type. Within the scope of this project, it has not been possible to review and evaluate all existing data, but the experimental series which have been reviewed as part of this study include:

- Chapter on Design of Detection Systems from the SFPE Handbook [10].
- NIST experimental review of various methods of fire detection [21]
- RISE Research Institutes of Sweden evaluation of fire detection performance in buildings with high ceilings [22]
- Hughes Associates and University of Maryland meta-analysis of previous experimental work [23]
- NIST and Nuclear Regulatory Commission analysis of previous experimental work [24]
- FPRF project reported in 2008 which focuses on understanding the nature of fire detection and predicting the detection performance [27-30]

In this review, we have made a conscious decision not to explore in detail work conducted before 2000’s given the wealth of more recent data. It is clear from an analysis of the available experimental data is that there is a broad distribution of time to detection from less than a minute to up to 10 minutes, depending on the type of detector, type of fire and room configuration.

2.4 Typical Building Fire Fuel Loads

The question of fuel loads has been debated since the turn of the 20th century at least. The earliest publication that was found compiling fire loads in the US in peer reviewed literature was from 1991 [45], although reports have been identified published considerably earlier [46]. Assessments of fuel loads in buildings with different occupancies have been conducted on numerous occasions. Not all such references are provided here but there are some excellent summaries, see for example [25, 26]. A common finding for such studies is that fuel loads in buildings are difficult and time consuming to estimate and that they vary significantly depending on the building use (or occupancy) and even within similar types of occupancies the fuel load can vary., e.g. the fire load in a wood processing facility in Switzerland has been cited to have a fire load range of 80-4923 MJ/m^2 [25]. The fire load requires some definition. In the scope of this project, we have divided the total fire load into that which relates to the contents (not fixed) and that which relates to the structure (including surface cover such as gypsum sheets). Considering the contents as the fire load as discussed in this chapter, we can think of them as impacted by the introduction of early suppression due to early detection as introduced by Fontana et al. [25] in the SFPE Handbook, see Figure 3.

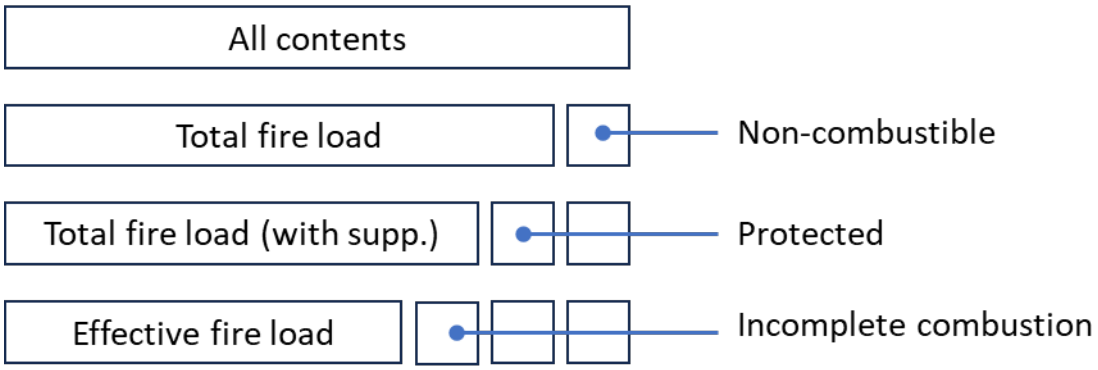

Figure 3: Illustration of impact of early detection and suppression on available fire load (modified from Fontana et al. [25]).

In recent years, the Fire Protection Research Foundation (FPRF) funded a project to develop a digital methodology to estimate fuel loads for specific buildings to enable the development of a fuel load for bespoke applications using machine learning and photo analysis [26]. The FPRF study summarized typical fuel loads as a meta-analysis of previous studies. This work also resulted in a range of values, emphasizing the value of a method to rapidly estimate fuel loads in specific buildings. If a study were to be conducted of specific buildings rather than generic typologies, it would be worthwhile applying the developed fuel load estimation methodology to ensure a realistic estimation of fuel emissions. Nonetheless, this small study will focus on generic commercial buildings (an office and a shopping center application) and will therefore select average values which are reasonable for such building typologies.

The Eurocodes provide estimates of fuel loads in typical buildings (averages and 80% fractile values), see Table 2. Similarly, NFPA 557 provides a methodology for estimating fuel loads in US buildings for structural fire resistance design [32]. NFPA 557 does not, however, give as simple values for application in the methodology explored in this project. Therefore, estimates from the Eurocodes have been chosen as a proof-of-concept. Alternative values are unlikely to change the conclusions of the study.

Table 2: Fire load densities (MJ/m²) for different occupancies [47].

Occupancy	Average	80% fractile
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1500	1824
Office	**420**	**511**
Classroom of a school	285	347
Shopping centre	**600**	**730**
Theatre (cinema)	300	385
Transport (public space)	100	122

2.5 Typical Fire Development

In an uninhibited fire (not limited by fuel, oxygen or suppression agent) involving solid fuels, in particular cellulosic, there may be a period of low energy smouldering or overheating of a material, which can lead to ignition. This first phase in the fire is sometimes called the *incipient fire*. If the ignition source is suitably competent to ignite some material, which in the absence of the ignition source continues to burn, the fire can be described as having entered the phase of *established burning*. If sufficient fuel and oxygen are available, the fire will grow, the rate being dependent upon the fuel materials, their configuration and oxygen availability. If the fire is in an enclosure of limited size (particularly ceiling height being relatively low), the increased temperatures in the upper gas layer will heat all the fuels in the room, causing them to give off combustion gases. At a certain point in time, those gases will be ignited, and the enclosure will reach what is known as *flashover*, and the *fire growth stage* will transition into a *fully-developed fire*. The fire will continue to burn provided there is oxygen and fuel, or until it is extinguished. At this point the fire is said to *decay*, until ultimately reaching extinction. The terms highlighted in the text can be seen in Figure 2 which illustrates the stages of a fire. (Note that compartment flashover is not likely in spaces with high ceilings and have aspect ratios that are narrow and long. In the latter, traveling fires based on localized flashover like effects is possible.)

The length of the period of time until fire growth occurs leading to flashover and a fully-developed fire will vary for each specific fire scenario. Numerous experimental series have been published measuring the heat release rate from enclosure fires. Those which have been investigated to evaluate the potential impact of a fire have been chosen due to their relevance for an office or commercial setting and accessibility to data. Figure 4 shows the full room fire tests conducted at RISE in Sweden in the 1990's, showing the stages of the fire. The dotted line has been added as a typical fire growth similar to that identified in Figure 2, where the progressive involvement of the contents in the room increases to the point of flashover. Actual room fires (such as that shown in the continuous line) vary greatly in the initial fire growth stage. It should be noted that for single burning items, a t^2 fire growth rate can be used as an approximation. Such an approach can be used for fire detector and sprinkler activation estimates, as reflected in NFPA 72 and other such documents. However, in a compartment fire, where many fuel packages can become involved, such transitions are not as typical. The actual growth rate will be influenced by formation of the upper gas layer, which means slower growing fires can transition suddenly when the upper gas layer volatilizes materials in the lower regime. This is why, in Figure 3, there is such a rapid growth rate and transition from low energy fire to full room involvement. The dotted line illustrates the type of range in growth rates that could be expected, depending on the materials, compartment and ventilation.

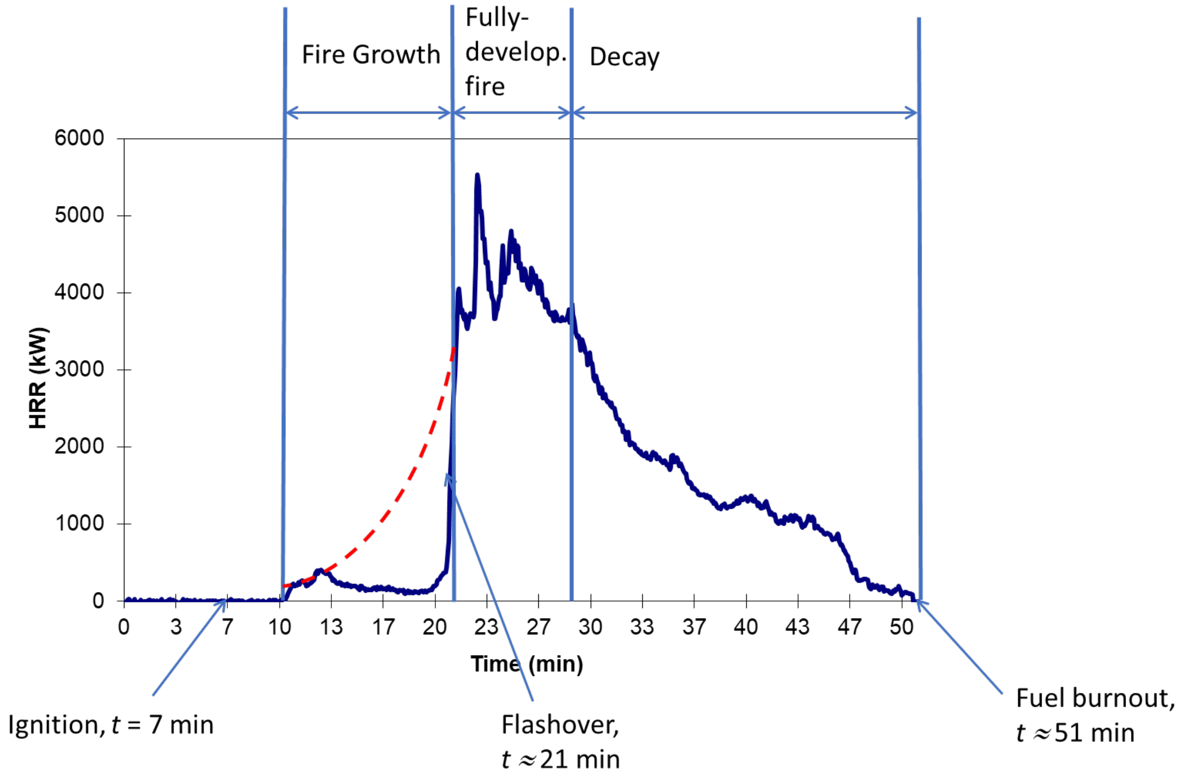

Figure 4: Division of fire development in a 16 m² room fire into different stages. NOTE that the times are approximate with the exception of the time of ignition (modified from [48]).

It is important to note that during the entire lifetime of the fire, effluents are being produced, many of which could result in environmental impacts (in addition to impacts to people and property). These typically follow the development of the fire and mirror the HRR curve, see Figure 5. The emissions data is scaled relative to the energy emitted by the fire, as described in the next Chapter. Therefore, the averaged emissions related to the HRR are used for a wide variety of species rather than the specific time resolved values.

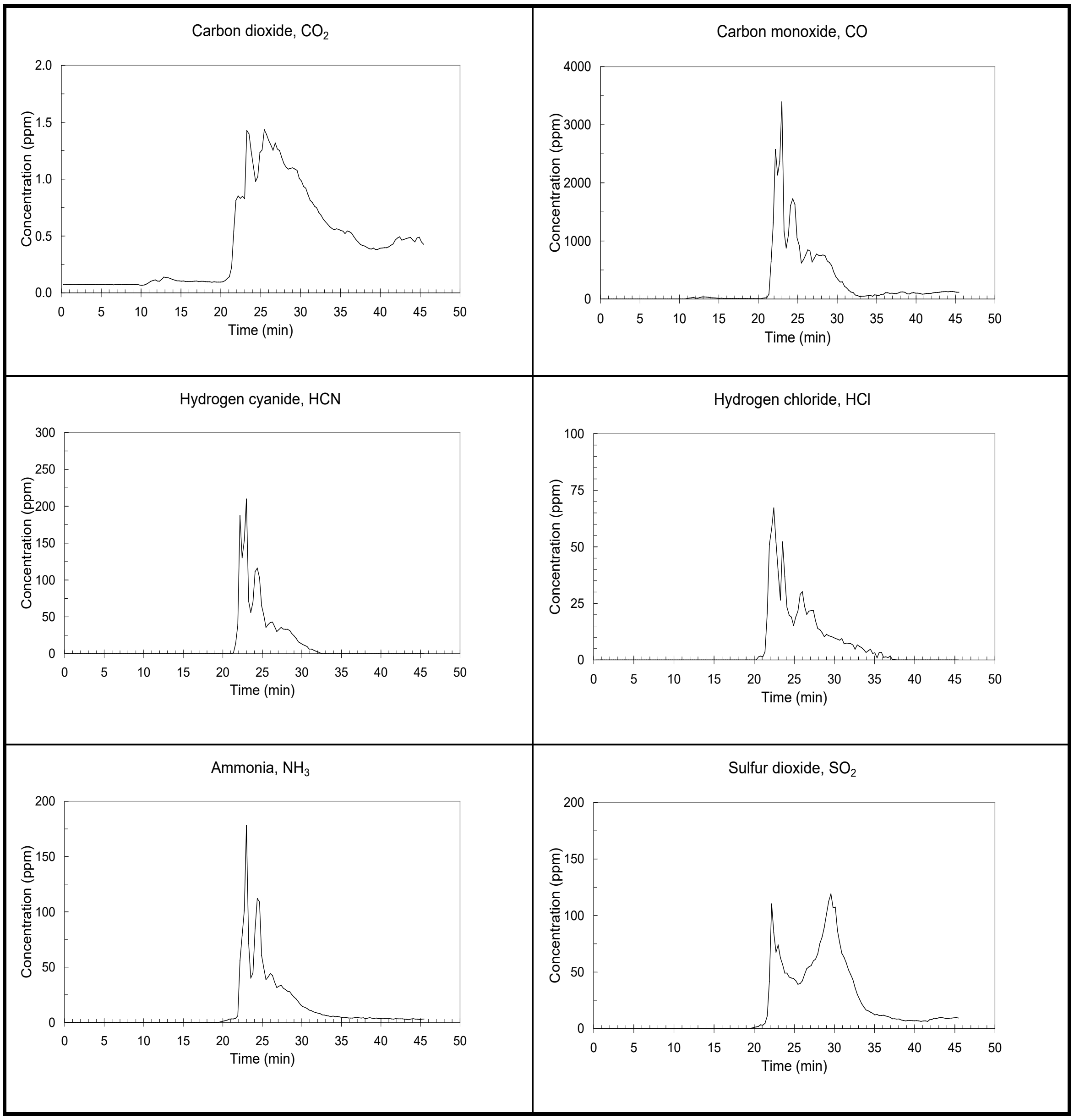

Figure 5: Collation of time resolved measurements of various toxic species measured in experiments and used for estimation of emissions in Fire Impact Tool. Note that the ignition time is t=7 minutes.

3 Modified Fire Impact Tool

3.1 Background

When faced with a fire incident, emergency responders must make strategic and tactical decisions quickly to minimize loss of life and damage to property and the environment. In 2020, the first working version of the Fire Impact Tool was published as a method to assess the environmental impact of different tactical decisions that might be made as part of a typical response [6].

Given the complexity of predicting the environmental impacts of fire, the Fire Impact Tool was developed to provide a basic structure for training responders about the environmental consequences of fires and firefighting operations. This tool does not provide absolute, perfectly accurate predictions for every possible fire scenario, nor does it propose the correct tactical response; rather, it provides a basis for discussion of choices made when fighting common fire scenarios and highlights the fact that there are both local and global impacts created by any fire and associated response.

The Fire Impact Tool is a starting point for ensuing research into the environmental impact of fires and firefighting. In short, the Fire Impact Tool was designed to be a framework into which increasingly improved information (both in breadth and depth) can be added over time to keep the tool current, strengthening the bridge between the scientific research and emergency responder communities, thereby helping emergency responders better understand how fire and firefighting operations impact the environment.

3.2 Overarching Structure

The original Fire Impact Tool was comprised of three components: fire models, environmental risk assessment (ERA) and lifecycle assessment (LCA). The fire models support the ERA and LCA calculations by establishing fire growth curves that determine the amount of damage done and the amount of effluents released to the environment for two types of fires- vehicles and enclosures. The tool uses ERA modelling to predict environmental impacts to the local surroundings from fire water run-off and it uses LCA modelling to predict global environmental impacts (not tied to the local environment). These components are discussed in more detail in the full Fire Impact Tool report [6] and an example use case is discussed in Appendix A.

A modified version of the Fire Impact Tool was used for this project. The ERA calculations and vehicle fire scenario have been removed so only a description of the enclosure fire model and the details of the LCA modelling are presented in this report. In Figure 6 the system boundaries for enclosure fires addressed in the modified Fire Impact Tool are shown.

The Fire Impact Tool includes fire emissions to the air in the global aspects of the environmental impact. Such local emissions are a topic of concern to the responder community, particularly in light of a 2010 declaration by the International Agency for Research on Cancer (IARC) that firefighters have an increased risk of certain types of cancer [49].

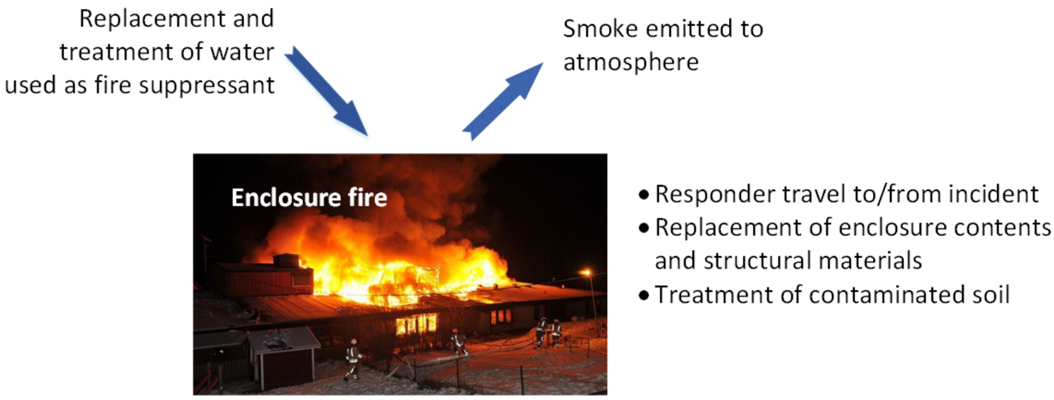

Figure 6: The system boundaries for the modified Fire Impact Tool include replacement and treatment of water as a fire suppressant, smoke from the fire, responder travel, treatment of contaminated soil, and replacement of enclosure contents and structural materials.

3.2.1 Enclosure fire scenario model

The enclosure fire scenario was originally developed to be representative of a school where a fire compartment can include four rooms, although it can be applied to represent other similar enclosure geometries. The user can input the size of room and room openings, fuel load, start and end of fully developed fire (although the fire will stop before the user-defined end time if all available fuel has been consumed), whether active suppression is used and the volume of water applied. Note that the choice of four rooms was arbitrary and does not relate to any specific building type in Sweden where the model was developed. In Table 3, the input parameters for defining the fire scenario for four compartments in the original Fire Impact Tool are shown. The modified tool is restricted to one compartment, as indicated in red in Table 3.

Table 3: Input parameters for defining the enclosure fire scenario. In this case, room one is not actively extinguished.

Fire Compartment Model Input					**Defaults**
Room number	**1**	**2**	**3**	**4**	
Opening average height dimension [m]	1.2	0	0	0	1.2
Opening area [m^2]	10	0	0	0	10
Room size [m^2]	100	0	0	0	60
Fuel load [MJ/m^2]*	600	0	0	0	250 - 450

Other modifications have been made to the enclosure fire scenario relative to the original version of the Fire Impact Tool in that the involvement of the contents and enclosure in the fire can be included in a gradual manner. It should be noted that the enclosure is a wooden frame enclosure which is assumed to be replaced once the fire has damaged the structure, i.e., moved beyond the interior surface material. If the active suppression option is selected, a module for estimating the size of the response and the contamination of extinguishing water is activated.

The fire model calculates the heat release rate based on the ventilation factor, assuming that all available oxygen is used for combustion [50] and that the fire is fully developed:

$$HRR = 1.518 * A_0\sqrt{H_0} \quad (1)$$

Where *HRR* is the heat release rate [MW], A_0 is the opening area [m^2], and H_0 is the average opening height [m]. This is reasonable given that the emissions created in the early stages of the fire are minor.

For simplicity, the Fire Impact Tool assumes that all fuel is burned inside the compartment, i.e., the model does not allow for a certain percentage of the fuel to burn outside the compartment. Using the given ventilation factor, a time stepping procedure is used to calculate how much energy is released from the fire. If the user prescribes a fuel load that is too low to maintain the fire for the time prescribed, the fire will stop burning when the fuel is consumed.

The emissions from the fire to the atmosphere are estimated based on data from an experimental study performed at RISE [48]. Three tests were performed with furnished rooms of size 4 x 4 x 2.5 m^3 with an opening of height 2 m and width 1.2 m. The contents in the room in experiment 1 are shown in Table 4. The HRR and species emissions for experiment 1 are used to exemplify typical fire development. The other two experiments had similar contents and performance.

Table 4: Contents of the rooms in the reference scenario for smoke emission from a room fire [51] .

Item	***#***	***Weight [kg]***	***Main combustible material***
Sofa	1	72	Wood, PUR, cotton
Armchair	2	19 × 2 = 38	Wood, leather, filling
Corner bookshelf	1	52	Particleboard, veneer
Bookshelf	3	30 X 3 = 90	Particleboard, veneer
Coffee table	1	26	Wood
Carpet	2 x 2 m	Approx. 20	Wood, synthetic
Curtains	10 m	5	Cotton
Books Exp 1	-	219	Paper
EU TV, Exp 1	1	31.4	Polystyrene

The amount of the gaseous emissions used in the model is based on the average of the three experiments and is directly scaled with the total energy of the fire, i.e., if the energy in the tool is doubled, twice as much pollution is assumed to be emitted as in the experiments.

If the active suppression option is selected, the amount of species in the water is based on an experimental study performed at FM Global [7, 11, 12]. The values per m^2 are used as input to the emissions in the Fire Impact tool. Therefore, if the floor area in the tool is doubled, twice as much pollution is assumed to be released to the water as in the experiments. The user inputs the amount of water used as a basis for the calculation of the pollutant concentrations.

The size of the room in the experiments was 4.6 x 6.1 x 2.4 m^3 with an opening of 1.2 x 2 m^2. The room also had four windows and an exterior door, with a window that was closed at the start of the fire. The size of the windows was 0.9 x 1.47 m^2 and the window in the exterior door was 0.51 x 0.9 m^2. All the windows fell out between 4 and 6 minutes from the ignition of the fire. The main combustible content in the room is shown in Table 5.

Table 5: Contents of the rooms in the reference scenario for contamination of extinguishment water (information extracted from Wieczorek et al. [7]).

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

3.2.2 Lifecycle Assessment (LCA) model

LCA is a methodology that is used to predict the environmental impacts associated with the whole or partial life of a product, process or activity; the subject of the assessment is usually referred to as a "system" [52]. An LCA can be conducted in compliance with the procedures specified in the International Organization for Standardization (ISO) standards ISO 14040 and ISO 14044 [53, 54], or non-standardized lifecycle *thinking* can be applied to virtually any situation. As depicted in Figure 7, a standard LCA study is structured to have four major components: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation of results.

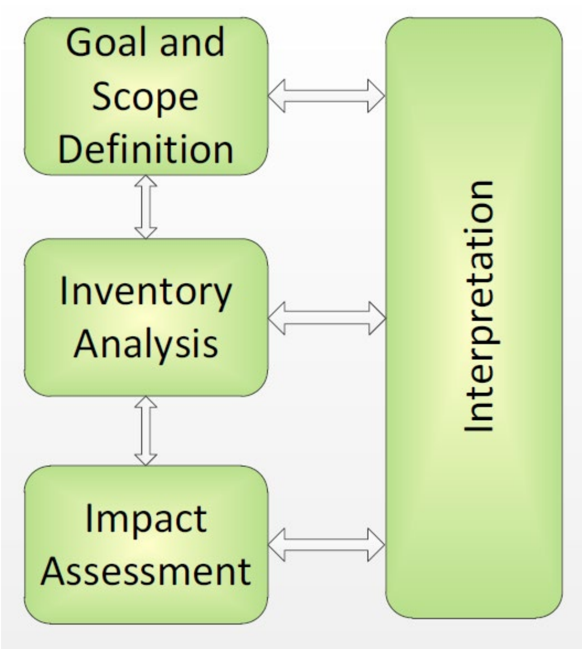

Figure 7: Components in an LCA analysis of a system.

Goal and Scope

This LCA model provides support for including global environmental consequences when considering the most appropriate course of action in response to a fire. It is understood that there are many factors that affect decisions made in response to fires, and that environmental impact may not always be the most important factor; however, it is not possible to balance environmental considerations against other factors without knowledge of their nature and magnitude.

The boundaries of the system used in this application of the model include the burning object, surroundings that are affected by the fire and its effluents, including smoke and subsequent treatment of run-off water or suppression agents. The system also includes fire suppression operations, replacement of fire suppressants, travel to/from the incident. Restoration of the enclosure contents and structural materials is also included on an increasing scale because there could be differing amounts of material to replace depending on the spread of the fire within the fire compartment.

The functional unit of the LCA models is one response to a specific fire. Since this is a comparative tool, the focus is on the differences between fire scenarios.

Inventory Analysis

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

The inventory data includes:

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

The fire effluents are either components of smoke or fire water run-off. The only parts of the fire water run-off included in this analysis are the replacement and treatment of suppressants.

Replacement of structural materials was accomplished by using the Athena Building Impact Estimator (ABIE) [55] to produces a bill of materials for a structure. The building has a concrete slab floor, wooden joists and beams, wooden exterior cladding, triple glazed windows, painted gypsum interior walls, and a tile roof. The ABIE also predicts the energy needed to construct the building. The output from the ABIE was used as input to LCA software to predict the impacts of replacing the structural materials lost in the fire.

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

The output from the LCA software is allocated in several different ways in the Fire Impact tool, as described below:

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

Impact Assessment

The Fire Impact tool uses the Eco-Scarcity 2013 method [56] for impact assessment. Life cycle inventory analysis is used to determine the impacts of design choices on the environment and human health by classifying and characterizing emissions and resource uses. Classification requires emissions to be allocated to specific impact categories, e.g., climate change, acidification and eutrophication. As part of this process, substances with similar impact are combined, e.g., substances that contribute to climate change are combined and characterized by their global warming potential (GWP). This enables life cycle practitioners to add up the contributions made by emissions or resource uses in relation to the same impact, creating an overall measure of the environmental pressure in this category or class of impact.

Depending on the goal of the LCA, the environmental impacts may be normalized and weighted to allow comparisons between categories. One important question concerns how to weight different impact categories against each other, e.g., how to weight GWP, acidification and eutrophication potential against each other. Typically, this is done using a damage model or a distance-to-target model. Damage models use aspects such as loss of equivalent lives or disappearance of species and distance-to-target models use environmental quality targets as a benchmark.

The ecological scarcity method applied in the Fire Impact Tool combines the environmental impacts using the metric of eco-points (UBP). Higher total eco-points correspond to a higher environmental burden. The eco-points are calculated using eco-factors. The eco-factors used in the present application are based on statutory environmental targets in Switzerland. Other national targets could be applied but the recalculation of eco-points for another country is outside of the scope of this project. As the model aims to compare different scenario choices, it is expected that the relative eco-points will not be greatly impacted by the country chosen for eco-point determination. The impact categories used in the Eco-Scarcity method are described in Table 6.

Table 6: Impact categories from the Eco-Scarcity impact assessment method [56]. Note that all units are in UBP, "Eco-points".

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

The key metrics of this method are eco-factors, which measure the environmental impact of pollutant emissions or resource extraction activities in eco-points (EP=UBP) per unit of quantity. The eco-points conversion table is reproduced from reference [56] in Appendix B. The reason for applying the eco-scarcity assessment method in the original Fire Impact Tool was because it specifically includes an impact category for persistent organic pollutants (POPs), which were an important factor for the intended use of the tool.

The POPs impact category is not significant in the modified Fire Impact Tool presented here, however, changing the impact assessment method to a more common one, such as ReCiPe H [57, 58], would require significant effort but would not add significant value, as the results in this report are comparative and presented in a relative manner.

Interpretation

The interpretation step in LCA involves analysis of the completeness and accuracy of the modelling process as well as analysis of the results. Conclusions and recommendations are made only after the model and results have been examined and the strengths and weaknesses identified. It is important to keep these considerations in mind when assessing the results presented in the following section.

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

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

4 Application of Fire Impact Tool to Assess Detection

4.1 Scenario Descriptions

For the applications presented in this project a single room model is used for the enclosure fire. The basic structure of the building is a concrete slab floor, wooden joists and beams, wooden exterior cladding, triple glazed windows, painted gypsum interior walls, and a roof with exterior ceramic tiles. A single fire load and room size has been selected for this first application, 600 MJ/m^2. All fuel has been assumed to burn inside the enclosure (i.e., the fuel excess factor was set to zero throughout). The room size has been chosen as 100 m^2 with an opening area of 10 m^2 and average opening height of 1,2 m. In those cases where the fire service has responded to the fire it has been assumed that 5 heavy vehicles have responded together with 1 ambulance and 2 small additional vehicles, all vehicles with 15 km one-way travel distance. This number could be slightly low but it was found that the fire service vehicle response was negligible relative to other environmental contributors and has not been investigated further.

Figure 8 illustrates the fire and damage development used as a basis for the scenario calculations. The environmental impact is determined based on a combination of the fire and damage development and the fire intervention scenarios. To calculate the environmental impact associated with these different scenarios a number of assumptions have been made:

- The fire is ignited at time 0 min. Once the fire is ignited, the item first ignited will be damaged and require replacement (corresponding to 1% of the contents).
- The fire growth period starts at approximately 5 min from ignition, when the fire moves beyond the item first ignited.
- Once the fire moves beyond the first item ignited, it is assumed that the fire spread is approximately exponential.
- Once approx. 50% of the contents are burning, it is assumed that surface material (part of the structure) will begin to be involved in the fire and need replacement. This involvement increases for 2 minutes until the point of flashover at 15 minutes. From 15-21 minutes it is assumed that all interior finish (gypsum boards, etc) will need to be changed post fire.
- Once the fire reaches flashover at 15 minutes from ignition, all contents are damaged and need replacement.
- At 6 minutes after flashover (at 21 minutes), it is assumed that the structure is involved in the fire and there will be a need to replace/repair the structure, up to full replacement at 22 minutes until the end of the fire.

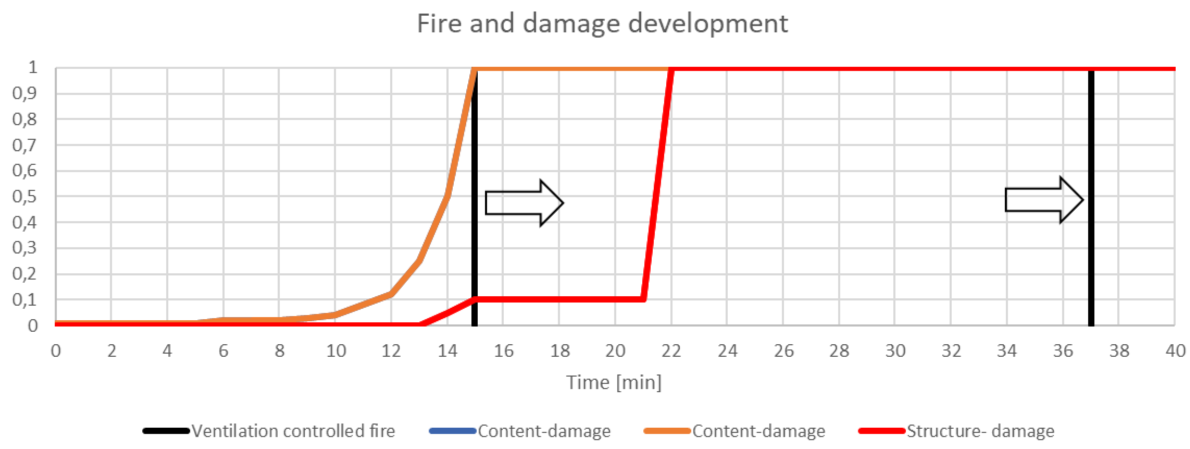

Figure 8: Schematic presentation of fire development and associated fire damage. Note that the ignition is at time t=0 min. The specific time progression corresponds to scenario 2, The first arrow corresponds to start of the ventilation controlled fire, the second arrow corresponds to the end of the ventilation controlled fire, in scenario 2 due to exhaustion of the fuel package.

The timing is presented for six scenarios in Table 7 based on the parameters introduced in Chapter 1 and the scenario descriptions above:

t_{det}= time from ignition until detection

t_{not} = time from detection until fire service notification

t_{resp}= time from notification until fire service arrive at fire

t_{setup} = time from fire service arrives at the fire until they setup on site

t_{agent}= time from fire service setup on site until fire suppression agent begins

t_{supp} = time from agent application begins until fire is suppressed (knocked down)

t_{ext} = time from initial suppression until fire is extinguished (suppressant no longer needed)

Table 7: Summary of timing for scenarios investigated. Note times are cumulative.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Description	Early det. + handheld extinguisher	Early det. + "let it burn"	Early det. + fire service suppression	Late det. + fire service suppression	Early det. + fire service suppression + minor contents damage	Early det. + fire service suppression + full contents damage
t_{ig} (min)	0	0	0	0	0	0
$+ t_{det}$ (min)	3	3	3	6	3	3
$+ t_{not}$ (min)	-	3	3	6	4	4
$+ t_{resp}$ (min)	-	13	13	16	14	14
$+ t_{setup}$ (min)	-	15	15	20	16	16
$+ t_{agent}$ (min)	5		15	20	4	4
$+ t_{supp}$ (min)	-		18	24	6	6
$+ t_{agent2}$ (min)					16	16
$+ t_{ext}$ (min)	7	37	18	24	16 (10% contents damage)	16 (all contents damaged)

The LCA input is schematically illustrated in Figure 9.

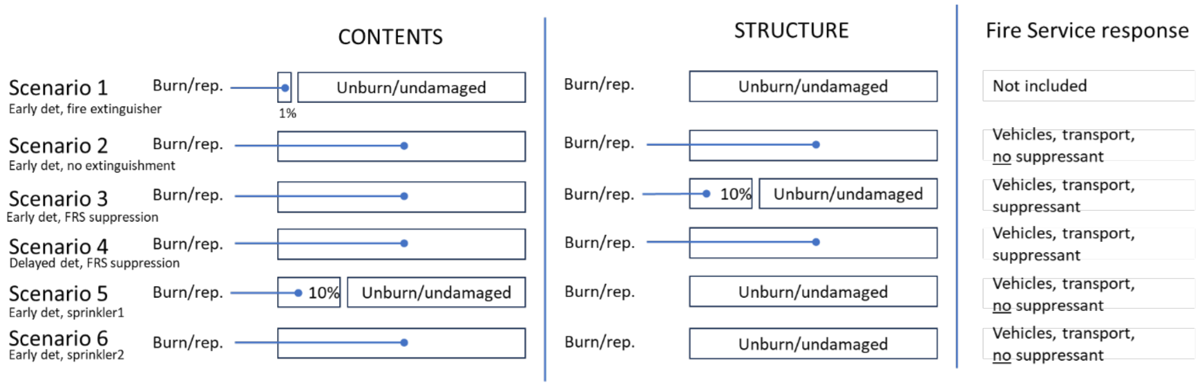

Figure 9: Schematic overview of the implications of each scenario in terms of LCA input.

4.2 Results

Scenario 1:

Description: Early detection and intervention with a fire extinguisher, no fire service response. From ignition it is assumed that the first item ignited will be replaced which corresponds to 1% of the contents.

Figure 10 summarizes the environmental impact of this scenario and its development over time. The rise in impact between 4-5 minutes corresponds to the deployment of the fire extinguisher at which point the environmental impact reaches its maximum. The scenario is cut off at 7 minutes, corresponding with extinction of the fire.

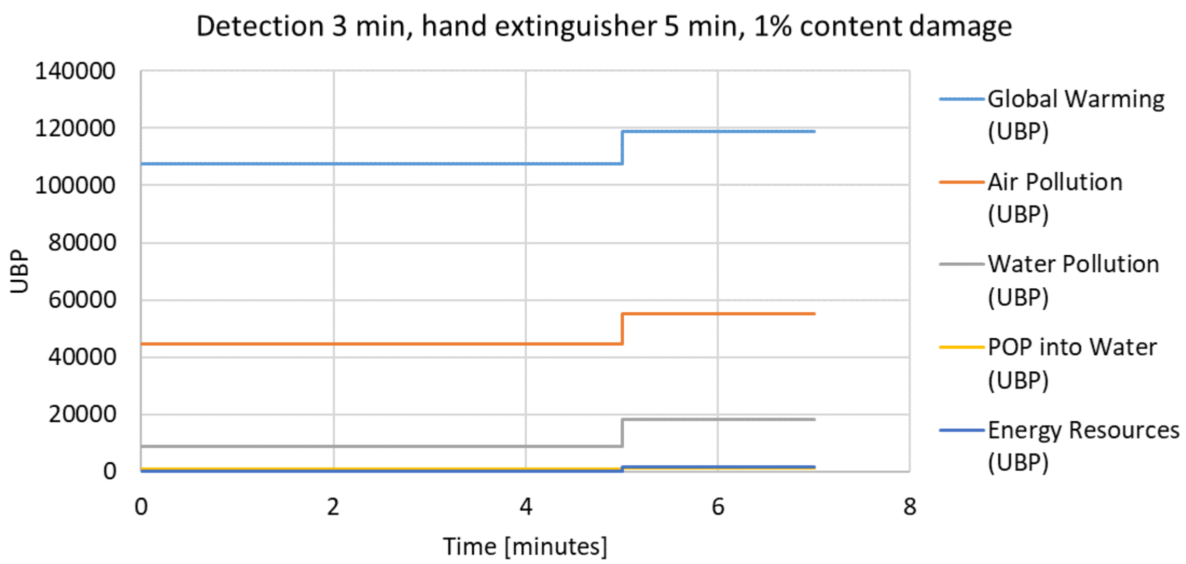

Figure 10: Environmental impact due to scenario 1 over time expressed as UPB. Note that t=0 is the time of ignition.

Scenario 2:

Description: Early detection (3 min) but no manual response, rather the fire service responds to the fire but does not attempt to extinguish. The fire service is automatically notified and time from notification to arrival at the scene is 10 minutes. A set-up time of 2 minutes is assumed. It takes approximately 37 minutes for the fuel to burn out, at which point the maximum environmental impact is reached.

Figure 11 summarizes the environmental impact of this scenario and its development over time. The rise in impact between 5-15 minutes corresponds to the burning contents (emissions) and the need to replace these. From 14 minutes there is inclusion of replacement of a small amount of the enclosure (interior finish). From 15 minutes, the fire service response is included (no water is included to suppress the fire, only transport) and from 22 minutes the full replacement of the structure is included. The small increase in environmental impact between 22 minutes and burnout at 37 minutes is due to fire emissions.

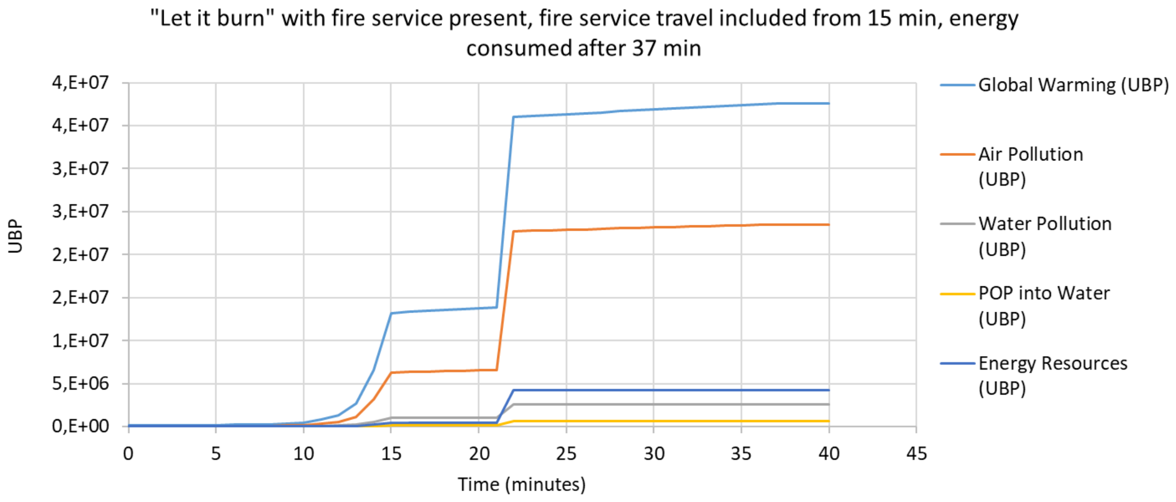

Figure 11: Environmental impact due to scenario 2 over time expressed as UPB. Note that t=0 is the time of ignition.

Scenario 3:

Description: Early detection (3 min), the fire service responds to the fire and commences suppression when they have arrived and set-up. The fire service is automatically notified and time from notification to arrival at the scene is 10 minutes. A set-up time of 2 minutes is assumed. Once suppression commences the fire is assumed to have been extinguished and maximum environmental impact is reached.

Figure 12 summarizes the environmental impact of this scenario and its development over time. The rise in impact between 5-15 minutes corresponds to the burning contents (emissions) and the need to replace these. From 14 minutes there is inclusion of replacement of a small amount of the enclosure (interior finish). From 15 minutes, the fire service response is included. The fire service extinguishes the fire with a generic amount of 1 000 liters of water application. A large part of the enclosure does not become involved in the fire in this scenario as the fire is extinguished prior to its involvement.

Figure 12: Environmental impact due to scenario 3 over time expressed as UPB. Note that t=0 is the time of ignition.

Scenario 4:

Description: Delayed detection (6 min), the fire service responds to the fire and commences suppression when they have arrived and set-up. The fire service is automatically notified and time from notification to arrival at the scene is 10 minutes. A set-up time of 2 minutes is assumed. Once suppression commences the fire is assumed to have been extinguished and maximum environmental impact is reached.

Figure 13 summarizes the environmental impact of this scenario and its development over time. The rise in impact between 5-15 minutes corresponds to the burning contents (emissions) and the need to replace these. From 14 minutes there is inclusion of replacement of a small amount of the enclosure (interior finish). From 15 minutes, the fire service response is included. The small delay in notification of the fire service means that the enclosure becomes involved in the fire before it can be extinguished. The fire service extinguishes the fire with a generic amount of 1 000 liters of water application. The full enclosure is included in the environmental impact from 22 minutes. The fire is extinguished at 24 minutes at which point the scenario ends.

Figure 13: Environmental impact due to scenario 4 over time expressed as UPB. Note that t=0 is the time of ignition.

Scenario 5:

<u>Description</u>: Early detection (3 min), the fire service responds to the fire and commences suppression when they have arrived and set-up. The fire service is automatically notified and time from notification to arrival at the scene is 10 minutes. A set-up time of 2 minutes is assumed. At the same time that the fire service is notified, a sprinkler system is activated. The sprinkler activation is tailored to a small fire and it is assumed that only 10% of the contents are damaged and need replacement.

Figure 14 summarizes the environmental impact of this scenario and its development over time. The rise in impact at 4 minutes is due to deployment of the sprinkler system and water damage to 10% of the contents. No damage is expected to the structure. The fire is rapidly suppressed by the sprinkler.

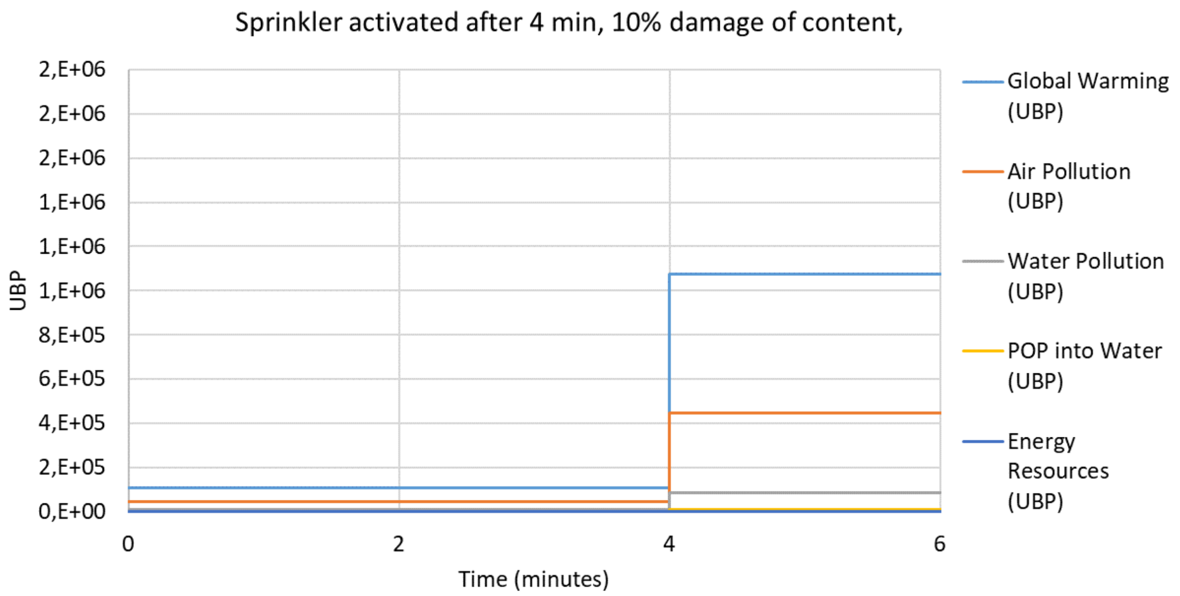

Figure 14: Environmental impact due to scenario 5 over time expressed as UPB. Note that t=0 is the time of ignition.

Scenario 6:

<u>Description</u>: Early detection (3 min), the fire service responds to the fire and commences suppression when they have arrived and set-up. The fire service is automatically notified and time from notification to arrival at the scene is 10 minutes. A set-up time of 2 minutes is assumed. At the same time that the fire service is notified, a sprinkler system is activated. The sprinkler activation is assumed to damage all contents and 100% are replaced.

Figure 15 summarizes the environmental impact of this scenario and its development over time. The rise in impact at 4 minutes is due to deployment of the sprinkler system and water damage to 100% of the contents. No damage is expected to the structure. The fire is rapidly suppressed by the sprinkler.

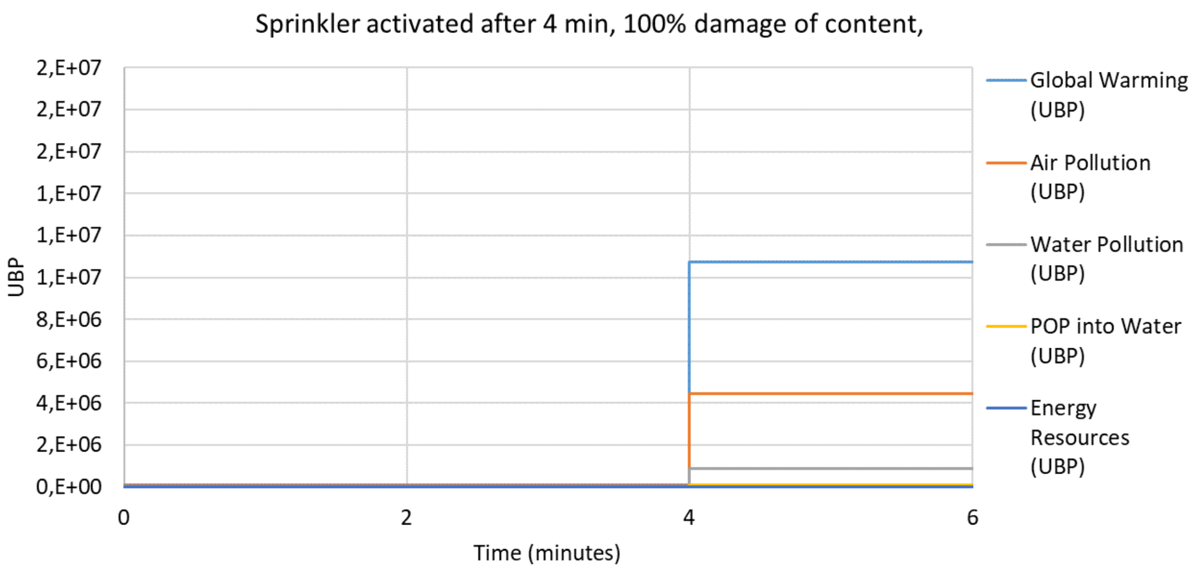

Figure 15: Environmental impact due to scenario 6 over time expressed as UPB. Note that t=0 is the time of ignition.

Comparison of scenarios 1-6:

While the presentation of environmental impact for each scenario and its development over time provides an understanding of at which point an environmental impact is included and the relative size of each contributing factor to the environmental impact of the individual scenarios, greatest insight is offered by a comparison between the various scenarios.

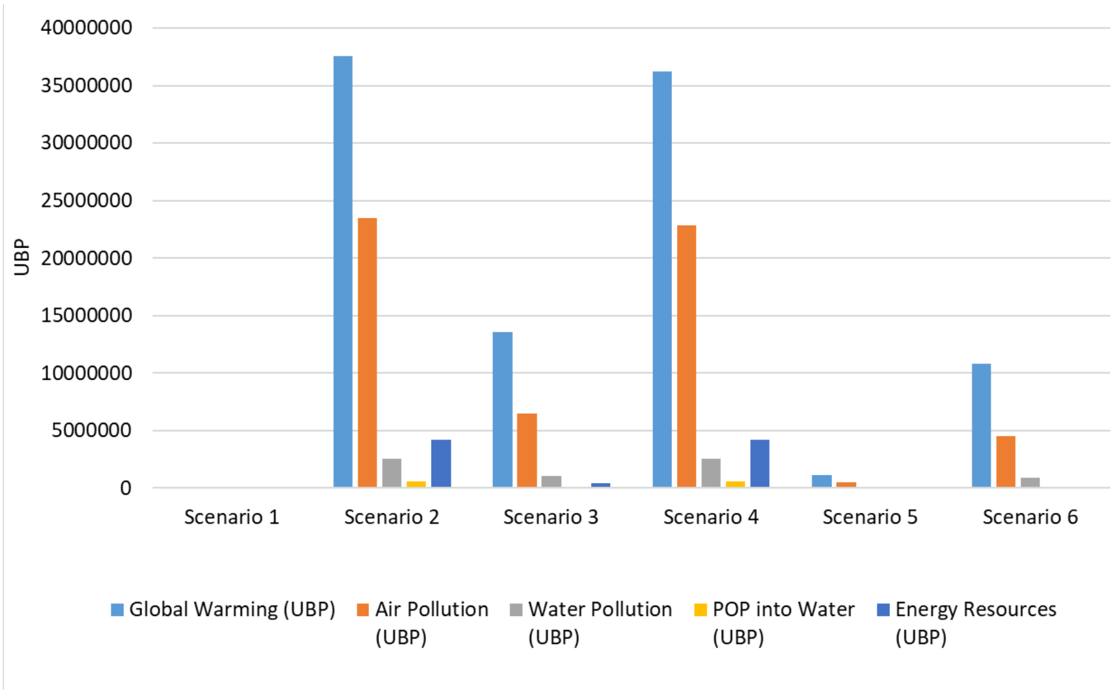

Figure 16: Comparison between all six scenarios.

To highlight the difference between the six scenarios, the highest category (Global warming) is also presented in Figure 17.

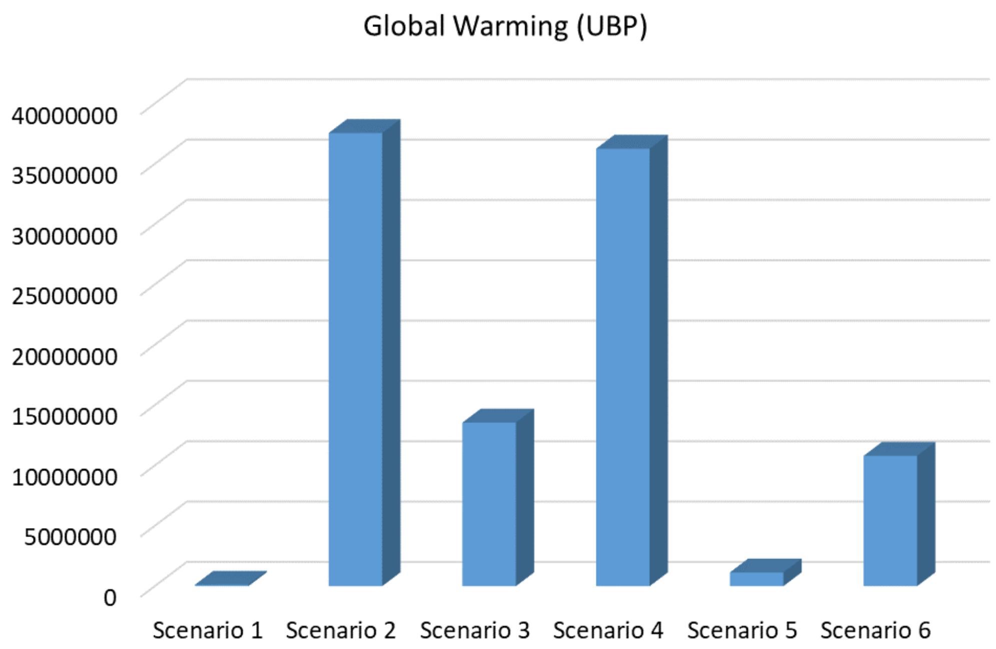

Figure 17: Comparison of Global warming potential for the six scenarios.

5 Discussion

An analysis of the environmental impact of a single story, timber-framed building, with contents that generically represent a range of occupancies, such as apartments, hotels, offices, medical suites, and similar, was undertaken using an updated version of the Fire Impact Tool. The specific aim was to investigate the potential contribution of early fire detection and early fire suppression to reducing the overall environmental impact of a fire in the structure. Fire service response and suppression activities were also included in the analysis. As part of the analysis, six scenarios were investigated, which ranged from early fire detection and suppression with a manual fire extinguisher, to no early detection and burnout without suppression activities. Environmental impact was estimated based on estimated percentage of contents and structure consumed and associated replacement, using environmental the ecological scarcity method, which combines environmental impacts using the metric of eco-points.

Based on the analysis, the outcomes show that early fire detection, response and extinguishment yields the best environmental results, i.e., lowest environmental impact. While this could be expected a priori, the analysis illustrates well the magnitude of reduced environmental impact for different types of interventions which occur at different times. This analysis supports other work which has looked at reduction in environmental impacts of fire using manual fire extinguishers [18] and automatic sprinkler systems [7,11-13], broadening the considerations to a different range of fuels, the contribution of the structure, and the contribution of fire service response and activities.

The analysis shows that the primary drivers of environmental impact from a fire in the scenarios considered were the structural materials and contents. While different structural materials may have lower environmental impacts from fire than the timber frame structure analyzed in this work, the contents involved in the fire would be expected to remain a significant contributor. Deployment of the fire service is a minor environmental cost relative to the cost of replacement of contents and structure. Replacement of the structure dominates once this has become involved in the fire.

While this first-order analysis reflects well the efficacy of early fire detection and suppression on reducing the environmental impact of fire in a building, there are some limitations to note, and further analysis that would be beneficial.

One limitation is that generic fire scenarios were used rather than the modeling of actual detection times for a specific set of conditions. In part this constraint was adopted due to the variability in conditions, which could yield a wide range of detection times, but likely not be significant to the outcome. For example, while one can model a range of factors such as fuel load distribution, ventilation openings and detector locations, for the compartment sizes selected, the variation in detection time would not be expected to be significant based on past fire tests found in the literature, in comparison to activation times of automatic suppression or fire service response times. However, future analysis should assess this more specifically.

Another limitation is that the sprinklers are assumed to be automatically activated at the same time as early detection in this work. Again, this limiting assumption was made given the relatively small variation between fire detection and sprinkler actuation times, particularly for flaming fires, in relatively small compartments. In future work, especially where a wider range of compartment configurations is evaluated, this can be included if more precise modeling of detection and sprinkler activation times is desired.

Lastly, while the outcomes illustrate the efficacy of early fire detection and suppression for a single structural material (timber) and building layout (single story, single compartment) with a given fuel load (contents), variation in each of these parameters is warranted as part of future research. These variables were limited in this scoping study as only a proof of concept was targeted, and it allowed for applying the building typology that was already implemented into the Fire Impact Tool. Future analyses that include variations in structural material, compartment configuration and contents will require new LCA calculations and heat release rate profiles / fire modeling calculations.

6 Conclusions

For the building typology, structural system and contents assumptions used in this study, findings show that early detection and extinguishment in combination is the best way to minimize the environmental impact of fires in buildings. Early fire detection and manual response with a fire extinguisher (or other) when the fire is very small limits the impacts most. Early fire detection, which notifies the fire service, coupled with automatic fire suppression (e.g., sprinklers), is also very effective, in that it gives the fire service the earliest opportunity to respond, and begins suppression of the fire automatically, so that the fire service will need fewer resources to extinguish any fire that may still be burning when they arrive. These actions are particularly important since the major contributors to the environmental impact of fire are structural components and contents that are consumed and/or damage by the fire and need to be replaced (resulting in carbon contributions related to the fire and to replacement). Additional research is recommended to expand the assessment to other building typologies, structural materials, building and compartment configurations, and fuel loads. More targeted modeling of fire detection and automatic fire suppression actuation may also be beneficial.

7 Future Research Needs

This proof-of-concept research clearly indicates the significant benefits of early fire detection and fire suppression on reducing the environmental impact of building fires. However, as noted in the report, a number of limitations and simplifying assumptions were made in this first order analysis. To further explore the benefits of early fire detection and fire suppression on reducing the environmental impact of building fires, the following future research tasks are suggested:

- Conduct similar analyses with different structural materials to explore the magnitude of impact of early fire detection and suppression relative to different structural materials for the same fire scenarios.
- For the same building typology with different structural materials, vary the fuel loads to explore the magnitude of impact of early fire detection and suppression relative to different fuel loads for the assessed structural materials and fire scenarios.
- For the same building typology, vary compartment configurations and ventilation factors to explore the magnitude of impact of early fire detection and suppression relative to these factors for the assessed structural materials and fire scenarios.
- Explore the relative importance of modeling more specific fire detector and fire suppression system actuation on the overall reduction in environmental impact. (That is, is it necessary to conduct such detailed assessments or is use of simplifying assumptions sufficient for the purpose.)
- Explore different building typologies and associated compartment and ventilation configurations and fuel loads to explore the magnitude of impact of early fire detection and suppression relative to different building uses and configurations.
- In the case that environmental impacts of large, uncontrolled building fires is of interest, explore in more detail the environmental impacts of fire suppression activities along with emission from the fire and rebuild impacts (e.g., in the case of warehouse fire with harmful /hazardous chemicals or materials storage).

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Appendix A – Example use case for original Fire Impact Tool

The following use case is replicated from [6] and describes a school fire in which two possible outcomes are compared. The ERA results are not included as they are not of interest to this project.

The following analysis is based on the Grillby school fire reported by [59] in which a fire started, probably in a cloakroom, and spread into two parts of the school: a "pavilion" and an "expedition", which are part of the same fire compartment. The school was evacuated quickly with no injuries, removing life safety as a strategic priority. Police established an incident perimeter prior to the arrival of the fire services.

The fire service strategy was to limit the fire spread to the pavilion, if possible, then limit it to the expedition, and then the library, as fallback positions if necessary. A diagram of the affected school building is shown in Figure 18.

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

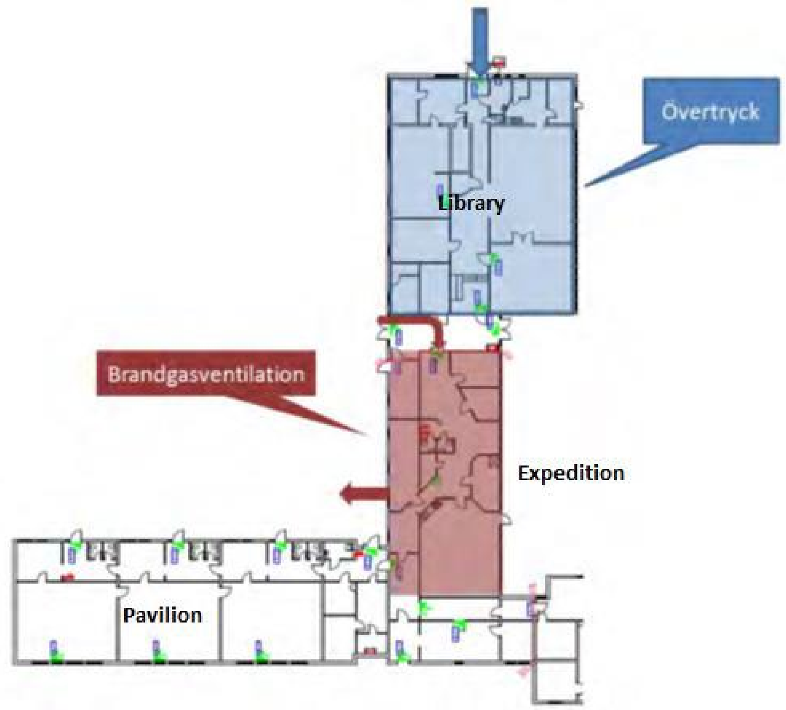

Figure 18: Grillby school fire configuration. Fire started in Pavilion and spread to Expedition, but not to Library.

Fire Impact tool setup

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

- The default of 1.2 m for the average opening height dimension will be used.
- The opening area will be 100 m^2, based on the default ratio of opening area to room area used for smaller classrooms.

- The rooms are approximately the same size according to Figure 18, and they are much bigger than a standard classroom so 600 m^2 is chosen.
- A fuel load of 350 MJ/m^2 is used for the pavilion and expedition, which is in the centre of the default range. The library is given a higher fuel load of 450 MJ/m^2 due to the extra load of books.
- The fire started in the pavilion and burned for several minutes before reaching the fully developed phase so 5 minutes is chosen as the start time.
- The response was finished within about 4 hours of the initial alarm so 240 minutes will be used for the end time of the fire in the pavilion.
- It is not clear when the fire spread to the expedition, so an estimate of 30 minutes is chosen.
- It is also not clear when the fire ended in the expedition, so an estimate of 60 minutes is chosen.
- The fire did not spread to the library.

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

Comparison scenario 2 is removed from both the fire and response models for the initial setup. Scenario 1 will represent the actual response for this part of the analysis. The fire model input is shown in Table 8 and the response input is listed below and shown in Table 9:

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

Table 8: Fire compartment model input for the initial analysis of the Grillby school fire.

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

Table 9: Response model for the initial analysis of the Grillby school fire.

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

For the initial analysis the global impacts presented in Figure 19 show that the "Let it Burn" case is worse than scenario 1 in all categories except POP into Water. The impacts in scenario 1 are split roughly equally between the pavilion and the expedition in all categories (not shown here).

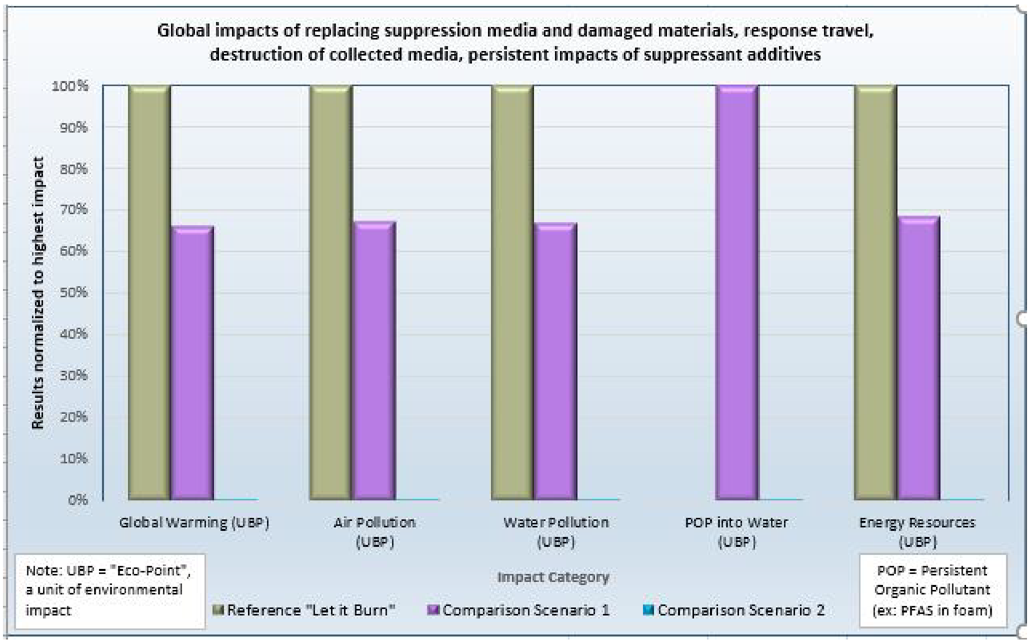

Figure 19: Global results for initial analysis of the Grillby school fire.

The distribution of global impacts according to their sources is shown in Figure 20, where most of the impacts come from replacing the building materials. A portion of response travel is assigned to Room 3 (library) because active suppression was used to prevent the fire from spreading into it. The same portion of active suppression is also assigned to Room 1 (pavilion) and Room 2 (expedition), but contributions from other sources obscure the relatively small contribution from response travel for Room 1 and Room 2.

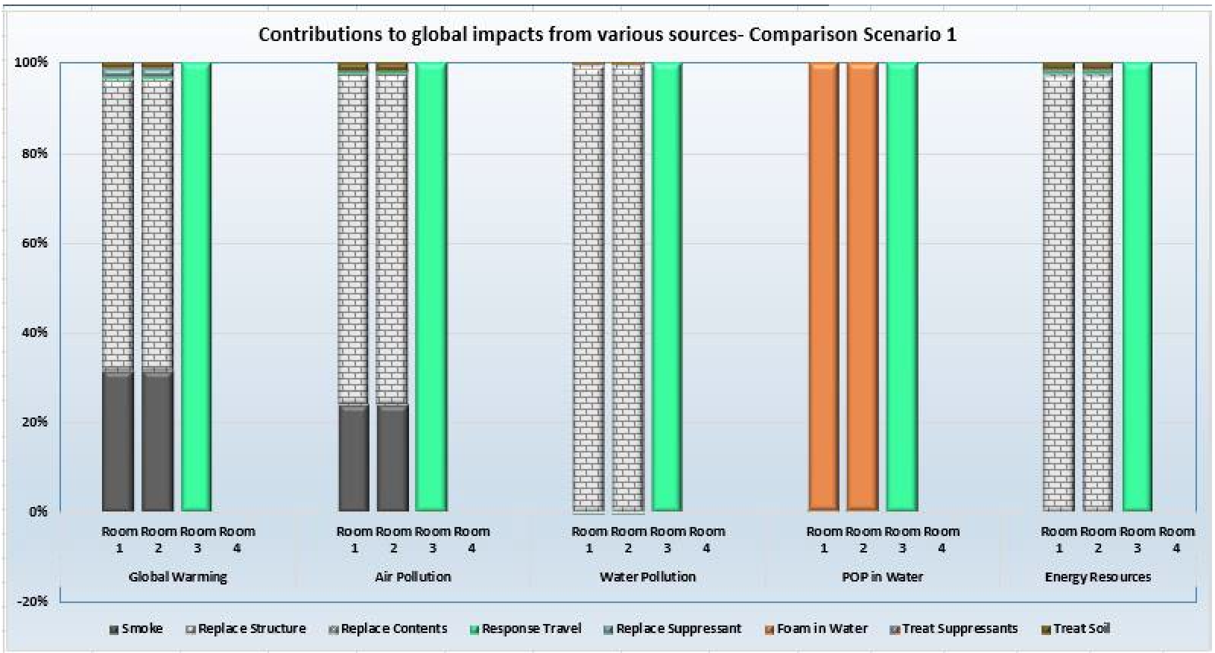

Figure 20: Distribution of global impacts by their source for the initial analysis of the Grillby school fire.

Alternative outcome

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

Table 10: Fire compartment input comparing the initial analysis (scenario 1) with a scenario in which the library burns (scenario 2).

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

The response input is the same as the initial analysis for scenario 1, shown in Table 11, and 10 % more suppression media used for scenario 2. All other inputs are equal.

Table 11: Response input comparing the initial analysis (scenario 1) with a scenario in which the library burns (scenario 2).

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

The global results shown in Figure 21 show higher impacts for scenario 2 in three categories and virtually no change in two categories. The Water Pollution and Energy Resources categories are not sensitive to the changes in the water and foam used for fire suppression in scenario 2, although differences in these impacts are seen in the local results.

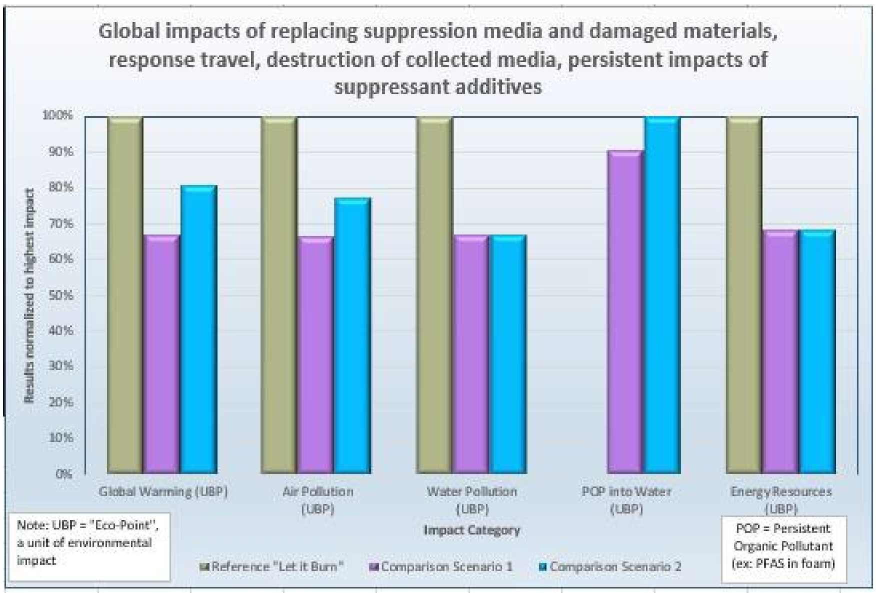

Figure 21: Global impact results comparing the initial analysis (scenario 1) with the fire spreading to the library (scenario 2)

In Figure 22 the contributions to global impacts by their source are presented for scenario 2 and can be compared with the results shown in Figure 20 for scenario 1. Since the fire has spread to the library in scenario 2 the response travel is no longer the only contributor to global impacts for Room 3. The results for Room 3 now look very much like the results for Room 1 and Room 2, in which replacing the building materials is the dominant contributor in all categories.

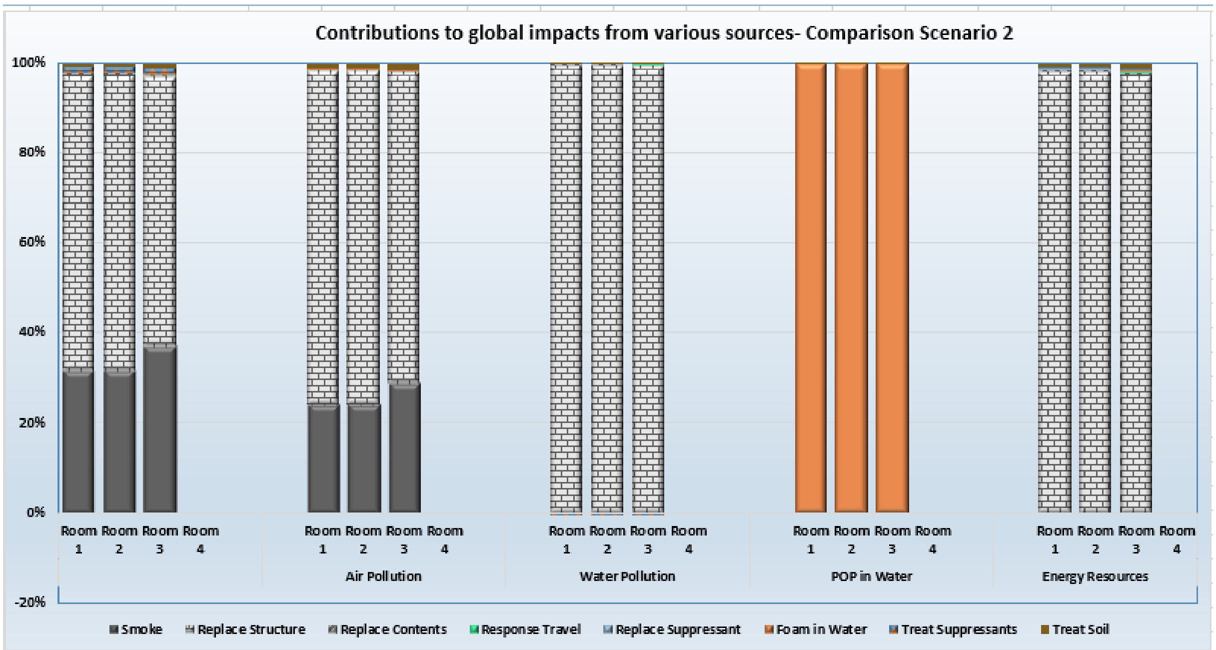

Figure 22: Distribution of global impacts by their source for the alternative outcome that the fire spreads to the Grillby school library.

The breakdown of global impacts by room and impact category is shown in Figure 23. The additional impacts from the fire spreading to the library, which has a higher fuel load than the other two rooms, cause the total impacts per category slightly higher (except for the POP into Water category) than the ”Let it Burn” reference case. This is because of the impacts associated with the suppression media. Note that the difference in magnitude between scenario 2 and the reference case is insignificant when uncertainties in the model results are considered.

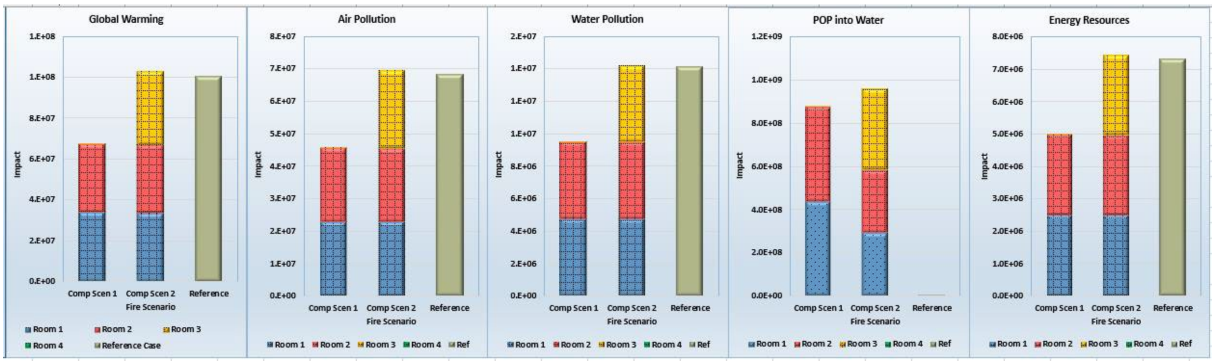

Figure 23: Breakdown of global impacts by room and impact.

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

Appendix B –Ecological scarcity impact assessment method eco-factors

Overview of eco-factors for 2013

	Normalization flow		Ecofactor 2013	UBP per
Emissions to air				
CO_2	53 040 000	t CO_2-eq	0.46	g CO_2-eq
Ozone-depleting substances	191	t R11-eq.	8 500	g R11-eq
NMVOC	89 025	t	14	g
NO_x	78 704	t	39	g
NH_3 (as N)	51 463	t	82	g NH_3-N
SO_2	12 861	t $SO_{2\text{-eq}}$	21	g $SO_{2\text{-eq}}$
PM10	20 470	t	140	g
PM2.5–10	20 470	t	140	g
PM2.5	20 470	t	140	g
Diesel soot	1 661	t	38 000	g
Carcinogenic substances (Benzene, Dioxins and Furans, PAHs)	0.9	CTUh	$2.7 * 10^{12}$	CTUh
Benzene	-		810	g
Dioxins and Furans	-		$7.9 * 10^{10}$	g
PAHs	-		1 400 [2]	g BAP-eq
Lead	23	t	22 000	g
Cadmium	1.26	t	460 000	g
Mercury	1.05	t	210 000	g
Zinc	378	t	5 600	g
Radioactive emissions	1.08	TBq C-14-eq	0.0008	kBq C-14-eq
Emissions to surface waters				
Nitrogen (as N)	36 197	t	57	g N
Phosphorus (as P)	1 854	t	890	g P
COD	37 002	t	6.8	g
Arsenic	10.7	t	10 000	g
Lead	27.4	t	4 200	g
Cadmium	0.66	t	250 000	g
Chromium	22.6	t	12 000	g
Copper	81.1	t	13 000	g
Nickel	62.4	t	11 000	g
Mercury	0.20	t	860 000	g
Zinc	123	t	6 200	g
Radioactive emissions to domestic waters	0.289	TBq U-235-eq	0.22	kBq U-235-eq
Radioactive emissions to seas	3.85	TBq C14-eq	81	kBq C14-eq
Oil emissions to the sea	6 210	t	270	g
AOX (as Cl^-)	249.6	t	170	g Cl
Chloroform	2.9	t	3 400	g
PAHs	0.328	t	14 000	g
Benzo(a)pyrene	15.7	kg	1 900 000	g
Endocrine disruptors	2.9	kg E2-eq	7 800 000	g E2-eq
Persistent organic pollutants	290	t 2,4,6-T-eq	17	g 2,4,6-T-eq

	Normalization flow		Ecofactor 2013	UBP per
Emissions to groundwater				
Nitrogen (as N)	34 000	t	120	g NO_3-N
Emissions to soil				
Lead	29.4	t	17 000	g
Cadmium	2.2	t	270 000	g
Copper	118	t	14 000	g
Zinc	763	t	2 800	g
Plant protection products	8 241	t Glyphosat-eq	150	g Glyphosat-eq
Resources				
Primary energy carriers	1 428	PJ-eq	3.4	MJ Öl-eq
Land use, settlement area	2 437	km².a SF-eq	300	m².a SF-eq
Primary mineral resources	904	t Sb-eq	1 100	g Sb-eq
Gravel	33 460	1000 t	0.03	g
Freshwater Switzerland	2.61	km³	23	m³
Freshwater OECD	2.61	km³	609	m³
Wastes				
C to landfill	183 222	t	5.5	g C
Hazardous wastes to underground disposal sites	37 223	t	27	g
High-level radioactive wastes	146.6	m³ HAA-eq	46 000	cm³ HAA-eq
Noise				
Noise road	803 882	HAP	3 400 000	HAP
• Passenger transportation			21	vkm
• Transportation of goods			210	vkm
Noise train	803 882	HAP	4 300 000	HAP
• Passenger transportation			5.2	pkm
• Transportation of goods			15	tkm
Noise aircraft	803 882	HAP	4 100 000	HAP
• Passenger transportation			1.4	pkm
• Transportation of goods			14	tkm

[1] Value derived from PM10 critical flow and PM2.5 proportion

[2] Ecofactor for PAH, world average

[3] Value calculated from ratio of current to critical flow of emissions to soil

Temporal reference: The figures are based on the data available in 2011 and 2012.